Horses vs. Machines

A Comparative Energy Analysis between Eighteenth Century- and Modern Copper Mining

Amos Strömberg

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Bachelor's degree in Human Ecology
Human Ecology Division
Department of Human Ecology
Faculty of Social Sciences
Lund University

Author: Amos Strömberg
Supervisor: Andreas Roos
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“Only a people serving an apprenticeship to nature can be trusted with machines”

– Sir Herbert Edward Read (1955)

Abstract:

This study shows the positive benefits of early 18th century copper mining in terms of energy efficiency due to the utilization of animate power, pre-industrial machinery, biofuels and a small-scale of organization. Based on the concept of embodied energy, this study calculates the inputs in early 18th century Falun Coppermine in Sweden and compares it with present-day Chibuluma Coppermine in Zambia. The results show that the raising of copper ore in Falun Coppermine in Sweden was 14 times more energy efficient per unit of copper ore compared to the Chibuluma Coppermine in Zambia. With a growing concern for a potential peak copper as a result of declining ore grades, a discussion on future copper supply is crucial. Drawing on E. F. Schumacher's *Small Is Beautiful* (1973), this study presents alternative perspectives on metal extraction, arguing that mining does not have to be large-scale nor fossil fuel driven to be energy efficient, but can even save energy if pre-industrial methods of metal extraction are applied. In relation to Podolinsky's principle, this thesis also argues that the energy efficiency of human labour degrades if a high level of per capita material consumption is assumed. Lastly, with reference to an increase of copper demand per capita, I discuss the feasibility of degrowth and the necessity for a downscaling in copper consumption.

Keywords: *Copper mining, embodied energy, small-scale mining, degrowth, copper ore grade, Podolinsky's principle, large-scale mining, 18th century mining*

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Words and phrases

Copper ore	A piece of rock which contains enough metallic copper to be economically viable to extract.
Gangue	The commercially worthless material in the ore surrounding the wanted metal.
Ore grade	The ratio of how much pure metallic copper exists in the ore. For example, if a piece of rock weighs 1 kg and has a copper ore grade of 3%, the rock contains 30 grams of metallic copper.
Emergy	The amount of all energy required in the processes and manufacturing of products, services and work.

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1. Introduction

In 2018 I attended Ende Gelände and with hundreds of other environmental activists and occupied one of the coal mines outside of Köln. Upon seeing the vast, desert landscape of a modern open-pit coal mine, the enormous, almost sci-fi indulging bucket-wheel excavators, and feeling my nostrils being clogged and blackened with dust, I remember a question emerging in my head: is *this* what my modern lifestyle is built upon? I would come to realize that these abysmal open-pit coal mines are only a small part of the mining architecture of the modern system and its technologies – including mobile phones, solar panels, wind farms, electric vehicles, tractors for food production, trains for transportation. One single Swedish wind turbine can contain more than 500 tonnes of steel (Andersen 2015: 17). In other words, practically each and every object seen in a city or in one's home which isn't of organic matter, has instead been mined (Franks 2015). This physical reality behind energy, materials and products are imperative to scrutinize. Even Socrates more than two thousand years ago was well aware of the inextricable web of metals needed in practically all societies; the farmer was the producer of food, but he or she would need an iron plough and hence also blacksmiths and miners (Futter 2018: 24). However, while such extractive practices were an integral part of a local community in pre-industrial mining villages, metals today appear merely as oblivious ghost ingredients for our society. They are in constant demand but still produced in the unknown. The 'green' economy has nurtured the production of these ghost ingredients, and thus also exacerbated one of the most socioecologically damaging industries in operation today, such as the pernicious processes of deep-sea mining (Ponting 2007: 325; Ericsson et al.: 2019: 112; Maus et al. 2020; Childs 2020). The advancement of this "smart" and large-scale mining trajectory has, due to the social inequalities and land appropriations it implies, been met with violent repression by local and rural people ever since the 18th century and well into modern days (Rule 1971: 183-188; Arboleda 2020: 2-3). Here, in a sense, an oxymoron can be recognized; modern welfare is inextricably dependent on a myriad of metals – metals that have to come from the very foul mining operations which environmental organizations condemn.

The response to this situation is often that there are simply no other alternatives (Smith 2011). This is however questionable, because the phenomenon of mining appears in a variety of different forms throughout history, and modern large-scale mining is but one of them. As opposed to large-scale mining, the concept of artisanal small-scale mining (such as 18th century copper mining) is in fact still a thriving method, although often looked upon with scepticism and as being socially eroding and "inefficient" (Noetstaller 1987: 15). Yet, in a report published by IIED, it was stated that compared to large-scale mining, artisanal small-scale mining "uses less energy, releases fewer greenhouse gasses and produces less waste rock and tailings per unit of gold" (Buxton 2013: 5). The principal aim of this thesis is to investigate whether the same pattern can be seen in early 18th century small-scale copper mining, with a focus on energy.

Similar studies have been made. When it comes to industrial and fossil fuel driven agriculture, the advantages of producing the same amount of food through small-scale, fossil-free agriculture are recognizable (Roos 2015). For example, Rydberg & Jansén (2002: 13), in examining the energetic differences between modern and traditional agriculture, propose that:

> A decrease in available fuels and minerals might cause a change in the choice of technology and ecological technology might then be reintroduced into our society as a whole and not only into the agricultural sector.[1]

Conversely, as the fossil era dwindles, it could jeopardize the very feasibility of a continued metal supply, be it on surface, undersea or in space. It would then be crucial to have alternative means of extracting natural resources. As Ulf Sundberg suggested, when conducting an energy analysis on 17th century Swedish copper mining, "when the era of fossil fuels comes to an end, the forests will again capture a key role for the supply of energy (Sundberg 2013: 16).

In short, when the fossil era ends, the modern mining industry based on this source of energy may face serious repercussions. An economy operating within the sphere of animate power and biomass might then have to be implemented also in Northern countries. Even if modern mining shifted towards renewable technology, this would constitute an equal problem should the energy cost prove too high. As E. F. Schumacher notes, "if energy fails, everything fails" (Schumacher 2011 [1971]: 99). Furthermore, the ongoing decline in ore grade has spurred wild debates about the possibility of a soon-to-come peak production in many of the essential metals, including copper (Norgate & Jahanshahi 2006; Northey et al. 2013; Calvo et al. 2016). Consequently, if modern societies are not to deprive future generations of essential metals such as copper, it is crucial to question not only the current scale of metal consumption, but the very fossil fuel driven foundation which modern mining industries rest upon.

In a work published by the farmers organization Via Campesina, titled *Small Scale Sustainable Farmers are Cooling Down the Earth*, it was argued that traditional agriculture producing food without the means of fossil fuels and heavy machinery served as a force in "cooling down the planet" (Via Campesina 2009). While such functions might be more applicable to agriculture than mining, this thesis stems from the idea that pre-industrial mining methods, being entirely based on animate power and biomass, might be an environmentally positive alternative to modern fossil fuel driven mining.

1.1 Purpose & research questions

In essence, my interest lies in the dilemma of metal demand for a 'green' economy and the environmental consequences this metallurgical demand implies. The purpose of this thesis is to scrutinize 18th century- and modern copper mining in order to provide alternative perspectives on metal extraction. My scope of investigation relates to the ratio of embodied energy in labour, fuels and machinery used per unit of copper ore raised. This will be done through a quantitative comparison of energetic differences between early 18th century and modern copper mining. I aim to contribute to the field of Human Ecology and environmental history. Drawing from research done on the increased energy efficiency of traditional agriculture as opposed to modern, fossil-driven agriculture (Roos 2015; Rydberg & Jansén 2002), I intend to investigate whether the same pattern can be found in 18th century labour-intensive copper mining as well. I will also explore the concept of small-scale mining and its potential advantages to large-scale mining. This is important in order to deepen the understanding of energetic implications of technological shifts during the course of history, as

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[1] The term 'ecological technology' is here referring to horsepower.

well as to offer new perspectives on present day means of production. While it might be obvious that small-scale mining will naturally consume less energy, this thesis is concerned with the amount of energy spent per unit of copper ore raised. As follows, this thesis attempts to answer the following three questions:

1. Was copper mining in the early 18th century more energy efficient per unit of copper ore compared to modern copper mining?

2. Based on the result of the first question, to what degree is small-scale mining advantageous to large-scale mining in terms of energy efficiency?

3. What are the consequences of an ever-increasing demand for copper since the 18th century, coupled with a continuing decline in ore grade?

In order to answer this, I chose to investigate how a copper mine in the 18th century of Sweden contrasts to modern copper mining in terms of energy input per unit of copper ore. While the limited scope of this thesis forced me to put many delimitations, I have chosen to focus primarily on energy and emergy input to be able to discuss whether or not small-scale mining in the early 18th century was more sustainable and energy efficient than modern large-scale mining. Even though energy flow is not a measure of environmental impact, it can serve as an indication (Dincer 1999: 846).

1.2 Background

An attempt to give a rich treatment on the history of copper mining from the 18th century into modern times is well beyond the scope of this thesis. Instead, this section will focus on factors that are particularly important in order to understand in what ways copper extraction has changed and accelerated with regards to scale, energy and technology. While a rich quantity of research is offered on 18th century copper mining in terms of economics (Burt 1995), labour organization (Rule 1971) and the introduction of the steam engine (Greener 2015; Symons 2003), this thesis is concerned with copper mining done *without the use of fossil fuels;* that is, the extraction of copper with means of wooden technology and biofuels. This was the case in Falun Coppermine in Sweden in the early 18th century (Sundberg 2013).

Copper mining in the 18th century

Originally emerging from supernovas, metals such as copper are found in the crust of the earth. Copper is one of the metals occurring naturally in pure metallic form, and it was the first metal to be extracted and successfully manipulated by humankind (Smil 2016: 1). Thenceforth, copper has been widely used in societies for jewellery, toolmaking and in modern days as a fundamental element for electrical conductivity. In the 18th century, copper was mainly used for building, plumbing and house utensils (Burt 1995: 29).

