An Energy Analysis of the Production at the Great Copper Mountain of Falun During the Mid 17th Century

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ABSTRACT

An analysis is made of the energy inputs in the production of copper in Falun, Sweden, in the mid 17th century. This mine produced at that time more than half of the world production of copper. The dominant role of the forests is identified and the contribution to Sweden's wealth and security described, enabling Sweden to develop to the most powerful nation in Northern Europe during the period 1560-1720.

Key Words: *forest energy, copper production, energy analysis, history 17th century*

PURPOSE AND SOURCES

This study is an attempt to view the production in the Great Copper Mountain (Stora Kopparberget) in Falun in an energy perspective when the production peaked in the mid 17th century and copper was a main contributor to Sweden's wealth and power (refer to Figure 9). The analysis is mainly based on Sten Lindroth's monumental two volumes [3] and on Rydberg [6], [7], [8] and also on information from several of the more popular accounts published by the present company STORA [9].

THE HISTORY

It is now believed that the mining of the mountain began in the 9th century by farmers living in the nearby Dal River valley. Early they joined in a kind of corporation or cooperative, a *"Bergslag"* ("Mountain Team" or "Master Miners") of which the first documents date back to June 16, 1288. Already at that time the Crown initiated a degree of control over the corporation, and in 1367 King Magnus Eriksson issued the first known letter of privilege, or charter, beginning:

> *"We, Magnus, by the Grace of God King of Sweden, Norway, and Scania, greet You, the master-miners and all the common people of Kopparberg, with our Lord."*

This study focuses on the inputs of energy for the mining and processing of raw copper during the peak period 1640-80. Copper mining terminated in 1895. In total, about 400 000 tonne of raw copper was exploited during the 1 000 years of operation.

The *"Bergslag"* organization, in which the Mountain Men's share of the mine and processing of copper was regulated, lasted for centuries but finally became obsolete. A reform to a private enterprise was made in 1862 and in 1888 a share-holding company was organized - Stora Kopparbergs Bergslags AB, now STORA, still owning and mining the mountain. It claims to be the oldest industrial corporation in the world still in operation.

THE ORE AND THE PHYSICAL ENVIRONMENT

The content of copper in the ore varied between 1.7 and 7% in the form of copper pyrite ($CuFeS_2$ containing 34.5% Cu, 30.5% Fe and 35% S). Occasionally lenses of about 5% Cu were mined and even pieces with up to 30% Cu were found (Figure 1).

The mine is located on a gently sloping side of the mountain. Uphill about 2 km away there is a lake system at an altitude of 54 metres above the mine (lake Vällan). The stream from the lake passes only about 0.5 km from the mine and falls another 15 metres before running out into the lake Runn about 1 km from the mine. The lake Runn is connected with the big Dal River through a short outlet. During the spring flood, the water-level exceeds the lake's, and floated logs in the river can be brought into the lake. These conditions created an unusually favourable setting for the exploitation of hydropower and for the supply of floated timber. The region is richly forested with pine, spruce and birch, all of which were used as fuel sources. The landscape is gently undulating with many lakes and brooks. The winter lasts from December to late March. These conditions are described in more detail later on with illustrations in Figure 5, 6 and 8.

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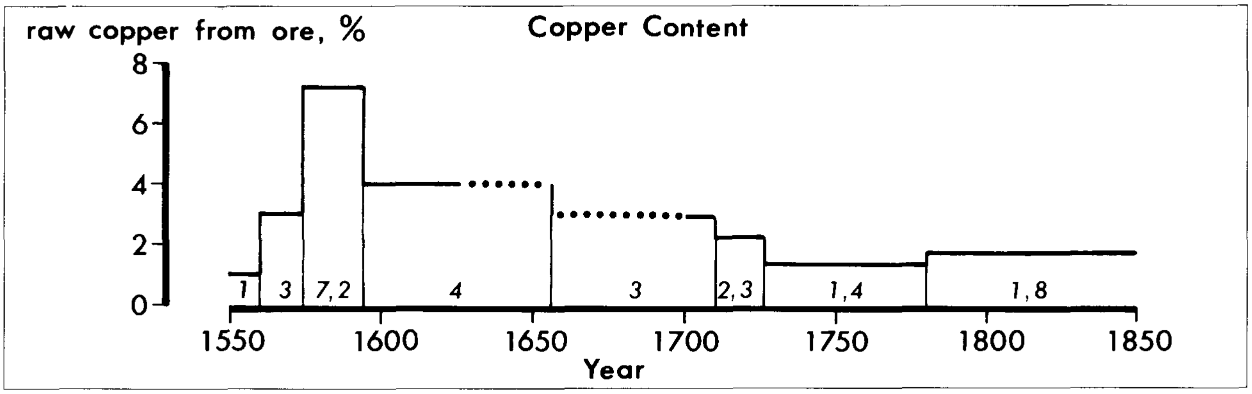

Figure 1. Yield of raw copper from the ore (in%). [3 Vol.2, p.263]