The major producers of copper in the world between the 17th and 18th century were England and Sweden (Burt 1995: 29; Sundberg 2013: 4). In England, copper was extracted mainly through a compilation of small mining communities in the county of Cornwall, employing more than seven thousand people in the late 18th century (Rule 1971: 9); whereas in Sweden, copper production was concentrated around the Great Copper Mountain in Dalarna employing occasionally more than a thousand people (Burt 1995: 23-24; Sunberg 2013: 12). Metal production in these times was more a matter of metal 'trade' than industries (Smil 2016: 19). That is to say, instead of industrial global production, metals were transported and sold locally between miners, smelters and merchants (ibid.). Also, in contrast to what some may think, miners were often not restricted to only mining. Instead, many would work as part-time miners and part-time subsistence farmers, involved in a local web of a pre-capitalist family economy (Burt 1995: 24-25).

Until the latter parts of the 18th century, both Cornwall and Falun Coppermine would extract copper mainly or entirely without the use of coal. Particularly Sweden, enjoying a natural abundance of forests and streams, would just like Russia do well without coal even at the advent of the Industrial Revolution (Symons 2003: 48; Paulsson 1999: 18-19; Smil 2016: 22). In Cornwall, the access to local forest was by contrast considerably more limited. Yet, neither here would steam engines be deployed on a large scale at least until the second half of the 18th century. As Francis Trevithick writes (1872: 20), only first by the 1760s had "the steam pumping apparatus […] driven the horse quite out of the field", and only after this would Cornwall show significant signs of industrialization (Deacon 2014: 278; Rule 1972: 182-183). Thus, the raising of copper ore would until the second half of the 18th century operate within the sphere of what Robert Marks calls the 'biological regime'; that is, copper was extracted and produced through animate power and biofuel, and not coal (Marks 2015).

Mining is per definition an extractive process and thus will have an impact on the environment, be it on a small or large scale. Concerning Cornwall, "historic non-ferrous metalliferous mining and ore concentration has resulted in the contamination of large tracts […] by metals and metalloids", and the mining processes in Falun Coppermine have for centuries thereafter led to sulfur dioxide emissions and soil acidification (Camm et al. 2004: 2; Ek et al. 2001). Written accounts of such contaminations tell stories of geese lying dead after drinking from the red rivers near copper mines (Trevithick 1872: 15-16). The widespread use of timber and firewood would also have dire consequences not the least on forests, and the raising and smelting of copper and other metals served as one of the main drivers of deforestation in the pre-modern era (Smil 2004: 551; Rydberg 1971: 1). The use of waterwheels also required extensive formation of adits (underground tunnels) and dams and would in some places largely impact the local landscape (Palmer & Neaverson 2002: 71). In terms of carbon dioxide emissions, however, biomass such as firewood and charcoal are considered carbon neutral as long as its production was free from fossil fuels (Pierobon et al. 2015: 186). This was the case in Falun Coppermine, where firewood and charcoal were produced and hauled with horses and humans (Sundberg 2013: 11-12).

Copper mining in the 21st century

In modern society, copper remains one of the most crucial metals, predominantly for the use in electric equipment. Apart from this, copper is used for infrastructure, plumbing, building and as one of the key elements in green technologies such as electric vehicles and wind turbines (Feary & Cullinan 2019: 6; Harmsen et al. 2013: 67; Sverdrup et al. 2014: 158). Consequently, the rate of extraction has assumed unprecedented scales, and during the 20th century humans produced 90% of all the copper produced in human history (Henckens & Worrell 2020: 3).

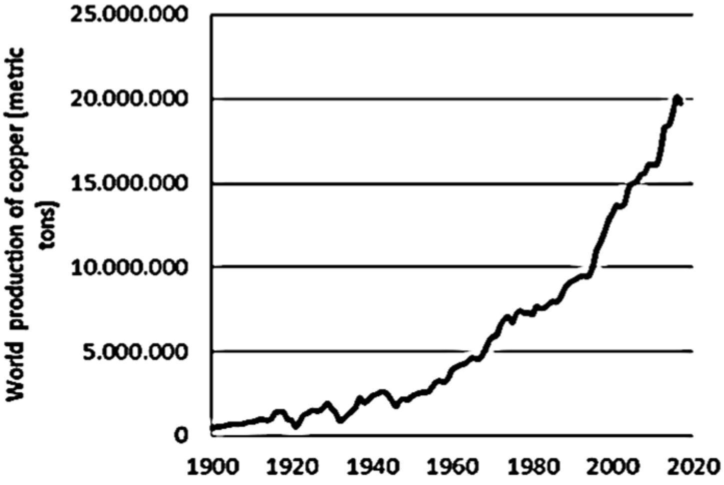

Figure 1. World copper production between year 1900–2017 (Henckens & Worrell 2020).

Modern mining industries, such as copper mining, also belong to some of the most energy-intensive of all industries (Calvo et al. 2016: 1). The most common method to extract metals today is through open-cast mining, which accounts for at least 70 % of all the world's metal production and which has also been described as the "most environmentally damaging of all methods" (Ponting 2007: 325). With the use of electricity, fossil fuels and heavy machinery, open-cast mining consists of "the digging of vast pits, the removal of whole mountain tops, the destruction of topsoil and the creation of large amounts of waste" (ibid.). In the U.S., mining of ore is the industry which releases most toxic elements and stands for more than half of all the country's industrial emissions (Diamond 2005: 481). The mining of copper releases thousands of tonnes of sulfur dioxide annually into the air (Lindahl 2014: 8). In the year 2019, with a production of about 300 000 tonnes refined copper, Boliden of Sweden emitted at least 6,1 million tonnes of CO2, an equivalent to more than what half of Luxembourg's population releases in one year (Boliden 2019: 16; Knoema 2019). The amount of CO2 emissions is expected to triple by the year 2050 (Henckens & Worrell 2020: 5).

Moreover, commercially useless waste rock known as gangue, end up in landfills next to the mine. These landfills can today cover a surface equal to several hundred football fields (Ponting 2007: 325). While in the 18th century about 46 tonnes of waste material had to be moved per tonne copper, in modern times at least 500 tonnes of waste are generated per tonne copper produced (Pryce 1778: 186; Wiertz 1999: 404).[2] A recent geographical study investigating the total direct land use of modern mining, concluded that 57 277 km^2 of the planet's surface, an area equivalent to about half the area of Portugal, is today covered with mines (Maus et al. 2020).

The decline in ore grade

Geologically speaking, 99.2% of the earth's crust consists of 12 elements of which 4 are the metals aluminium, iron, magnesium and manganese. All other metals, including copper, are found in the remaining 0.8% of the crust. Copper is therefore one of the metals considered geochemically scarce (Norgate & Jahanshahi 2006: 2). Also, every unit of copper ore unearthed from the ground, as with any other metal, contains a varying percentage of copper. This ratio, referred to as ore grade, has decreased significantly during the last centuries (see Figure 2). As the ore grade declines, more energy is required to treat and liberate the metallic copper from the ore as the process entails more complex technology. Milling, for example, becomes more intricate, and larger quantities of chemicals have to be implemented in the comminution process (Koppelaar & Koppelaar 2016: 4). While in the 18th century the ore grade of copper would for long periods of time average around 3%, in some cases reaching as high as 30%, the world average copper ore grade of today is around 0.6% (Lindroth 1955b: 255; Calvo et al. 2016: 2). The emissions of CO2 are also exacerbated with a decline in ore grade, rising from 3,8 tonnes of CO2 to 19,1 tonnes of CO2 per tonne copper at an ore grade decline from 3% to 0.5% (Norgate & Jahanshahi 2006: 8).[3] This is a fundamental geological difference between 18th century and present-day copper mining (see Figure 2).

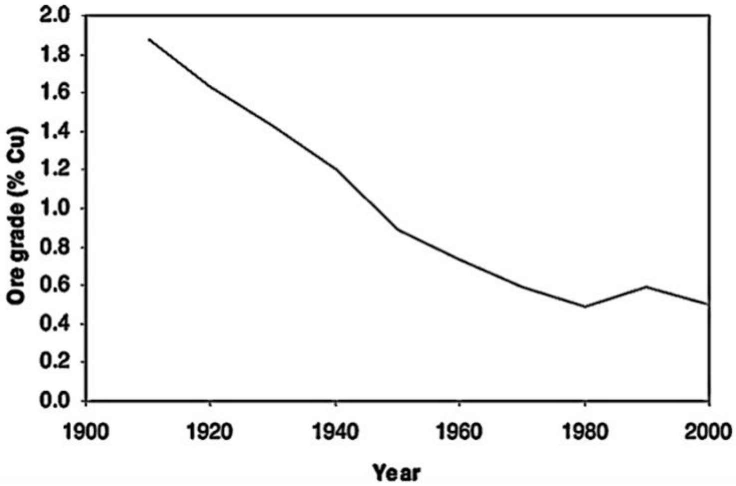

Figure 2. Decline in average copper ore grade in the U.S. between year 1900–2000 (Norgate & Jahanshahi 2006: 2).

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[2] It should be noted that this increase in waste rock is partly or entirely due to a difference in copper ore grade.

[3] These numbers of CO2 emissions concern modern copper mining where the use of fossil fuels is prevalent and are thus not necessarily applicable to copper mining in the 18th century.

As the demand for copper continues, so does the ore grade continue to decline. If the ore grade falls below 0.5%, the exponential rise in energy input for mineral liberation turns so high as to hit the 'mineralogical barrier', from which after the energy input increases with up to a thousand times and beyond (Harmsen et al. 2013: 68). Only the so-far witnessed decline from 3% to 0.5% has increased the input of embodied energy in mining and processing by up to 500% (Norgate & Jahanshahi 2006: 8). As the availability of rich copper ore becomes even scarcer, industries might soon be compelled to extract from deep crustal rocks with an ore grade of as low as 0.006% (Norgate & Jahanshahi 2006: 2; Calvo et al. 2016: 2). Mining this deep is "extremely challenging, costly and comes with large environmental impacts (Henckens & Worrell 2020: 4). This has sparked a debate about an impending peak copper, which may "well be realised during this century" (Northey et al. 2013: 190). One study, based on Hubbert's model of peak oil, suggested that the global peak in copper will arrive sometime in the coming four decades (Calvo et al. 2016: 2). Others argue against this, asserting that "higher-grade deposits are still out there" (Ericsson et al. 2019: 111).

To sum up, the increased demand for copper in the modern era has exhausted many of the natural reserves of high copper ore grade which were readily accessible in the 18th century. This pattern can be seen as a mirror image of the history of oil, which in the early 20th century was seeping on the surface, but after decades of extraction today has to be drilled from deep undersea. In other words, copper miners of the 18th century had access to the 'low-hanging fruits' of high-quality copper ore which today is being desperately sought for on the ocean floors and even in extra-terrestrial asteroids (Sale 2017: 193).

1.3 Earlier research

For studies on energy use in human society throughout history, Vaclav Smil is one of the most prominent researchers on the subject. His work *Energy in World History* (1994) covers many of the technologies and energetic processes employed in human societies.

In his master's thesis *Is 'Renewable Energy' a Myth?* (2015), Andreas Roos conducted a comparative energy analysis between early 20th century traditional agriculture and modern agriculture. In comparing a historical case of an agricultural system based on animate power with a modern agricultural farm based on agrofuels, he offered other ways of looking critically at the concept of 'renewable' technology. His results were that "the energy efficiency of a traditional agriculture driven by muscle work is ten times more energy efficient than modern day agriculture driven by agrofuel" (Roos 2015: 2).

Ulf Sundberg in his work *An Energy Analysis of the Production at the Great Copper Mountain of Falun During the Mid 17th Century* (1991), made an energy analysis of Falun Coppermine, including the estimated energy requirements of horses, human labour, machinery, timber and charcoal in the production of copper.

1.4 Structure of thesis

In section 1, I give a brief introduction and overarching background to the thesis and its purpose. In section 2, I outline the approach and theories of relevance to the thesis. In section 3, I give an overview of the research design and structure of the thesis, methods used, and an introduction to the two cases that will be examined. In section 4, I first give an overview of the main processes in 18th century and 21st century copper mining respectively. This is followed by an energy analysis of the two cases and presentation of the results. In section 5, I analyse the two cases studied, drawing from the theories used. In section 6, I provide some concluding remarks on the energy analysis, tying the results together with larger perspectives.

2. Theoretical approach

This section will cover the three main theories which this thesis rests on. The first one is that of Podolinsky's principle in which the human body is seen as a heat engine superior to machines in performing work. The second principle, 'small is beautiful', builds on the idea that small-scale organization of resource production is inherently socially and environmentally advantageous to large-scale production. The last one is an umbrella of theories within the degrowth movement, mainly focusing on the downscaling of resource consumption in order to curve environmental consequences and resource exhaustion. These three theories will comprise the foundational lenses of the thesis.

2.1 Podolinsky's principle

In the light of looking at modern people as being subjected to techno-fetichism (Hornborg 2015), this thesis questions the sustainability and efficiency of modern high-technology, in this case mining technology. The Russian physician Sergei Podolinsky of the 19th century has been credited with being "the first explicitly to scrutinize the economic process from a thermodynamic perspective" (quoted in Burkett 2004: 32). In other words, Podolinsky was the first to assess estimations of embodied energy within agricultural processes. Stemming from ideas of thermodynamics and the laws of entropy, Podolinsky attempted to "develop an agricultural energetics" by calculating the energy productivity of human labour in agriculture (Burkett 2004: 37). His work has both inspired several writers within the field of ecological economics and has also been subject to criticism (for a critical review, see Foster & Burkett 2006).

Podolinsky, in observing how energy from the sun is captured on the surface of the Earth by plants, concluded that humans serve as (one of) the most vital organisms to encapsulate this energy and delay its dispersion back into space ([1880] 2004: 63-64). Podolinsky argued that humans, through the process of cultivation, cannot only preserve but "*increase the quantity of solar energy accumulated on the earth*" ([1880] 2004: 64, emphasis not added). This can be done for example by cultivating plants in desert places where they would not naturally be able to grow. In looking at the amount of human and animal labour spent per hectare in French agriculture to produce certain crops, he estimated that humans can accumulate 41 calories on the earth's surface for each calorie spent (ibid.: 65).

Consequently, as opposed to inanimate machines which were dependent on human muscular intervention in order to not disintegrate, Podolinsky adapted Sadi Carnot's notion and asserted that humans and some animals could be seen as 'perfect machines' ([1880] 2004: 66, 70). Moreover, the process of crop cultivation, animal domestication, and artisan work made by hand was considered as "useful work" since it increased the amount of solar energy stored on earth before being dispersed into space ([1880] 2004: 66). For this thesis, "artisan" work such as copper mining is thus of relevance, in the sense that copper mining was a process engaging such forms of useful work.

2.2 Small is beautiful

The idea that small-scale organization of human societies, cities and industries is intrinsically favourable to large-scale sizes, derives mainly from Leopold Kohr in his work *The Breakdown of Nations* (1957). Here, Kohr argued that the very cause to social misery and environmental degradation is not the underdevelopment of poorer countries, but instead the ubiquitous strive for "bigness" in the Northern hemisphere (Kohr 1957: 4). He goes on arguing that "the purpose of economic activity is not the increase in production but the satisfaction of human wants" (Kohr 1957: 95-96).

The optimist view of small-scale organization was developed further by the economist Ernest Friedrich Schumacher in his book *Small is Beautiful* (1973). In Schumacher's words, "small-scale operations, no matter how numerous, are always *less likely* to be harmful to the natural environment than large-scale ones, simply because their individual force is small in relation to the recuperative forces of nature" (Schumacher 2011: 22, emphasis added). Contemporary research has shown that small-scale operations "use capital more productively than large ones", largely because less complex technology is utilized, and a simpler economic standard enforcing frugality (Noetstaller 1987: 21). One of the main points conveyed is a critique against the modern status quo of gigantism comprised of large-scale industries and globalization, which is argued to not only dehumanize but also alienate people from the environment. For this thesis, it is the relationship between small-scale production and environmental destruction which is of most relevance.

In his book *Human Scale* (2017), Kirkpatrick Sale built upon the same concept of small-scale. According to him, the main principles of such a human-scale economy consists of "family-farm agriculture, the decentralizaton of industry, worker ownership and self-management of firms and factories, and alternative technologies and all that they imply" (Sale 2017: 197). The propagation of small-scale as a sustainable way of organizing entities and industries of production has also been conveyed by sociologists such as Emile Durkheim who wrote that "small-scale industry […] displays a relative harmony between worker and employer" and that "it is only in large-scale industry that these relations are in a sickly state" (quoted in Sale, 2017:214). That being said, this thesis will apply the theory of small-scale on 18th century small-scale mining, in which it is particularly the proposed correlation between small-scale and environmental sustainability which will be of most interest.

2.3 Degrowth

In its broadest sense, degrowth implies a direct critique to the concept of economic growth. As an umbrella concept of theories, degrowth ties together the branches political ecology and ecological economy, as well as the notion of 'small is beautiful', with the aim in understanding how a downscaling of the economy could be accomplished. It also argues that the only way to mitigate climate change and prevent a future environmental and economic crisis is to re-direct modern society into an lower consumption of natural resources (Kallis et al. 2015: 3). For ecological economists, degrowth implies "an equitable downscaling of production and consumption that will reduce societies' throughput of energy and raw materials” (ibid.: 3-4). What technologies, industries and means of production should prevail in a ‘degrowth’ economy, is a matter of debate (Sekulova et al. 2013: 2). For this thesis, primarily the idea of degrowth for the consumption of metals such as copper is of relevance. Similar variations to degrowth have emerged, such as ‘blue degrowth’ partly raising critique against novel cases of extracting metals through deep-sea mining (Childs 2020). Since the ongoing transition away from fossil fuels into a ‘green’ economy has drastically increased the demand for metals used in renewable technology, the question has been posed that “if global environmental policy seeks to transition towards the widespread adoption of green technology and green infrastructure, then how far is humanity prepared to go to supply the metals needed to build it?” (Childs 2020: 119). In other words, given that the modern mining industry is not seldomly regarded as one of the most destructive processes in existence, should there be any limit? This question is of high relevance to this thesis and will be discussed with reference to the difference between 18th century and 21st century copper consumption.

2.4 Summary

This chapter has addressed the three principal theories and principles which will be used to discuss the results of the comparative energy analysis. Due to vast differences in the two examples of 18th century and 21st century copper mining, Podolinsky’s principle will mainly concern 18th century mining. The theory of small-scale production of natural resources has also been addressed, which will be used as a tool to discuss the potential benefits of small-scale organization. Lastly, the most relevant theories for this thesis from the Degrowth movement have been conveyed, which will also be used in the analysis as a framework in discussing possible solutions to a continuing declining copper ore grade.

3. Method

In this section, I intend to provide an overview of the method-related choices I have made and why I have made them, an overview of the research design, as well as the research methods of this study.

3.1 Structured, focused comparison

This thesis is based on a structured, focused comparison (George & Bennett 2005: 67). The comparison will be “structured” in that I will pose questions concerning the two cases that reflect my research questions, and “focused” in that both cases will centre around the relationship between energy input and copper ore output. The 18th century case studied will be Falun Coppermine in Sweden. The second case studied will be the contemporary Chibuluma Coppermine in the Zambia Copperbelt Province. The reason why I have chosen the latter case, is because the Chibuluma Coppermine has a similar copper ore grade as was commonplace in Falun Coppermine in the early 18th century.

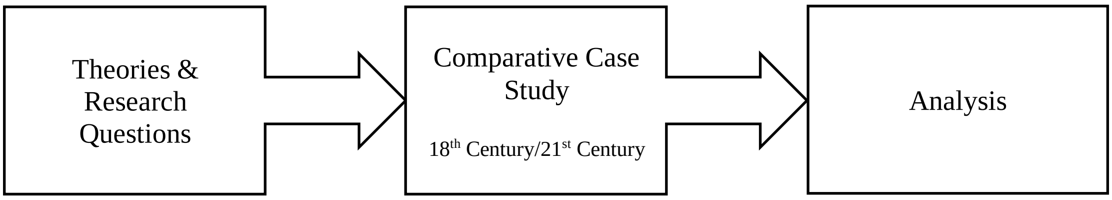

Figure 3. A visualization of the research design of this study (figure derived from Roos 2015: 15)

I acknowledge that the comparison of mining of copper ore in the 18th century, and the mining of copper ore today, do not "resemble each other in every respect but one" (George & Bennett 2005: 151). Indeed, some may criticize the choice of comparison, as they indeed differ both production-wise and chronologically. However, just as similar comparisons of energy flow have been done regarding agriculture (Roos 2015; Rydberg & Jansén 2002), I argue that the contrasting differences between 18th century and 21st century mining are what makes a comparison important.