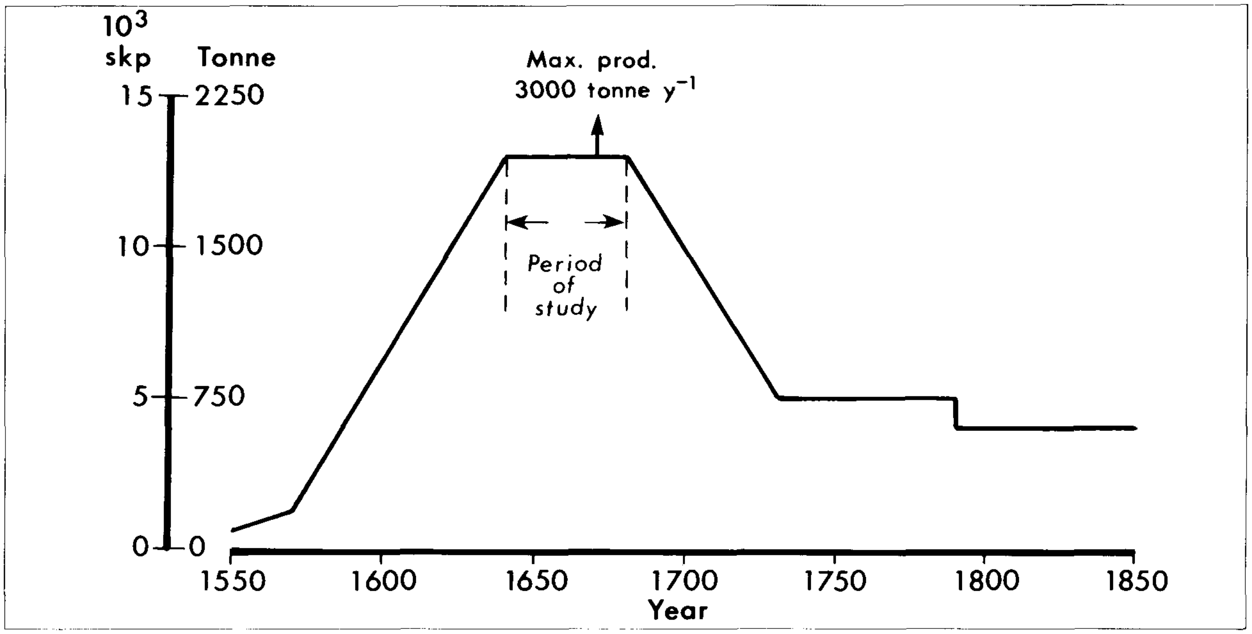

Figure 2. Annual production of raw copper at the Falu Copper Mine (1 skp ,skeppund = 0.150 tonne. Adapted from Lindroth [3].

A BRIEF OVERVIEW OF THE PRODUCTION PROCESS

The production from rock into raw copper (containing about 90% Cu) consists of the following phases: mining, assorting of the ore, "*skrädning*" (dressing), "*kallrostning*" (roasting), "*sulubruket*", "*vändrostning*" (dead roasting) and "*rostbruket*". The refining of raw copper to "pure" copper (in Swedish "*garning*") to a Cu-content of about 97-99% is not included in this study as it was carried out in nearby Säter (and in Avesta after 1636) about 30 and 60 km, respectively, downstream along the Dal River. (Swedish terminology is partly used in order to avoid misunderstanding). Table 1 describes these phases in more detail.

THE PRODUCTION

The annual production of raw copper is shown in Figure 2, [3].

THE ORGANIZATION OF THE MINING AND PROCESSING

The "*Bergslag*" of the mine, the corporation, was for centuries the following. Every shareholder had a certain share and a specific section of the mine and had to arrange for both the mining and the smelting of the copper himself. There were about 1 200 shares. These two stages in production were combined in every operating unit, and the right to take ore from the mine required possession of a

Table 1. Overview of Copper Process at the Falu Copper Mine (17th Century).

Operation	Upgrading	Description of Process	Consumption of Wood & Charcoal
MINING	Rock to ore	Heating the rock with wood. Each fire about 5 m^3 wood, burning about 6-7 hours. Probably about 60 fires each day, labour force about 250-300 men (includes work for the breaking and transport of the rock)	50 000 "*Stavrum*" = about 100 000 m^3 stacked or 65 000 m^3 solid wood, floated in the East and West Dal River to Daglöstägten, cut up in lengths of 0.6 m with axe. Logsize length 3-3.6 m, diam 30 cm
"SKRÄDNING"	Ore to assorted ore	Crushing of ore to pieces of suitable size of about two fists, assorting	None
"(KALL) ROSTNING"	(roasting) refer to Figure 3.Ore to "*kallrostad*" ore (*kallrostverk*)	Wood and ore charged in layers in open ovens. Sulphur and iron oxidized (S to SO_2 , Fe to Fe_2O_3 and Fe_3O_4), generating heat. 2-3 weeks (up to 7-8 weeks in big ovens)	"*Hultved, 1,8 m lång*". Fuel wood 1.8 m long. Annual consumption of wood 500-1000 m^3 solid
"SULUBRUKET" (refer to Figure 4)	Ore "*kallrostverk*" to "*skärsten*"	Heating with charcoal in ovens and bellows. 12-14 days (up to 30 days) in each oven set up	6.5-7.8 m^3 solid (5-6 "*stigar*") for 12-14 "*lass*" (one "*lass*" 0.45 tonne) of roasted ore = 5.4-6.3 tonne per day, see "*Rostbruket*"
"VÄND ROSTNING" (deadroasting) ("*trottsten*")	"*Skärsten*" to "*verk*"	Heating of "*skärsten*" with wood in up to 7-9 repeated operations, between which the size was successively reduced with hammers from a size of two fists to a size of chicken eggs. Some charcoal used in the last burns. Minimum time 5-6 weeks, often more. S oxidized to SO_2 generating heat	Annual consumption of wood probably around 500-1000 m^3 solid
"ROSTBRUKET" (refer to Figure 4)	"*Verk*" ("*trottsten*") to raw copper (about 90% Cu)	Smelting of "*verk*" in ovens of same types as in "*Sulubruket*", but smaller hearth (0.6 • 0.6 • 0.45 m), first warmed with three fires, total 1.3 m^3 solid wood. Each charge four "*fat verk*" and one "*fat*" (tray) coal in the mid layer. Slag tapped 2-3 times per shift. Copper tapped after $1^{1/2}$ days. 25-30 charges per 7-9 hours shift. Production $2^{1/4}$-4 *skd* (=0.34-0.60) tonne per day (often less)	5-7 "*stigar*" (10-14 m^3) charcoal per day. Corresponds to 30 m^3 solid wood (± 20%) per tonne raw copper. The total consumption of charcoal for "*Sulubruket*" and "*Rostbruket*" was about 250 000 "*stigar*" (•60 000 tonne), corresponding to a wood consumption of 400-440 000 m^3 solid wood y^{-1} [8, pp.12-14]
"GARNING" (not made in the Falun region, but in Säter about 30 km south west)	Raw copper to copper (97-99% Cu)	Smelting in "*flamugn*" (oven with bellows) with rich inlet of air. Remaining sulphur oxidized and iron to slag. 12.5-15% reduction of mass. Gold- and silver remains	One "*stig*" coal per "*skd*". Corresponds to 7.4 m^3 solid per tonne 0.5 "*stig*" coal per "*skd*" raw copper [3, Vol.2, p.354]

1) Note: *The name of the town is Falun, but in Swedish the "n" is dropped for the Falu mine (Sw: Falu gruva) and for other similar compounded words.*