Initially, this thesis was to be focused on copper mining in Cornwall, England. However, I would soon come to realize that Cornwall was one of the very first geographical zones in Europe to implement steam engines on a larger scale in their mines (Symons 2003: 48). Also, the quantitative data of Cornish copper mines in the 18th century proved shallow. Since my research question was concerned with not only 18th century copper mining, but copper extraction done without the use of fossil fuels, I had to switch my focus to Falun Coppermine in Sweden. As follows, although the largest share of the statistical data of the first table (pt. 1) is based on Falun Coppermine, I decided to still include various qualitative descriptions of copper mining from primary sources in Cornwall. I judged this diversity could strengthen the reliability of the processes described even further, as opposed to confining the sources to the works on Falun Coppermine.

As with modern copper mining, much of the research conveyed on this matter is focused on world average numbers. At first, I had set my mind on the Aitik Coppermine in Sweden, but would soon find out that this mine has a copper ore grade of less than 0.5%, making it an unfair case to be compared with Falun Coppermine (which had an ore grade of at least 3%). Consequently, in order to make the structured comparison as similar as possible, I decided to find a modern example of copper mining with a similar ore grade as existed in the 18th century. This is why the second table (pt 2) is focused primarily on the Chibuluma Coppermine in Zambia, which is an exceptionally rare modern-day example of a coppermine with an ore grade of 3%. However, this also means that whilst Falun Coppermine (being on of the world's main producers of copper at its time) can more easily be seen as representative for 18th century copper mining in a whole, the same is not the case with the Chibuluma Coppermine. In this thesis, when modern copper mining is spoken of based on the results of the tables, it should be remembered that it is a very rough generalization.

3.2 Treatment of data

As noted, the quantitative archival data on early 18th century copper mining is in many ways scarce. For example, children and females in the number of workers, are not included in primary sources, and at other times data of raised copper ore is completely absent for several decades, as is the case with the latter part of the 17th century of Falun Coppermine.

Concerning Cornwall, from the year 1588 it would take more than a hundred years before primary source of descriptions of copper mines arose again, which is through the written journeys of Cecilia Fiennes in 1695 (Symons 2003: 33). Still, many descriptive sources are drawn from Cornwall, such as the primary source of William Pryce who in his work *Mineralogia Cornubiensis* (1778) offers plentiful valuable observations. A handful of data is also borrowed from Sir Charles Lemon in his work *The Statistics of the Copper Mines of Cornwall* (1838).

Of the data on Falun Coppermine, most of it is based on the secondary source of Sten Lindroth's two volumes *Gruvbrytning och Kopparhantering vid Stora Kopparberget* (1955, part 1 & 2), which offer a variety of accounts on historical copper statistics including number of workers, horses and machines utilized.

3.3 Demarcation

Initially my aim was to compare "environmental impacts" of pre-industrial mining and modern mining. However, upon realizing that environmental impacts can be anything from arsenic contamination to deforestation, I decided to narrow it down to energy input per unit of copper ore.

There was much back and forth in deciding if the thesis should be concerned with the whole process of copper production, or only the raising of copper ore. Even if the processes of smelting of copper in the pre-modern era were not particularly complex, they are so in the modern era. Due to the enlarged quantities of information and data which have to be accounted for in a comparison study, I decided to restrict the cases of comparison to copper ore before it is being smelted. Incorporating an energy analysis of modern smelting factories, including the different phases of leeching, stripping and electrowinning, I judged would become too overwhelming in relation to the timeline of the thesis.

Many noteworthy social historical aspects of copper mining, especially in Cornwall, were found during the course of archival research, which also had to be put aside. The historical turning point in Cornish copper mining offering a mix of admiration and detestation concerning the steam engine, is in many respects relevant to this study. However, such questions of when and why Europeans shifted from waterpower to steam power are offered by Andreas Malm in his work *Fossil Capital* (2016), and the size of the thesis would not allow for much of it to be included. The phase of mineral prospecting in the 18th century and 21st century has also been excluded.

3.4 Energy analysis

Energy analysis is a thermodynamic tool to investigate the amount of energy input and output of a certain system. Since the work done by Sergei Podolinsky in the 19th century, assessing estimations based on thermodynamics is fairly new within research on sustainability (Dincer & Abu-Rayash 2020: 120). This can provide quantitative information on fuel use and energy efficiency (Dincer & Acar 2018: 24). This thesis incorporates inputs such as human and animal labour converted into energy units. This was done in the same way for both the case of

18th century and 21st century respectively. Energy loss in the form of heat was not accounted for.
The reason as to why I have chosen to focus on energy is because it provides an analytical framework for understanding the efficiency of different technologies and forms of labour, and because it can be used as a mirror of sustainability and environmental impact (Dincer 1999: 846; Dincer & Abu-Rayash 2020: 121). For example, thermodynamic estimations have shown that modern mechanized agriculture can have an EROI ratio of 40:1; that is, for each calorie worth of food produced, 40 calories have had to be put into the production (Varma 2003: 1). As machinery becomes heavier, more fossil fuels have to be used, lowering the EROI (Roos 2015).

In calculating the energy in machinery, labour, various fuels and other forms of inputs, an analysis in embodied energy has been conducted. Embodied energy, also called *emergy,* attempts to cover the intrinsic quantity of “nature” embodied in a certain process or material object (Odum, 1988). For example, the diesel used in a truck has a direct calorific energy content; embodied energy, however, is the energy that was required to produce the truck, including the component parts such as the metals and rubber wheels.

3.5 Validity and reliability

As Ulf Sundberg acknowledges, the numbers presented in the tables can only be based on qualified assumptions (Sundberg 2013: 11). For example, concerning Falun Coppermine, due to lack of data, the annual amount of raised copper ore from the second half of the 17th century is not provided. As a consequence, I have had to assume that certain ratios and numbers were similar between different decades. While acknowledging the evident gaps of information in various archival accounts, such as having to assume how much copper ore was produced in the 17th century based on data from the 18th century, I have attempted to reach as reliable results as possible. Furthermore, the statistics offered by Sir Charles Lemon (1838) is referred to by other historians, although Lemon does not convey any sources. In order to strengthen the reliability of my data, I have thus based most of the raw statistical numbers from sources on Falun Coppermine, while letting Cornwall serve mostly as an overarching source of information. Lastly, it is likely that the inclusion of the processes of smelting in both cases would drastically change the outcome and results, since phase of copper smelting in the 18th century required tremendous amounts of firewood and charcoal (Sundberg 2013). This can indeed be seen as a weakness; yet, for reasons conveyed (in section 1.3), I decided to exclude it.

4. Comparative Energy Analysis

Here, the material is presented and analysed with reference to the background, the theoretical perspective, and the earlier research. After a description of the various processes and technologies, I present the two cases of copper mining.

4.1 Energy analysis: 18th century copper mining

In order to answer the research questions of this thesis, the various phases of mining will be disassembled and converted into energy units. Firstly, to do so, it is important to understand the key principal work tasks encompassing 18th century copper mining. This section will consist of a short walkthrough of machinery and work tasks surrounding copper mining in the 18th century and ending with a quantitative table showing the amount of energy input (MJ) per tonne copper ore.

Small machinery, high concentration

The beginning of the 18th century in Europe is an important time, because wood-based technology had undergone centuries of development, in some cases assuming highly advanced machines such as the flatrod system (Lindroth 1955: 332, 335; Smil 2004: 551-553). These technologies would soon fall in shadow with the introduction of the steam engine. Thus, European copper mining in the early 18th century can be seen as operating during the zenith of wooden technology. As has already been noted, Sweden was naturally abundant on both timber and waterpower, while the access to coal was limited (Paulsson 1999: 18-19). For example, one steam engine was erected in a mine in Dalarna in the year 1728, but since no coal was available, the engine, having to be powered with firewood, proved too costly and was disposed of soon thereafter (Paulsson 1999: 19). In the beginning of the 18th century, Cornwall and Falun Coppermine extracted and smelted copper mostly or wholly through the use of horses, fuelwood, timber, charcoal, waterwheels and artisanal human labour.

As described by Francis Trevithick, prior to the steam engine, “mineral had been raised by horse-whims from the Cornish mines in buckets, barrels or kibbals, made of wood, and bound with iron” (Trevithick 1872: 98). The draining of the mines was done with hand-pumps and more elaborate machines such as the rag-and-chain pump. The same would be the case in Falun Coppermine. What was uniform with these technologies was that they consisted mainly of wood, with small quantities of leather and iron (Trevithick 1872: 2). The rag-and-chain pump was most often worked by hand but could also be attached to a waterwheel (Borlase 1758: 171). The transportation and hauling of copper ore in the mine and to the smelting house was done in wooden wagons or barrows drawn either by horse, oxen or manual labour (Trevithick 1872: 99).

Table 1. Overview of the processes of copper mining (18th century).[4]

Operation	**Upgrade**	**Description of Process**	**Required Input**
Excavation	From rock to ore	Heating the bedrock with firewood after which digging by hand begins. Unearthed ore was transported and elevated with horses	Firewood and/or explosives, hand-drills, pickaxes, wagons, candles, horses, manual labour
Crushing & sorting (“spalling”)	From ore to assorted, smaller grains of ore	The first phase in dressing of the ore consisted in pulverizing the rocks with sledgehammers “to the size of a man’s fist” and loading them into wagons (Pryce 1778: 52, 215, 234; Symons 2003: 20)	Manual labour, sledgehammer, wagons
Washing	Assorted and washed ore	The sorted ore was washed and sieved in buckets or in natural streams (Pryce 1778: 52)	Manual labour, wooden buckets, water
Milling & sorting (“stamping”)	Fine-grained and washed ore into sand	The ore was crushed and pulverized into fine sand. Usually with the use of a stamp mill, which according to Pryce was worked by one man and five boys (Pryce 1778: 230, 328)	Manual labour, stamp mills, waterwheels
Washing & sorting (“sieving”)	Fine-grained, re-assorted and re-washed ore into fine sand	The ore was washed once more before being transported to the smelting house. This was done with sieves and wooden tubs filled with water (Pryce 1778: 234-235)	Manual labour, wooden tubs, sieves (made out of brass copper) (Pryce 1778: 323)

In energetical terms, timber and firewood were by far the largest expenditures in 18th century mining. Human labour, horsepower, candles and the embodied energy in machinery comprised a significantly smaller share of the total input of energy. Before explosives were commonplace, firewood was instead used in a method called fire-setting, as a way to crush the bedrock. While explosives were sometimes used together with fire-setting, the latter method was the dominant one and would be used also long after the Industrial Revolution (Rydberg 1971: 1). For this reason I will not include explosives in the table. In the 1680s, Falun

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[4] Based on Cornish non-steam driven copper mining in the 18th century. The processes were similar to those of Falun Coppermine. The table design of Ulf Sundberg is used (Sundberg 2013: 6).

Coppermine consumed an average of 17 m^3 of firewood per 150 'baskets' of copper ore annually which equals to 248 kg firewood per tonne copper ore (Lindroth 1955a: 267). Timber was used to construct scaffolding, technology and stabilizing the ceilings and walls in the shafts (Leifchild 1968: 154). In the year 1836, the total consumption of timber used in Cornish mines was 144,800 trees (Leifchild 1968: 155), while the total output of copper ore was 140 981 tonnes (Lemon 1838: 70). Therefore, it can be assumed that a little more than one tree was used per tonne copper ore.[5] I will assume this ratio to be a recurrent ratio through the beginning of the 18th century. According to Ulf Sundberg, an estimated 69 500 man-days and about 62 500 horse-days were required for the sawing and transporting of timber and firewood to the mine in the production of 1 800 tonnes of copper (Sundberg 2013: 11-12). I will assume a man-day to consist of 10 hours of work per day, and one horse-day 8 hours of work per day.This equates to 38,6 man-days per tonne copper, or about 1,5 man-days and 1,3 horse-days per tonne copper ore.

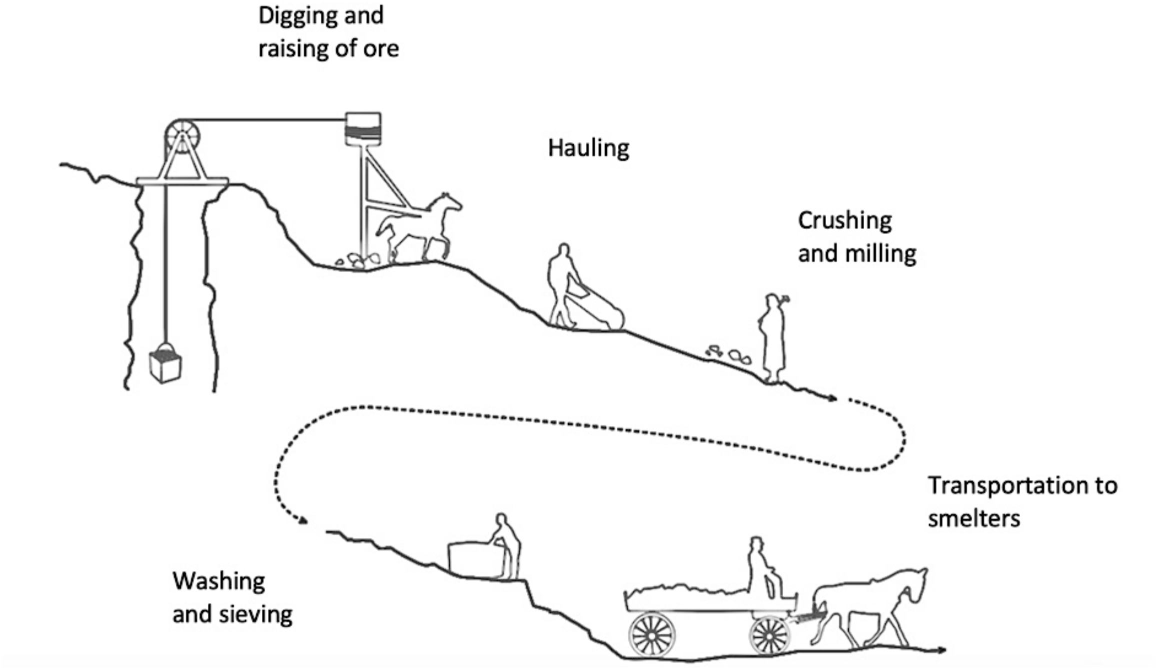

Figure 4. The phases of mining and processing of copper ore in the 18th century. Illustration by Theodor Runerheim.

While horses were sometimes used at horse-whims to drain water from the mines, their most common task was to wind or pull up the extracted ores (Pryce 1778: 331). Horses worked night and day, 300 days per year and all seasons of the year (Lindroth 1955: 305; Sundberg 2013: 8). In Falun Coppermine in the 17th century, Ulf Sundberg suggests that 340 000 horse-days were required in the production of 1 800 tonnes of copper, equivalent to about 190 horse-days per tonne (Sundberg 2013: 11-12). Unfortunately, there is no documentation of the

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[5] Cornwall had other mines beside copper, such as tin and pit-coal. The production of this was however minimal in comparison. In the year 1836, the production of tin in Cornwall was less than 3 % of that of copper ore. See Carne, 1836, p. 261.

amount of raised *copper ore* in the period 1620–1690 (Lindroth 1955b: 260). However, since the ore grade would average around 3% between the years 1630–1716, I will assume the ratio of copper ore risen per copper to be similar to the year of 1723, that is, 26,8 tonnes of copper ore had to be extracted to produce one tonne of copper (Lindroth 1955b: 257, 263; Ayres 2002: 131). As follows, an estimated number of 7,08 horse-days were required per tonne copper ore. It should be noted that this number can be assumed to have been smaller, since Ulf Sundberg's estimation concerns the whole process from excavation to smelting.

The smaller copper mines in the periphery of Falun Coppermine could in the 17th and 18th century employ between 18–200 people (Lindroth 1955: 402-406). However, the amount of copper ore raised from these mines is not conveyed. Instead, a more reliable number is offered from the year 1723, in which Falun Coppermine employed 607 workers while producing 21 461 tonnes copper ore (Rydberg 1971: 7; Lindroth 1955b: 257). Ulf Sundberg suggests that for an annual production of 1 800 tonnes copper, an estimated 550 man-days were required per tonne copper (Sundberg 2013: 12). This gives roughly 21 man-days per tonne copper ore.

4.2 Case of analysis 1: Falun Coppermine (year 1723)

The following table (Table 2) is based on the information and calculations previously conveyed.

Table 2. Estimation of the Energy and Emergy of Machinery, Materials and Labour used per Tonne Copper Ore in Falun Coppermine, Sweden, Year 1723

Input	*Input*	*Energy (MJ) per Tonne Copper Ore*	*Embodied Energy (MJ) per Tonne Copper Ore*	*Total Energy Input (MJ) per Tonne Copper Ore*
Horse-days[a]	7	140	378	518
Man-days[b]	21	168	117.6	285.6
Trees[c]	1.03 (tonne)	–	38	38
Wax[d]	2.79 (kg)	148	2,8	150.8
Firewood[e]	248 (kg)	3 968	1 066	5 034
Traditional machines[f]	–	–	4.6	4.6
Total:		4 424	1 607	**6 031**

Note: The annual amount of raised copper ore this year (1723) was 21 461 tonnes, with an average ore grade of 3% (Lindroth 1955b: 257; Ayres 2002: 131).
Energy unit in MJ = Megajoule.

Comments

[a] Data based on Sundberg 2013: 11. One horse working for 8 hours requires about 20 MJ of digestible energy per day (Smil 1994: 86). Embodied energy: feed requirement for idle horses is about 50 MJ per HD (horse-day) (ibid.). Construction of stable: 0,48 kg wood/HD = 2 MJ/HD. Harness = 0,11 kg leather/HD = 1,1 MJ/HD. Horseshoes: 0,03 kg iron/HD = 0,9 MJ/HD (ibid.). Veterinary care: 1h human labour/horse-year = 800 kJ/horse-year = 2,19 kJ/horse-day (Rydberg & Jansén 2002: 20, 22). Total: 54 MJ per horse-day.

[b] Data based on Sundberg 2013: 12. Assuming 10 hours of work in one man-day (Sundberg 2013: 12). Net food energy cost for human labour is 800 kJ per hour of work = 8 MJ per day for 10 hours (Smil 1994: 85-86). Embodied energy: humans consume 3,2 MJ per day when inactive but awake and 2,4 MJ when asleep for 8 hours (Fluck 1992: 33) which equals 5,6 MJ per man-day.

[c] Timber was used to stabilize the walls as to prevent the shafts from collapsing. In the year 1836, Cornish copper mines consumed about 1,03 trees/tonne copper ore (Leifchild 1968: 155; Lemon 1838: 70). I have assumed each tree being a 15-meter-tall pine tree weighing 1 tonne. The sawing and transportation of timber required about 1,5 man-days and 1,3 horse-days per tonne copper ore = 38 MJ (Sundberg 2013: 11-12).

[d] In the year 1836, the Consolidated copper mines in Cornwall used 2,79 kg of candles per tonne copper ore (Lemon 1838: 76). I have assumed the candles being made out of beeswax, although it could've been tallow. The energy content of beeswax is 53 MJ per kg and the embodied energy about 1 MJ/kg (Heidelberg 2003: 4)

[e] In the 1680s, Falun Coppermine consumed 248 kg firewood per tonne copper ore (Lindroth 1955a: 267). I have assumed the same ratio for 1723. Firewood has an energy content of 16 MJ/kg (Sepp 2014 et al.: 5), with an embodied energy of 4.3 MJ/kg (Sathre 2007: 53).

[f] In the year 1723 I have assumed Falun Coppermine used six horse-whims, two windlasses, one stamp mill and one rag-and-chain pump. In counting the presumed embodied energy in these machines, I have used the material used in a reconstructed medieval treadwheel, which consisted of 2 tonnes of wood and at least 45 kg of iron (Lindquist 1981). This equals an embodied energy of 9950 MJ per machine.

How ‘small-scale’ was Falun Coppermine?

Falun Coppermine was for its time without doubt a gigantic operation, encompassing guilds and master miners, employing hundreds of workers and standing for a main contribution to Sweden’s wealth and power (Sundberg 2013: 4, 8). However, compared to Cornwall, where in the year 1787 a total of 7 196 worked in the copper mines, the number of workers in Falun Coppermine pales (Rule 1971: 9). Even if accounting for all families tied to the miners in Falun Coppermine which amounted to about 30-40 000 people (Sundberg 2013: 12); in modern terms, this would still be regarded as a ‘micropolitan’ area within the range of an ideal, small city (Sale 2017: 136, 144). According to Richard Noetstaller, even though there is no universal consensus in defining small-scale, he suggests that any operation having a large input of labour per unit of metal, while raising at maximum 150 000 tonnes of ore per year, can be regarded as small-scale (Noetstaller 1987: 3, 5). Also, small-scale mining is usually “characterized by the extensive use of human energy aided only by simple tools, […] while loading and transport of ore and concentrate is in large part also by hand” (Noetstaller 1987: 15). As such, Falun Coppermine, producing far below 150 000 tonnes of copper annually, can be regarded as a small-scale operation. It should be added, that Falun Coppermine also made use of rather advanced machinery in the form of waterwheels, horse-whims and flatrod systems. One might regard it as not only small-scale, but an advanced form of small-scale production.