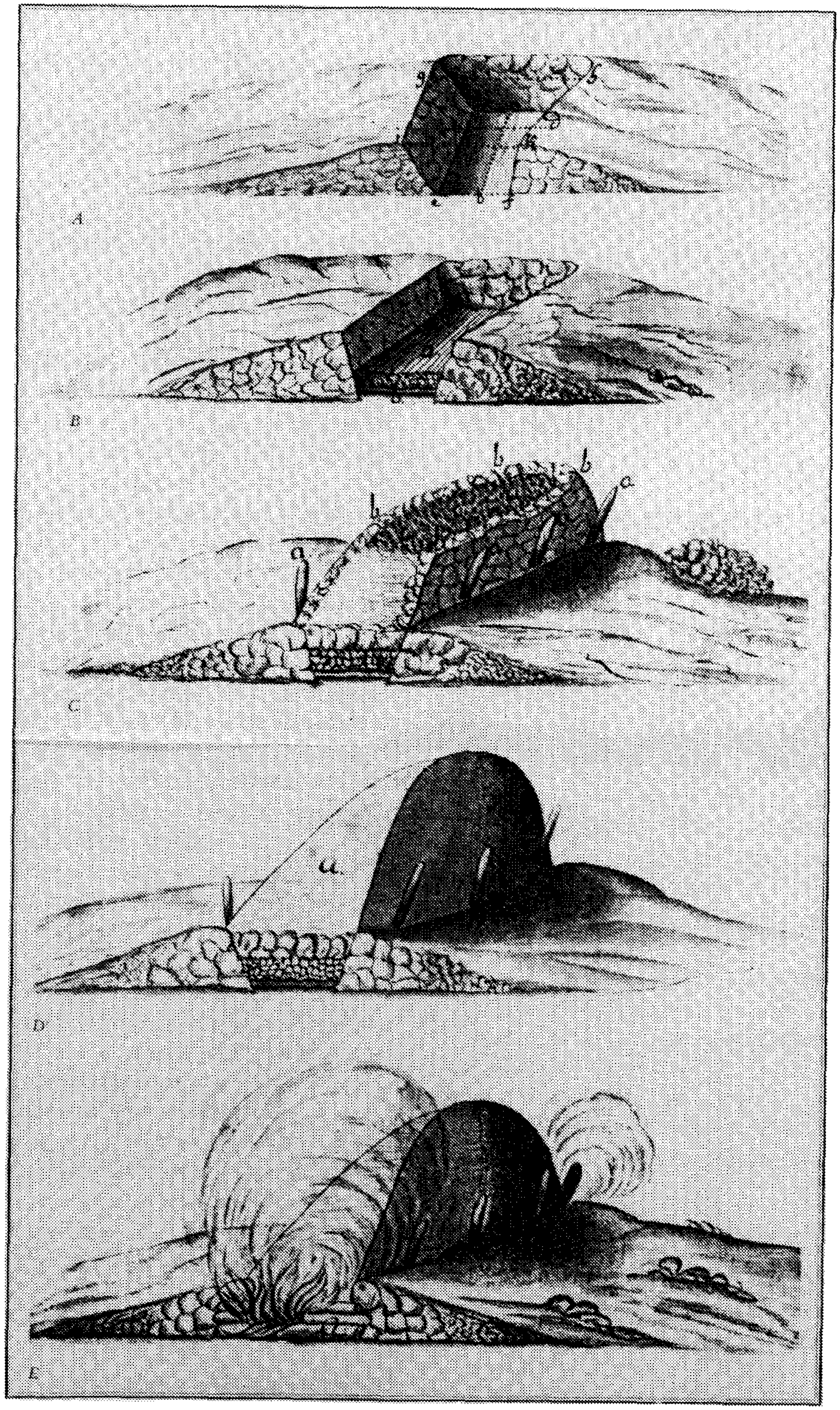

Figure 3. *"Kallroste"*. Cold roasting of ore. For details see Table 1. Source: Lindroth [3].

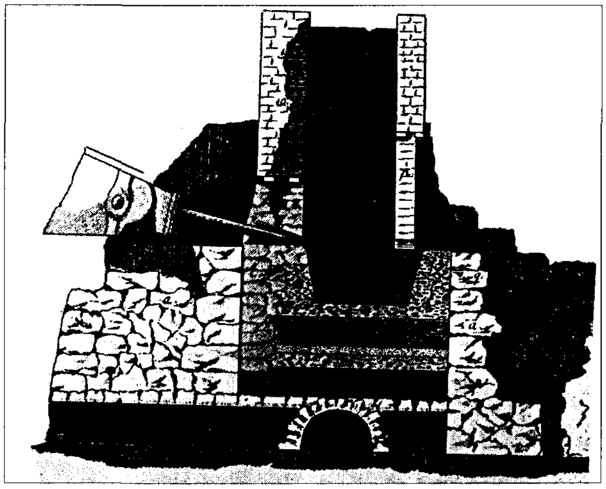

Figure 4. Oven for smelting *"Sulubruket"* and *"Rostbruket"*, described in Table 1. Source: Lindroth [3].

smelting furnace. The members usually had several shares. The shares could be sold and inherited.

The operating units were led by the Master Miners. A Council of fourteen members, elected by the Mountain Team, administered the *"Bergslag"*, and two of them, holding the title Master Miner, exercised the highest authority. The Council was to meet every Sunday and "have a talk", and a major meeting was held every month. Two bailiffs, appointed by the King, looked after the interests of the Crown.

In addition, the men of the mine had a highly exclusive and powerful association with strict ethical rules and its own judicial power, "Convivium Sancti Georgii in monte cupri" (St. George's Guild in the copper mountain). This Guild, established in the 15th century, still exists but now as a national society for engineers in all mining and metal works, Sancte Örjens Gille.

The processing was performed in furnaces and foundries in the Falu area, often at the same place, to which the ore was transported. The foundries were always at a stream that could supply the bellows with hydro power. In 1640 there were 147 furnaces and 127 foundries (see map, Figure 5). The map also shows the watershed of lake Vällan west of the Falu mine *"Falu gruva"*.

THE SUPPLY OF WOOD AND CHARCOAL

The mine, furnaces and foundries consumed enormous quantities of fuel, about 20-25% as wood in the round and the balance (converted to wood equivalents) as charcoal.