4.3 Energy analysis: modern copper mining

While the principle of copper mining and processing is conceptually similar to that of 18th century copper mining, the scale and technology used assume other forms and magnitudes. In contrast to sources of 18th century copper mining, however, there already exists ample research concerning both direct and embodied energy input per tonne copper ore. For this reason, the descriptive part of this section will focus more on the implications of declining copper ore grades.

Big machinery, small concentration

With an average copper ore grade of less than 0.5% worldwide, heavy machinery, complex technological and chemical processes are needed to find, extract and process copper ore. At an initial copper ore grade of 0.6%, only the stages from excavation and milling alone stand for up to 60% of the total energy consumption in the whole copper industry (Gaines 1980: 1). The main reason why the embodied energy increases substantially as the ore grade declines, is because considerably larger inputs of steel balls used in the milling as well as chemicals in the flotation process have to be added as the grind size needs to be smaller (Koppelaar & Koppelaar 2016: 4). This section will cover a short description of the various stages of modern copper mining, followed by an energy analysis.

The evolution of the mining sector in the past three centuries have seen similar patterns as in the agricultural sector. In the U.S., the number of iron mines decreased from 321 to 9 since the 1950s (Sale 2017: 193). In Sweden, between the years 1910–2015, the number of mines dropped from 500 to 15 (Sten 2018: 1). On par with this decrease, the amount of manual labour also declined and was being compensated with fossil fuels and heavy machinery.

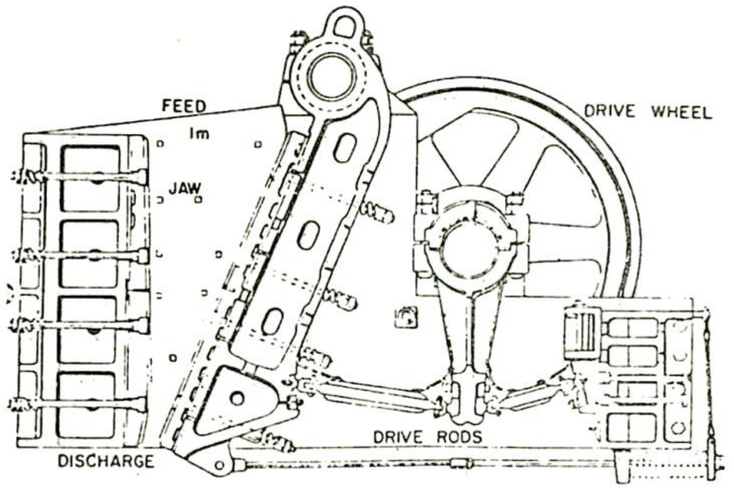

Figure 5. Jaw crusher. The rocks are let down in the “feed” and crushed in the “jaw”. Modern jaw crushers can deliver a power of 400 kW (500 horsepower) and weigh more than 124 tonnes. The machine is usually situated underground. Source: Gaines 1980, p. 31.

Most processes in modern copper mining are powered by fossil fuels (Norgate & Jahanshahi 2006: 1). The stages of copper mining and processing in modern open-pit mining involve several phases of heavy machinery and chemical processes. The principal steps are as follows:

Table 3. Overview of the processes of copper mining (21st century)[6]

Operation	Upgrade	Description of Process	Required Input
Excavation	From rock to ore	With the use of bucket-wheel excavators, a wide surface is dug out in layers, from which the copper ore can be removed and quarried	Bucket-wheel excavators, haul trucks, dozers, loading trucks, blasting & grinding equipment, manual labour
Crushing & Milling	From ore to pulverized ore	The pulverization of the ore is done with machines through various steps	Jaw crusher, gyratory crusher, cone crusher, rod mill, ball mill, manual labour
Mineral Liberation (Comminution)	Cleansed and concentrated ore containing 20%–30% copper	After milling has been done, the ore undergoes a process of mineral liberation called ‘comminution’ (i.e., the separation of metallic copper from gangue rock). This is often done through a chemical process called froth flotation	Chemicals, manual labour

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[6] Information based on Gaines 1980, p. 30

Transportation		The transportation of copper ore between the above stations and to the smelting industry is done either in diesel-driven trucks or by train (Eriksson & Lindeström 2012: 76)	Truck or train

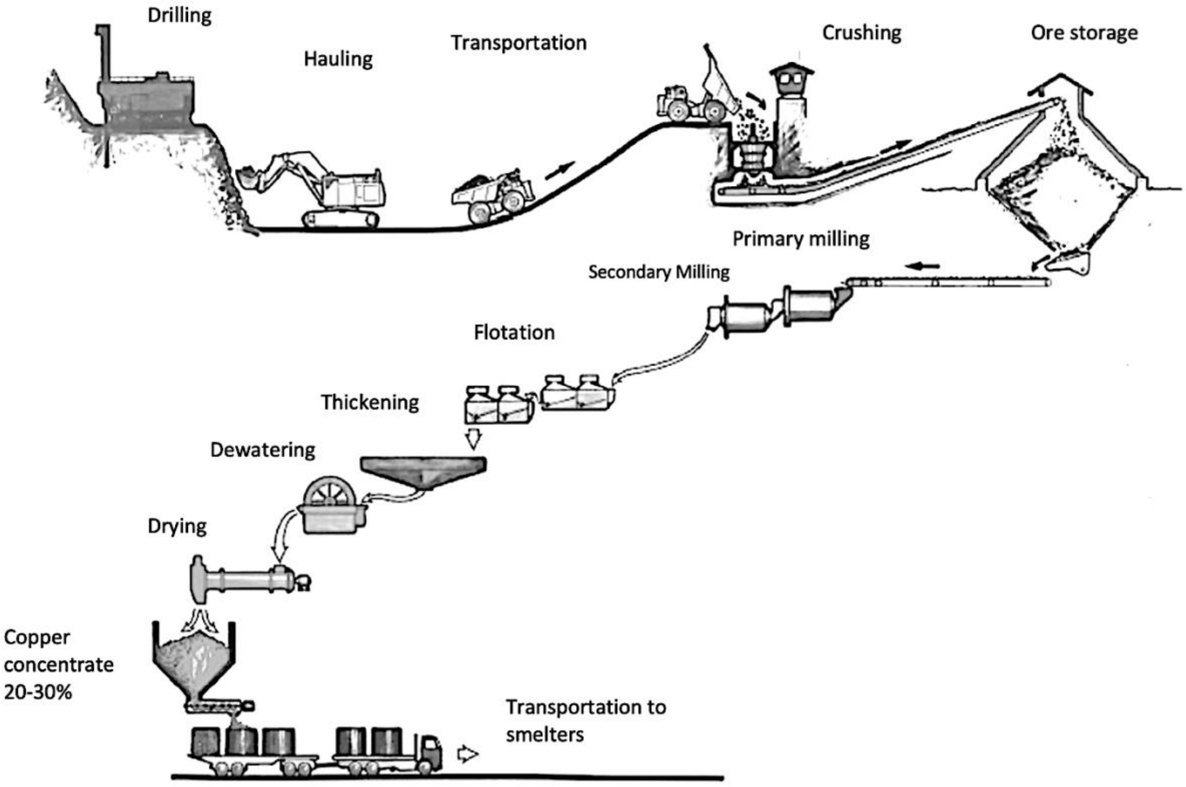


Figure 6. The phases of mining and processing of copper ore in modern copper mines (Minde & Liljeholm 2005: 2).

As already noted, the decline of copper ore grade has a significant impact on energy use. The lower ore the grade, the more advanced technology is required to liberate the copper metal from the gangue. Grind size needs to be smaller and it requires more energy to process the ores. Koppelaar and Koppelaar (2016) suggest that the energy input to excavate and process copper at an ore grade of 0.5 % (and a mine depth of 300 m) is 54 420 Mj/ton of copper ore. To add to this, the embodied energy of these processes at the same ore grade is about 48 000 MJ/tonne copper ore (Norgate & Jahanshahi 2006: 4). Note that a grade of 0.5% is the world average copper ore grade in modern times; in fact, it is not uncommon with an even lower ore grade.

4.4 Case of analysis 2: the Chibuluma Coppermine (year 2015)

The following table (Table 5) is primarily based on Chibuluma Coppermine in Zambia, in the year 2015, in which 604 000 tonnes of copper ore was produced, while employing 340 workers (Dale 2017). The Chibuluma Coppermine is an active copper mine with one of the highest average copper ore grades in the world, at 3%. The mine is a highly mechanized underground mine which lies in the Copperbelt Province in Zambia. It is owned by the South African company Metorex and the mine is well known for an exceptionally high ore grade of 3% (Miningforzambia 2016). The deposit is expected to be depleted in the coming years (ibid.). Between the years 2015–2017, Chibuluma copper mine had an average power consumption of 16 882 kWh per tonne copper ore, equivalent to 60 775 MJ (Annual Report 2017: 27). Since the report does not mention embodied energy, I have assumed this was not included in the numbers. Despite the high ore grade, the energy consumption per tonne copper ore is in this case somewhat higher than the average of 60 000 MJ per tonne copper ore which is suggested by Koppelaar and Koppelaar (2016: 1) for underground mines at an ore grade of 0.5%. However, the energy cost is found to "accelerate significantly" first as the ore grade falls below 0.5% (ibid.).

Table 4. Estimation of the Energy and Emergy in the Machinery, Materials and Labour used per Tonne Copper Ore in Chibuluma Coppermine, Zambia, Year 2015

Input	*Input*	*Energy (MJ) per Tonne Copper Ore*	*Embodied Energy (MJ) per Tonne Copper Ore*	*Total Energy Input (MJ) per Tonne Copper Ore*
Mineral liberation[a]	–	–	18 140	18 140
Hydroelectricity[b]	16 882 (kWh)	60 775	8 557	69 332
Man-days[c]	0,12	0,86	182,29	183,15
Machines[d]	–	–	64,79	64,79
Diesel[e]	0,59 (liters)	21,77	18,52	40,29
Explosives[f]	0,69 (kg)	–	45,26	45,26
Total:		60 797,6	26 826,6	**87 624**

Note: The annual amount of risen copper ore this year (2015) was 604 000 tonnes, with an average ore grade of 3% (Annual report 2017; Dale 2017).
Energy unit in MJ = Megajoule.

Comments

[a] The embodied energy as an effect of smaller grinding size (a phase in mineral liberation) at an ore grade of 3% is about 18 140 MJ per tonne copper ore (Norgate & Jahanshahi 2006: 4-5).

[b] Between 2015–2017 the Chibuluma copper mine used an average of 16 882 kWh per tonne copper ore of which most were hydro-electrical energy (Annual report 2017: 23, 27). This equals 60 775 MJ per tonne copper ore. Embodied energy: the embodied energy of hydroelectricity, including all stages from planning and dam construction with a life-span of about 100 years, is 8 557 MJ per year (Atlason & Unnthorsson 2015: 8)

[c] 340 humans employed and assuming 240 work days, 8 hours per day, and 800 kJ per hour (Smil 1994: 85-86) = 1,08 hours or 0,12 man-days per tonne copper ore = 0,86 MJ per tonne copper ore. Embodied energy: 4,2 liter oil equivalent per hour of work = 168,79 MJ per hour (Pimentel 2006: 14).

[d] For mining and processing, the Chibuluma copper mine used six ADTs (articulated dump trucks), six loaders, one boomer and two mining jumbos (metorexgroup.com). Together these machines have a total weight of 451 tonnes. In counting the embodied energy of machinery I have used Richard C. Fluck's suggestion of 86,77 MJ/kg where the embodied energy of rubber tires is also included (Fluck 1992: 120).

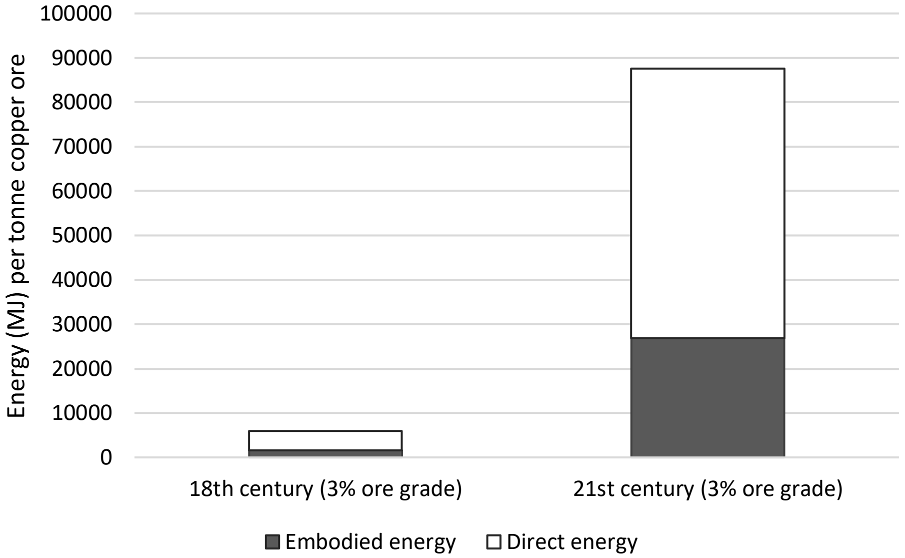
[e] The calorific value of diesel is 36,9 MJ/l. At an annual rate of 36M tonne copper ore, the machines in Aitik Coppermine consumed 0,59 liter diesel per tonne copper ore (Eriksson & Lindeström 2012: 76). I have assumed a similar ratio for Chibuluma Coppermine. The embodied energy of diesel is 31,39 MJ/l (Roos 2015: 36).

[f] At an annual rate of 36M tonne copper ore, Aitik Coppermine used 0,69 kg inorganic nitrates such as nitroglycerine per tonne copper ore (Eriksson & Lindeström 2012: 77). I have assumed a similar ratio for Chibuluma Coppermine. Nitroglycerine has an embodied energy of 65.6 MJ per kg (Ferreira 2017: 27). I have assumed the embodied energy of explosives was not accounted for in their annual report.

4.5 Results

As can be seen in Table 2, the biggest energy expenditure in early 18th century copper mining was firewood for fire-setting, while in modern copper mining (Table 5) it was direct energy in the form of hydroelectricity. In the early 18th century Falun Coppermine required 14 times less energy than the present day Chibuluma Coppermine to raise the same amount of copper ore. There is a significantly higher input of human work per tonne copper ore in the 18th century, as much as 175 times higher than in modern copper mining. This was to be expected, since traditional and what Schumacher calls 'low-tech' means of production ultimately requires a compensation of higher input of labour (Schumacher 2011: 143). However, depending on the per capita annual consumption of each individual labourer, the embodied energy of manual labour may drastically change. This will be further discussed in the following section.

Table 5. Energy Input per Tonne Copper Ore in the 18th Century versus 21st Century



Note: the chronological x-axis is a generalization.

5. Analysis & Discussion

This section is composed of an analytical discussion based on the above results. The first subsection (5.1) covers an analysis on the difference in ore grade and copper demand between the two time periods investigated, and the consequences of a declining ore grade. The second subsection (5.2) is meant to offer an analysis of the results in relation to Podolinsky's principle and the 'small is beautiful' concept. These subsections are meant to answer my three research questions: *Was copper mining in the early 18th century more energy efficient per unit of copper ore compared to modern copper mining? To what degree is small-scale mining advantageous to large-scale mining in terms of energy efficiency? What are the consequences of an ever-increasing demand for copper since the 18th century, coupled with a continuing decline in ore grade?*

5.1 Peak copper and degrowth

This section aims to cover the consequences of high demand for copper coupled with a decline in ore grade. A discussion will also be outlined on the incentives to argue for a downscaling in copper consumption, with relation to the degrowth movement.

Lately, several researchers have conveyed troubled warnings about a coming scarcity or even a complete peak in copper production (Sverdrup et al. 2014: 158). One of the main reasons for this is an accelerating decline in ore grade (Norgate & Jahanshahi 2006). So far, the modern example provided for (Table 5), has concerned a copper ore grade of 3%. As has been noted earlier, however, the world average copper ore grade today is usually between 0.6%–0.3% (Henckens & Worrell 2020: 5). Chibuluma Coppermine is thus by far not representative for modern copper mining in terms of ore grade. When the ore grade falls below 0.5%, the increase in energy input escalates remarkably (Norgate & Jahanshahi 2006). As seen in Table 7, when the ore grade falls to 0.3%, the amount of total energy input increases to 577 000 MJ per tonne copper ore. As such, many copper mines in today's world will require 6 times more energy per tonne copper ore than Chibuluma Coppermine does, and 95 times higher than Falun Coppermine in the 18th century.

Table 6. Average World Energy Input per Tonne Copper Ore at 0,3% Ore Grade (21st Century)

Input	*Energy (MJ) per Tonne Copper Ore*	*Embodied Energy (MJ) per Tonne Copper Ore*	*Total Energy (MJ) per Tonne Copper Ore*
Mining & processing[a]	447 000	–	447 000
Mineral liberation[b]	–	130 000	130 000
Total:			**577 000**

[a] Based on Koppelaar & Koppelaar (2016: 1). This is the energy cost per tonne 30%+ copper ore concentrate at 0.3% ore grade, being mined from underground mines at 300m depth.
[b] The embodied energy due to the effect of smaller grain size and an increased input of rod balls and flotation chemicals (Norgate & Jahanshahi 2006, p. 4-6). Note: this is the embodied energy at an ore grade of 0.5% and is most likely higher at 0.3%.

This exponential increase in energy input in relation to ore grade decline has given rise to several debates about a coming peak copper. Another cause to this potential peak is that of an ever-increasing copper demand. The estimated total amount of extractable copper on earth is 2 800 million tonnes, of which almost 30 % (800 million tonnes) have already been mined (Sverdrup 2014: 158). At a continuous present-day growth rate, copper production is expected to increase by 249% in the coming decades (Norgate & Jahanshahi 2006: 1). The warning of a coming peak copper is indeed not new. Already in the year 1924, in the *Engineering and Mining Journal* (1924: 122) a geologist wrote:

> The copper supply of the world will last hardly a score of years. […] Our civilization based on electrical power will dwindle and die.

Of course, the world's copper supply obviously lasted longer than a score of years. Still, the warning might not be too unfounded. Several studies predict that if current copper consumption continues, world copper resources may be exhausted in 13 years from the date of writing (Sverdrup 2014: 158). Should this happen, it could very well jeopardize the very foundation of modern society's electrical conducting system (Harmsen et al. 2013). Hopes in tackling copper exhaustion has been put on metal recycling, but from a thermodynamic perspective, the more the copper recycling, the higher the energy input (Mobbs 2018; Walter 2019). An alternative conductor metal would be aluminium, but the production of aluminium requires nearly four times as much energy as copper does (Smil 2016: 139). One solution would be to decrease the demand of copper. Should modern society scale down to the annual copper consumption of the early 18th century, that is, 2 500 tonnes per year, the world copper reserves would instead of 13 years last for about another 800 000 years (Ranestad 2019: 206). Surely, this discussion is pulling between the assumption in one end that humans will in fact exhaust all obtainable copper on the planet, and in the other end putting hopes in alternative sources of copper extraction such as deep-sea mining or asteroid mining in space. Predictions are always subject to inaccuracy, and a potential peak copper may indeed arrive further ahead in time.