Very early the supply of wood for the mining was based on floated timber in the Dal River. In 1649 and 1659 this supply was organized in the form of two companies, the first for the west and the second for the east branch of the Dal River. The companies were run by traders in Falun. The map (Figure 6) shows the extent of the later river drive association around 1950 and the sections used around 1650 (shaded). Many of the tributaries to the two main rivers were probably also used, and at that time there were most likely large areas of big, old growth timber close to the rivers, including a considerable supply of big, dead and dry trees; an excellent source of heating fuel. At the outlet of the lake Runn in the main river, at Daglöstägten (at Torsång on the map, Figure 5), the loose floated logs were taken up and cut with ax. The floated logs had a length of 3-3.6 metres and about 30 cm in diameter and were at Daglöstägten cut in a length of about 0.6 metre and transported on the lake and hauled up to the mine. Assuming 300 operating days per year, about 330 m^3 solid wood was daily thrown down in the mine for the fires. About 60 fires for the breaking of the rock were burning in the shafts of the mine at a prescribed time, about 6 hours per day.

The area closest to the mine was most likely a supply circle, perhaps with a radius of 3-5 km, for wood used in the furnaces, the *"kallrostning"* and *"vändrostning"* of the ore and also for domestic use in the town of Falun. The supply of charcoal then had to come from areas beyond this zone. The wood for charcoal burning was cut early during the year and piled for drying at the stump in the spring and summer. The charcoal burning was made in the fall and the charcoal was hauled on snow and ice in the winter to the many furnaces and foundries in and around Falun (compare the map in Figure 5). It can

Table 2. Annual consumption of fuel wood and charcoal used for energy, for the Falu Copper Mine in 1640-80.

Wood 100 00 m^3 solid	225m GWh y^{-1}
Charcoal 400 000m^3 solid	900 GWh y^{-1}

(as charcoal 0.43 • 900 = 387 GWh y^{-1})
(Wood: special weight 0.45, 18 MJ kg^{-1})

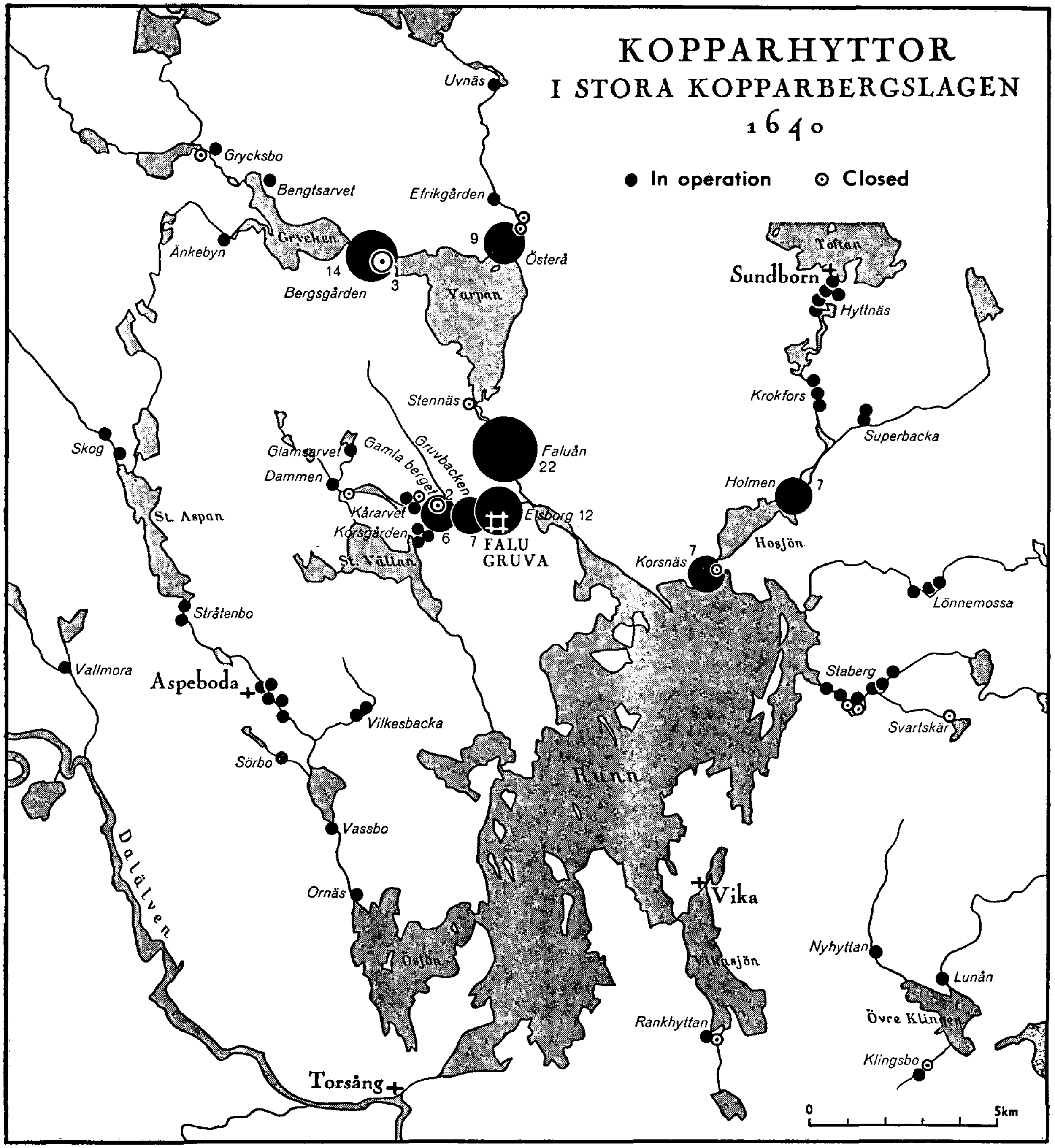

Figure 5. Copper foundries in 1640 (the size of the circles are in proportion to the number of foundries in the area). Source: [3, Vol.2, p.141].

be assessed that about one thousand loads arrived each day during the winter and that the average hauling distance probably was around 20-25 km with a maximum of perhaps 40-50 km.

The supply of wood and charcoal must have been a very sizeable operation. It must have required at least 2 500-3 000 man-years (of 200 man-days y^{-1}) but the number of individuals involved was probably double (a thumb rule in the steel industry was that there were five forest workers and haulers for every worker at the steel works).

The annual consumption for the mining and processing operation was about half a million cubic metres (Table 2).

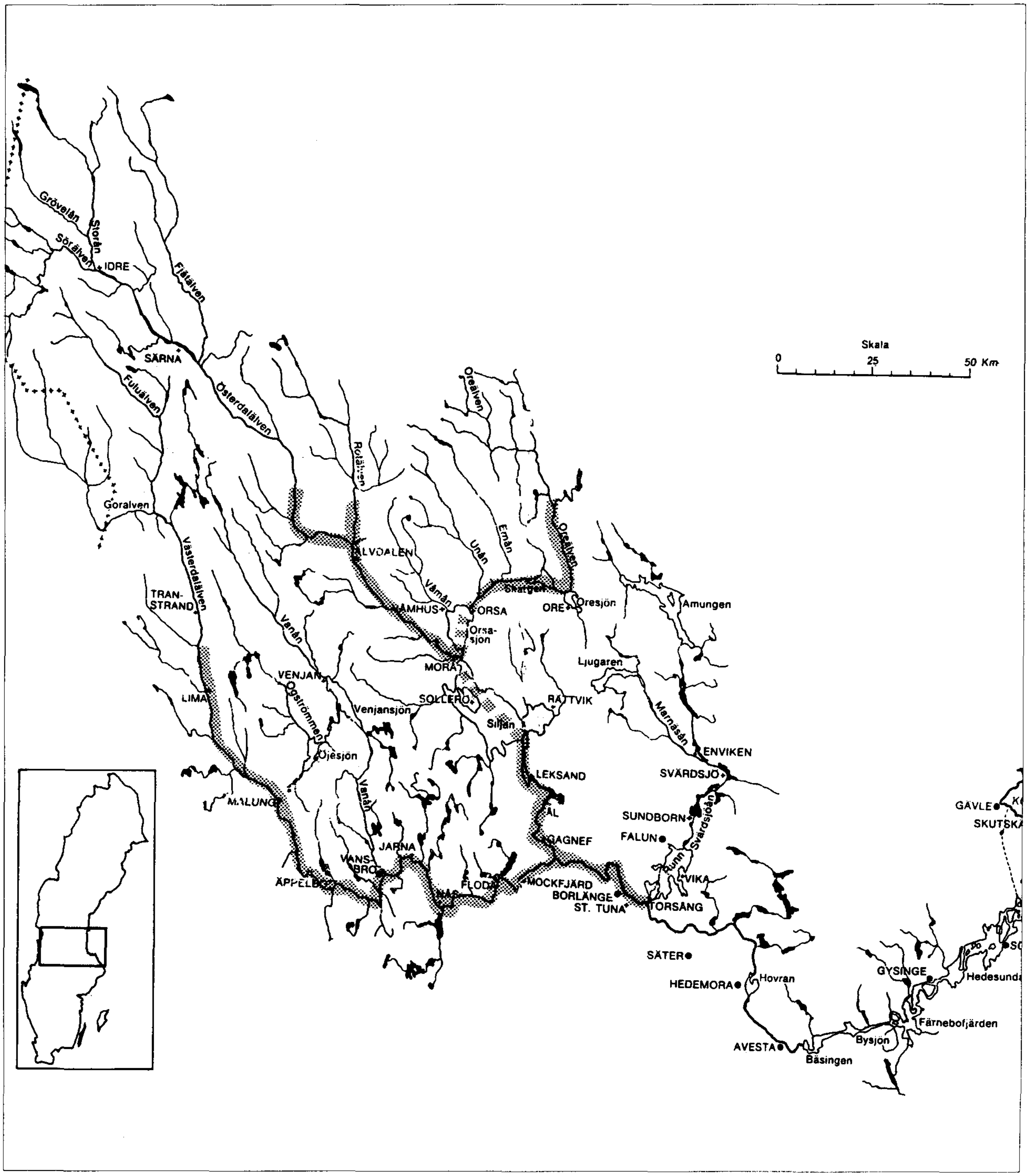

Figure 6. Map of the Dal River Drive Association in 1950 and the sections (shaded) used for the floating of loose logs to the mine in the mid 17th century. The map is based on Hellstrand [2].

In addition, considerable quantities of construction timber for a variety of uses, such as supporting walls in the mine, for dams, chutes and water-wheels, were also required but these quantities are not included here, nor wood for housing and domestic uses. The tapping of wood from the forest for the supply of energy to the Great Copper Mountain in Falun must have been a very large scale operation of its time, most likely without any comparison in the world.

HYDRO POWER

The drainage of water from mines is always a major problem, as it was in the Falu Copper mine. Until 1550, the water was brought up by hand- or horse-powered winches. After serious floods in the mine in the 1550's the first water-wheel was built in 1555 [3, Vol.1, p.110], marking the beginning of a systematic use of hydropower for the vertical lift of water and ore from the mine which was around 130 metres deep.

The ropes for the winches were mostly made of ox hide and herds of oxen were yearly driven to Falun by farmers in the south of Sweden. Large quantities of meat therefore became available in Falun, probably the origin of the still most popular sausage in Sweden, the *"Falu-korv"*.

The lake Vällan watershed, 2 km west of the mine, has an area of about 4 160 hectares with a runoff of about $12.5 \bullet 10^6$ m^3 y^{-1}, or about 0.4 tonne s^{-1}. The altitude of the lake is about 60-65 metres above the rim of the mine. A ditch was dug along the contour of the slope, terminating at an elevation of 54 metres above the mine about 200 metres away. From there chutes or pipes of roundwood carried the water to the water-wheels and the transmission of power between the wheels and the winches was made with a wooden construction, *"stånggångar"*. The storage capacity of the lakes were about 70-75% of the annual runoff, allowing a year round operation, except for unusually dry years. The watershed terminated in the lake Runn on about 10-15 metres lower elevation downstream of the mine.

The hydropower was used both for the mine and for the bellows of the 28 foundries located at the stream between the lakes Vällan and Runn (see Figure 5). With a discharge of water from lake Vällan of 0.4 tonne s^{-1} the generated gross power was 1.857 GWh y^{-1}. As power on the axle of the water-wheels, 25% is assumed with the following losses: of water 30%, of fall height 40%, transforming energy to power 40%. Thus $0.7 \bullet 0.6 \bullet 0.6 = 0.25$. Net power on the axle: $0.25 \bullet 1.857 = 0.464$ GWh y^{-1} plus 2.4 GWh y^{-1} at 100 foundries located at other streams operating 10 kW during 100 days of 24 hours, a total of 2.9 GWh y^{-1}.

ANIMAL POWER

The copper production encompassed large transportations, of which the following can be mentioned (the numbers in brackets denote an assessment of horse-days HD, and horses H).