Furthermore, one might argue that as world population increases, so will naturally the supply of copper also have to increase. While this is true, the advancement of copper mining has greatly augmented not only the production but also the per capita consumption of copper. If allocating all refined copper produced in the year 2020 to all humans in developed countries such as in Sweden, every individual would receive about 11 kg copper each (Henckens & Worrell 2020: 5). In the year 1700, however, each person would receive no more than 3 grams.[7] To put it differently, between the years 1700 and 2020, the yearly world production of copper increased with 80 times (Ranestad 2019: 206), while the copper demand from modern humans in the Northern hemisphere simultaneously increased with at least 36 times more

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[7] Numbers based on own calculation. In the year 2019 the world population was 7,7 billion with a production of 20 million tonne copper, and in the year 1700 the population was 641 million with a production of 2 500 tonne copper (Ranestad 2019: 206).

copper than humans demanded in the year 1700.[8] This correlates well with the theory within degrowth asserting that “efficiency improvements lead to more, not less, resource use” (Kallis 2017: 2). The pattern seen here is often referred to as the ‘rebound effect’, that is, when resource consumption increases despite technological efficiency (Turner 2013). However, in this case, while the consumption of copper has increased, the *energy* efficiency in raising copper ore has in fact deteriorated, despite technological progress (see Table 5). This means that the industrial changes in modern copper raising – compared to the early 18th century – seems to have led to an increase in consumption plus an energy *deficiency*. While this does offer a picture of the physical mountain of resources, which modern lifestyles demand, it raises the question: *should there be a limit to consumption?* To go back to Leopold Kohr (1957: 95-96) who proposed that “the purpose of economic activity is not the increase in production but the satisfaction of human wants”, one might ask if 11 kg of copper each year – more or less the equivalent of a football made of pure copper – is needed to satisfy human wants. The degrowth movement would most likely deem it an extreme overconsumption of copper, which might not have anything to do with the improvement of personal well-being. As the degrowth movement argues for a ‘dematerialization’ of resource consumption (Kallis et al. 2015), there might also be incentives to include geochemically scarce metals such as copper.

5.2 How beautiful is (affluent) small-scale?

This section aims to examine the proposition that energy efficiency improves as bodies of labour processes are reduced in size, using the results from the energy analysis of Falun Coppermine and the Chibuluma Coppermine. This section will also discuss Podolinsky’s principle from a critical perspective.

We have seen how Falun Coppermine, considered a small-scale mining operation by modern measures, is considerably more energy efficient per tonne copper ore than modern mining (a ratio of about 6 MJ/kg copper ore compared to 87 MJ/kg copper ore). The importance of machinery, albeit being smaller and less complex, is well illustrated around Falun Coppermine. As seen in Table 6, a total of 450 681 man-days were required to produce 21 461 tonnes of copper ore in the year 1723. With 607 employed workers, and assuming each person worked 300 days per year, it would take them roughly 2,5 years to produce the same amount of copper ore had they not made use of horse-whims, water wheels and other machinery.

What does this mean? As a thought experiment, in the year 2015 the Chibuluma Coppermine used about 529 million GJ (gigajoule) to raise 604 000 tonnes copper ore. Should the mine instead have raised the same amount of copper ore using the methods and technologies as Falun Coppermine did, they would have to spend only about 3,7 million GJ to raise the same amount of copper ore. However, this would take them about 28 years. As Richard Noetstaller writes, since small-scale mines “usually employ more labour-intensive methods with a lower degree of mechanization”, lower financial costs are required per unit of output in contrast to large-scale mines (Noetstaller 1987: 20). He also claims that it is “apparent that the primary effects on the environment created by [small-scale mines] are necessarily smaller than those of [large-scale mines]” (ibid.: 15). This gives reason to believe that if Chibuluma Coppermine

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[8] In China, the demand for copper is expected to increase to 290 kg per capita by the year 2050 (Dong et al. 2019).

adapted the mining methods used in Falun Coppermine, not only energy but also the financial costs and environmental impacts might have decreased in the raising of copper ore, given that such a substitution was realistic. Consequently, allowing an ore grade of at least around 3%, it would be theoretically possible for modern society to sate a certain proportion of copper demand using 18th century means of extraction. It would simply be a matter of time. However, the drastic decline in ore grade poses significant problems, and 18th century miners would most likely not able to extract copper from ores with the present-day ore grade of between 0.6%–0.3%.

It should also be highlighted the often-seen negative reputation of modern examples of small-scale mining. As Richard Noetstaller observes, since organizational incentives due to various reasons can be limited in developing countries, a “lack of sound management practices are frequently associated with small enterprises” (Noetstaller 1987: 22). This is relevant because of the fact that Sweden between 1611–1718 was one of the great European countries, witnessing “the Era of Great Power” (Lindberg & Rydberg 2017). As follows, Falun Coppermine in the early 18th century can be seen as *an advanced small-scale operation led under a highly organized and influential kingdom*. It is therefore questionable if Falun Coppermine can be comparable with modern cases of small-scale mines in developing countries, as the modern cases are oftentimes laden with poverty and corruption, lacking finance and managerial skills, and are affected by exploitative exterior markets (Noetstaller 1987: 21-22; Hentschel et al. 2002; ILO 2019).

In the light of Podolinsky’s principle and looking at human beings as ‘perfect’ heat engines, Table 2 and Table 5 offer ground for remarks on this assertation. If embodied energy and living standard of the working human is to be accounted for, the ratio between labour output and energy input changes substantially depending on the labourers’ material standard of living. Podolinsky, albeit vaguely, emphasized this contradiction in claiming that “[t]he economic coefficient of humans tends to diminish as their needs increase” ([1880] 2004: 71). For example, if the manual labour at 18th century Falun Coppermine would’ve consisted of a work team of present-day modernized Swedes with Western per capita consumption, the energy input from manual labour (21 man-days) per tonne copper ore alone would increase the operation’s total energy input by 600 % (based on Pimentel 2006: 14). Due to the embodied energy this work force of modern Swedes would possess; these 21 man-days in Falun Coppermine in the year 1723 would sum up to 35 445 MJ per tonne copper ore. As such, the work of human beings is only ‘perfect’ to the extent that a certain degree of living standard is assumed; because after the basic net labour energy cost of 800 kJ per hour has been met, humans will not work more efficiently despite an increase in calorie input. This is a remark also conveyed by Foster & Burkett (2006: 112).

Furthermore, the above reasoning can also be applied to the ‘small is beautiful’ principle. The notion that small-scale organization should be more energy efficient or environmentally friendly is only sustained insofar as the labourers incorporated are not possessing a particularly high per capita consumption. Kirkpatrick Sale argues that the foundation of small-scale production is inherently non-exploitative, and that in a hypothetical small-scale society “neither exploitation nor autocracy would be much of a possibility, for that would be at such odds with the general perception of the common good” (Sale 2017: 204). In viewing Falun Coppermine as a small-scale operation, the above statement is questionable. Falun Coppermine devoured at certain periods in the 17th century probably more forest than anywhere else on the planet for the cause of copper production (Sundberg 2013: 10). Cornwall of England also, despite consisting of small mining communities, showed definite signs of both local and global exploitation and deforestation, and would with the implementation of the steam engine produce even more copper than was at the time saleable (Rule 1971: 182-183). As Roger Burt explains, the rise of unprecedented copper production was due to “a positive climate for enterprise” (Burt 1995: 23). To put it differently, small-scale operations appear to risk being just as exploitative as large ones if influenced by exterior forces invigorating such practices.

6. Conclusion

The aim of this thesis was to scrutinize early 18th century and modern methods of raising copper ore in order to examine the sustainability of mining in relation to scale of the operation. With a similar ore grade, an energy analysis revealed that Falun Coppermine in the 18th century was 14 times more energy efficient per unit of copper ore compared to Chibuluma Coppermine in the 21st century. In terms of energy requirement per unit of copper ore, Falun Coppermine had a ratio of 6 MJ/kg copper ore whereas Chibuluma Coppermine had a ratio of 87 MJ/kg copper ore. In the early 18th century, Falun Coppermine was able to raise copper ore solely with the use of animate power and biofuels, while modern mining is wholly dependent on electricity and fossil fuels. The fundamental geological difference between the two time periods of comparison is that 18th century miners had access to a considerably higher average copper ore grade of at least 3%, whereas in modern times this has declined to between 0.6%–0.3% or lower, which calls for more complex technology and more energy intensive processes to liberate the metal from the gangue.

In opposition to the optimist view that small-scale is principally environmentally advantageous compared to large-scale production of resources (Sale 2017; Schumacher 2011; Kallis et al. 2015), I argue that small is only ‘beautiful’ to the degree that the humans in question live a lifestyle embodied with a relatively frugal material standard. As Kallis explains, a “worker embodies all the energy consumed for feeding, clothing, education and moving her around” (Kallis 2017: 4). In the same way, if the human in question embodies a high material standard of living, her body as a ‘perfect engine’ as suggested by Podolinsky is no more perfect and may also no longer be considered doing useful work. If Falun Coppermine in the year 1723 would have exchanged their labour force with modern day labour of the northern hemisphere, the energy cost per tonne copper ore would rise from 285 MJ to 35 445 MJ due to the embodied energy of modern human workers. This means that if Chibuluma Coppermine would in the year 2015 exclusively utilize 18th century methods to raise 604 000 tonne copper ore, they could save 525 million GJ of energy, but the process would require an additional 28 years to complete. Conversely, neither the ‘small is beautiful’ concept nor Podolinsky’s principle are in essence environmentally friendly or energy efficient but can only be regarded as such if the human(-s) in question embody a low per capita consumption.

With a continuing present-day growth rate, a peak copper is expected to arrive within 13 years (Sverdrup 2014: 158). However, if world copper consumption was scaled down to the level seen in the year 1700, copper reserves would last for another 800 000 years. The problem with re-implementing pre-industrial forms of metal extraction is the substantial decrease in readily accessible high-quality ores. As argued by several researchers, however, only if the modern economy is “slowed down” can an eventual peak in metal extraction be forestalled (Kallis 2017: 5). Thus, in order to avoid ending up in a mineralogical *cul-de-sac* and depriving future generations of elements such as copper, a descaling of copper consumption may be crucial. The amount of raised copper ore in the 18th century transformed to reach unprecedented levels due to the implementation of the steam engine, and henceforth, technological ‘improvement’ within the mining sector has managed only to elevate the scale raised copper ore, while deteriorating the energy efficiency and exacerbating consumer demand. Despite present efforts to introduce ever newer technologies within mines, such as robots, L. L. Gaines sees “little opportunity” in tackling copper ore decline with improved technology (Gaines 1980: 25). Accordingly, our best chance in curving an imminent exhaustion of copper supply is to remodel modern mining industries with inspiration from pre-industrial forms of raising metals A) to save energy by up to 14 times per unit of copper ore and B) to lower per capita copper demand. Future research could with benefit further examine the potential advantages of small-scale pre-industrial forms of metal extraction, such as financial cost, embodied land and carbon emissions per unit of metal, including also the phases of smelting.

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