Mining and processing

1. Transport of ore in the horizontal shafts of the mine, partly by horse (20 000 HD/100 H).
2. Winches, using horse-power, for the vertical lift of the ore, partly also using hydropower (20 000 HD/100 H).
3. Transport from the mine to the furnaces and from there to the foundries (67 500 HD/450 H).
4. Transport of raw copper to Säter, later to Avesta, about 30 and 40 km respectively, southwest of Falun (5 000 HD/50 H).

Wood and charcoal

5. Transport of roundwood to the rivers (horse, ox) (30 000 HD/300 H).
6. Floating of loose logs in the Dal River system to the conversion site at Daglöstägten and from there over the lake Runn to Falun.
7. Haulage of logs from the lake to the mine (12 500 HD/60 H).
8. Haulage of wood to the earth kiln, included in item 9.
9. Haulage of charcoal to the foundries (165 000 HD/1 000 H).
10. Haulage of construction timber for various purposes (20 000 HD/100 H).

Many of these horses or oxen were used also for other purposes. The assessment of the use of animal power can only be a qualified guess, itemized in the brackets above.

In total, it is estimated that the annual input of animal power was about 340 000 horse-days by about 2 000-2 500 horses for the direct production of 1 800 tonne of raw copper delivered to Säter or Avesta. About 75% of the input refers to the supplying

Table 3. Computation of the direct input of labour in effective man-days.

Total Input	Man-days	Men
At the mine, furnaces and oundries	455 000	2 100
For supplying of wood	69 500	560
For supplying of charcoal	432 000	2 400
TOTAL	956 500	5 730

Power input: 956 500 man-days of 10 h, 0.08 kW each = 0.77 GWh y^{-1}.

of wood and charcoal. Power input: 340 000 HD, 0.5 kW each, 10 hours = 1.7 GWh y^{-1}. As stated, these figures are uncertain.

INPUT OF LABOUR

Only few figures on the labour force are available (for example the number of miners, *"gruvdrängar"*, in 1677 were 1 063, [3 Vol.I, p.277]. An assessment is therefore very much an assumption, which can be supported by indirect computations on the basis of labour consumption per unit of input, for example man-days per m^3 wood or charcoal.

Such a computation of the direct input of labour in effective man-days results in the estimates given in Table 3.

SUMMARY OF INPUTS OF ANIMALS AND LABOUR

These estimates result in the following inputs:
0.55 man-days per kg raw copper
0.19 horse-days per kg raw copper

This refers to effective direct work. Most likely considerable inputs of supporting services were required perhaps amounting to an addition of about 20-30% of the figures above. Counting five family members per worker, the Copper Mountain supported a population of about 30-40 000 people.

THE ENERGY ANALYSIS

An energy analysis of production can be enlarged to include very remote flows of energy and matter or be confined to the direct inputs into a production system, neglecting the flows needed to make the item of input available, often termed indirect or

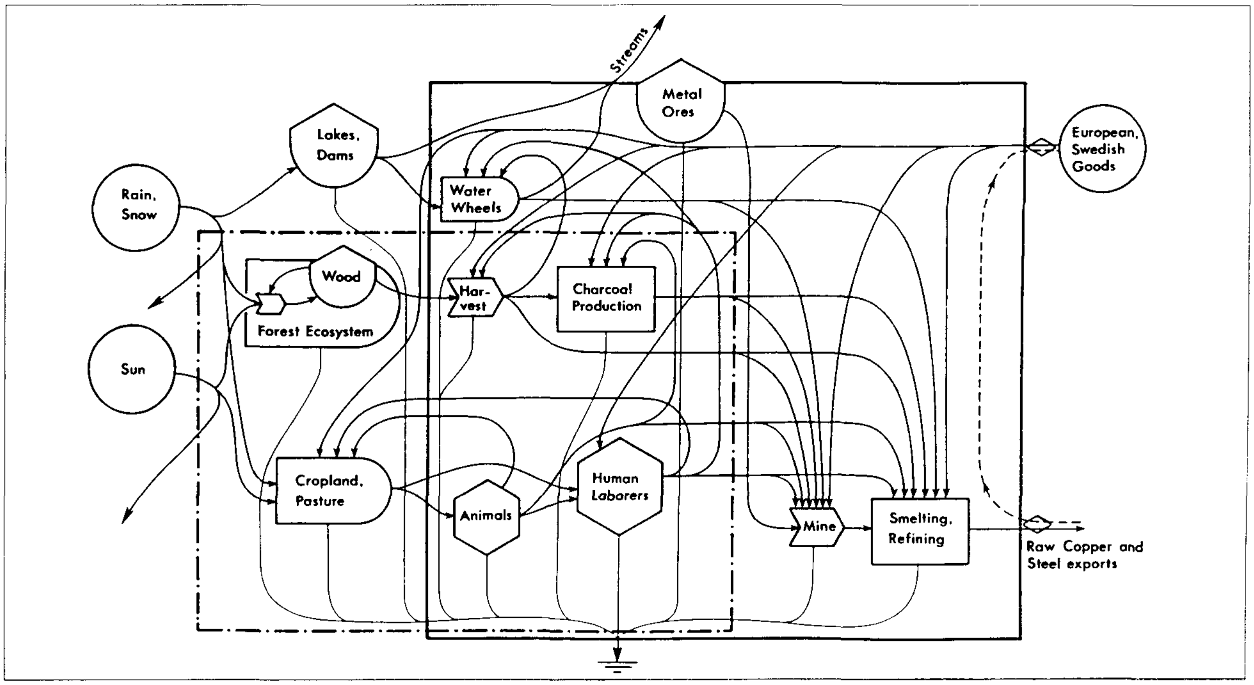

Figure 7. System boundary of the energy analysis identifying the direct energy requirements of the copper industry in the mid 1600's (indicated by solid boundary). The broken line indicates the system from which the special estimate of the input of net energy from the support system of the forests for the industry was made. The energy language diagramming of H.T. Odum [4] is used.

Table 4. Total annual input of direct energy of the whole operation of the Great Copper Mine during the period 1640-1680.

	Quality of energy	GWh y^{-1}
Forest energy		
Wood	Heat	225,00
As charcoal	Heat	900,00
TOTAL	Heat	1 125,00
Hydropower	Power	5,30
Horse, ox	Power	1,70
Human	Power	0,77

(It is assumed that the mine accounted for 80-90% of the total production of copper in Sweden. In assessments of the Swedish production of copper, e.g. Sundberg [11] the numbers above are increased with 15%).

Table 5. Conversion of human and animal power to gross energy inputs to the system, reduced with energies from the farm.

	Human	Animal
From power to nutrition	5,00	5,00
From work shift to day	1,50	1,50
From work day to work year	2,00	2,00
From work year to life year	2,00	1,30
Government services	1,30	1,10
PRODUCT	39,00	24,70
Reduction for energies from the farm on which they worked and lived, 75% for man, 80% for animal	• 0,25	• 0,20
RESULTING FACTORS[1]	10,00	5,00

[1] These factors are assessments of the author and are used in the computations in Table 7. The estimate of surplus forest energy computed from Table 5 and 6 is presented in Table 7.

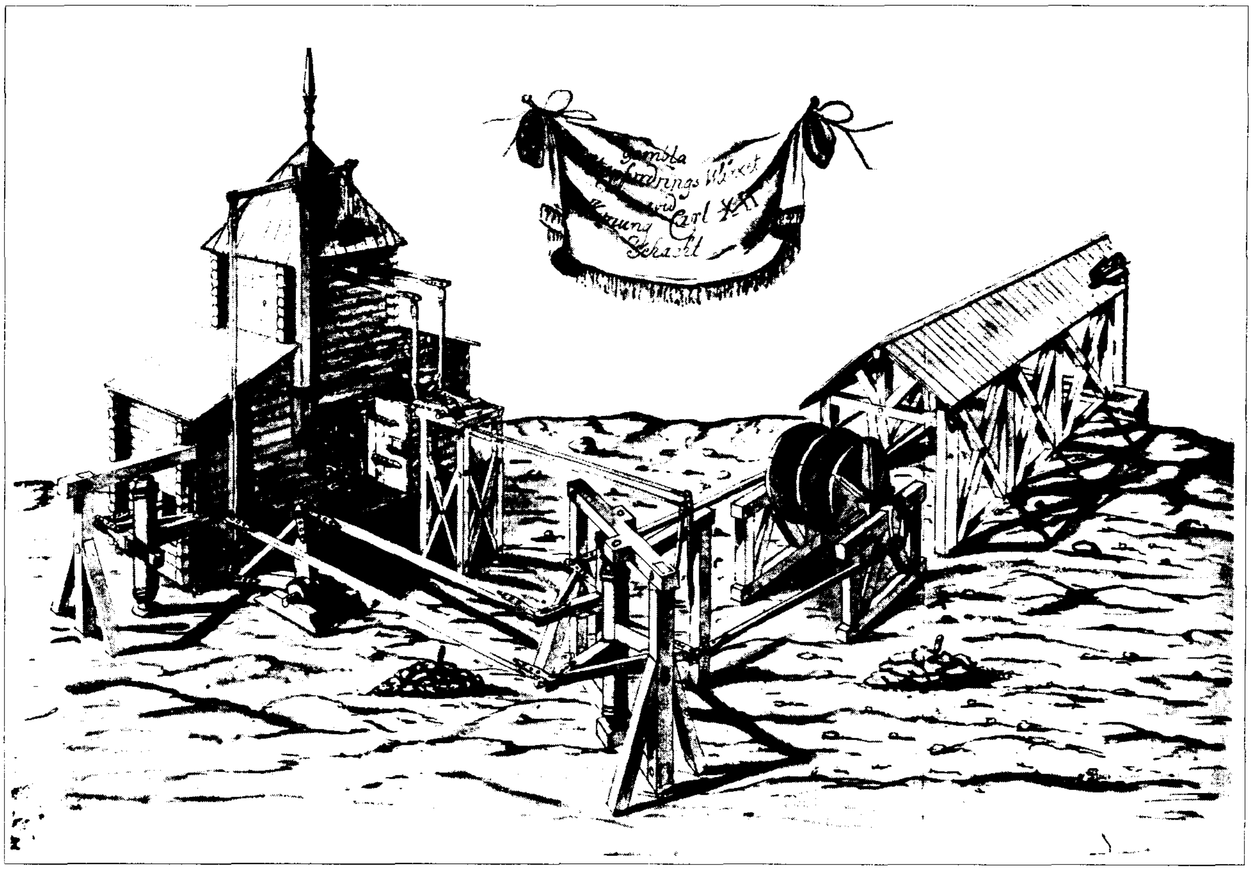

Figure 8. Example of power transmission from water-wheel to winch.

Table 6. Assessment of energy used up for delivery of forest energy to the point of final use.

Animals	Copper Horse-days	Steel Horse-days
Item 5 Logging to riverbanks	30 000	
7 Haulage to the mine	12 500	
8 Skidding to *kolmila*	40 000	
9 Hauling of charcoal	125 000	
10 Constr. timber	20 000	
TOTAL	227 500	2 800 000
of a total of 340 000 HD or 67%		
0.67 · 1.7 = 1.137 GWh	1,14 GWh y^{-1}	14 GWh y^{-1}
Labour	**Copper Man-days**	**Steel Man-days**
Item 5 Wood hauled to river bank	10 000	
7a Cutting	17 000	
7b Haulage	12 500	
7c River drive	20 000	
7d Conversion	20 000	
8-9 Charcoal, total	432 000	
TOTAL (MD)	511 000	3 000 000
of a total of 956 500 = 53.4%		
53.4% of 0.765 GWh y^{-1} = 0.77 GWh y^{1}	0,77 GWh y^{-1}	2.4 GWh y^{-1}
Loss of heat in charcoal burning	0.57 · 900 = 513 GWh y^{-1}	0.57·2 800 = 1 596 GWh y^{-1}

Note: Figures for steel from Sundberg, [11]

embodied energy. Boundaries for the production system must be drawn and the quantities of energy and matter itemized and specified.

There are two levels to the analysis. The main analysis is confined to the direct energy used up in the operations performed or closely tied to the activities of the corporation of the Great Copper Mountain. A graphical representation of the approach is shown in Figure 7. The dotted line represents a special analysis of the net energy input of the forest sector in the copper industry. Indirect or embodied energies are outside the boundary and regarded as externalities in the main analysis but included in the special analysis in order to arrive at net energy from the forests. The heat value of various compounds of the ore being oxidized are regarded as internalities used up in the production and is not itemized as input.

The assessment of the inputs of energy in the whole operation of the Great Copper Mine is summarized in Table 4.

NET FOREST ENERGY DELIVERED TO THE MINE, FURNACES AND FOUNDRIES

The inputs of forest energy in Table 4 are reduced with the energies used up for the delivery of wood and charcoal at the point of use, according to Cottrell's concept of "surplus energy" [1]. This involves reduction of the forest energy with animal and human energy in the forest work and wood transport and also with heat losses in the charcoal burning (57% of the energy content of wood).

As the animal and human energy is delivered power, these figures are multiplied with a factor of 5 and 10, respectively, in order to represent the energy inputs to the system (the derivations for these estimates are given in Table 5).

The forest system supplying energy to the mine and copper works is indicated by the broken line in the diagram in Figure 7. The energy used up in the forest system by animals and human labour is assessed in Table 6, which is a summary of the previous chapters on inputs of power of animal and human labour.

Some concluding remarks on the results of the two levels to the analysis explain the approach of this study. Table 4 presents the annual input of direct energy as indicated with the system boundary drawn with a full line in Figure 7. Table 7 gives the surplus or net energy from the forest sector as indicated by the dotted line in Figure 7 and represents the net contribution of energy of the forests to the economics of the copper production at the Great Copper Mountain of Falun.

Table 7. Surplus forest energy at the point of final use.

	GWh y^{-1}
Wood	225,0
Charcoal, 43% of 900 GWh y^{-1}	387,0
	612,0
Energy used up:	
by man 10 • 0.77 = 7.7	
by animals 5 • 1.14 = 5.7	-13,4
Surplus forest energy, about	600,0

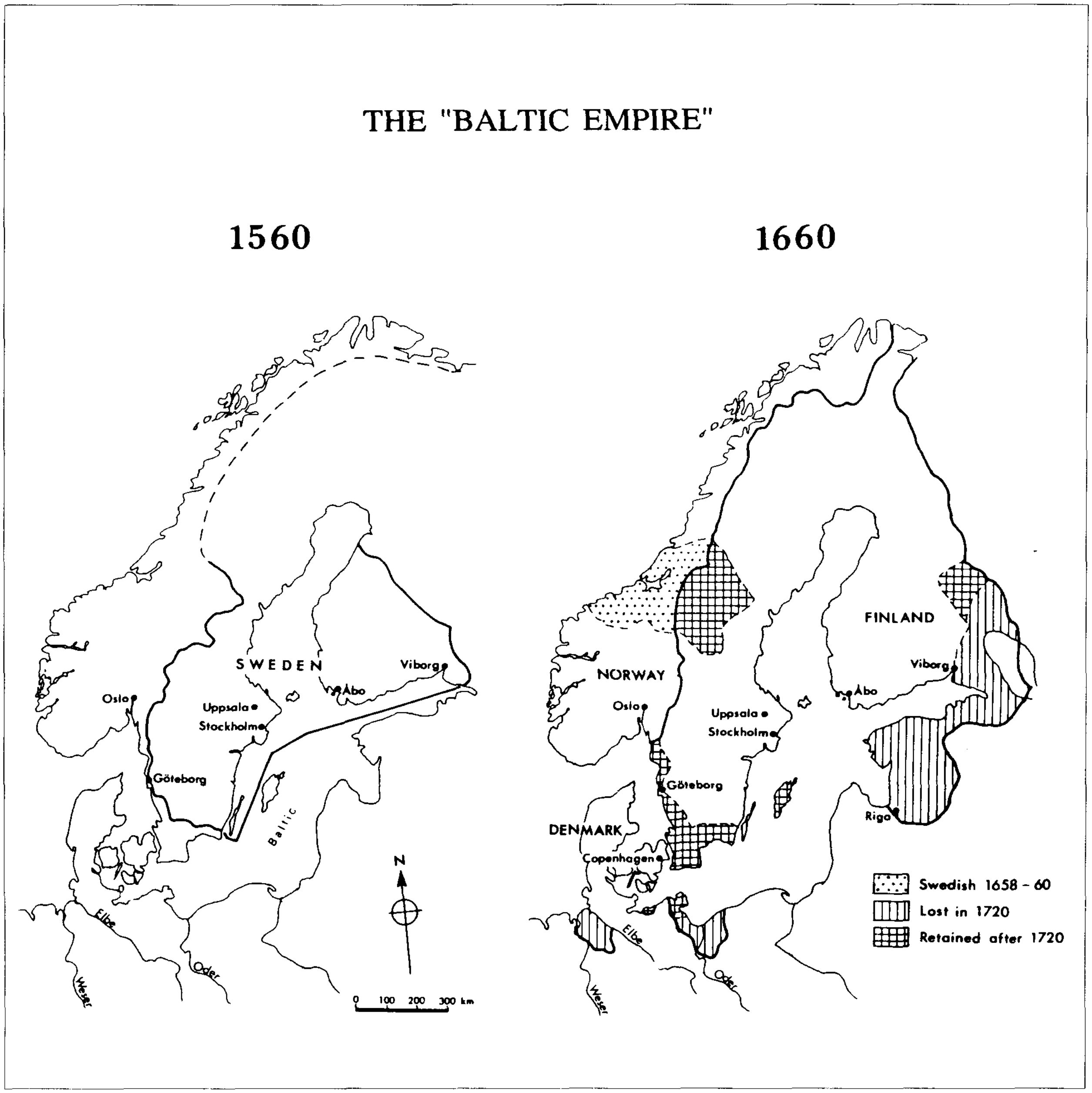

Figure 9. Swedish territory 1560 and 1660. The patches of land in Northern Germany had the purpose of controlling the trade on the big German rivers.

CONCLUDING REMARKS

The copper production at the Great Copper Mountain at Falun required during its peak period an input of forest energy of about 1 125 GWh y^{-1}. Hydropower, animals and humans only accounted for small but important energy inputs (Table 4). With deductions for the loss of energy in charcoal burning and energies used by humans and animals in forest and transport work, the net energy surplus from the forest to the copper production was about 600 GWh y^{-1}. These figures correspond, approximately, to 100 000 and 50 000 tonnes respectively of crude oil per year, at that time an enormous quantity of fuel for industrial production of one single enterprise.

The energy used for copper and steel production brought great revenues to the Swedish national economy and its security. It increased wealth and enabled Sweden to exercise an aggressive war strategy and to develop into the most powerful nation in Northern Europe. During the second half of the 16th century this region was in a chaotic state since the old power structures such as the Hanseatic League and the German Order had collapsed. With the purpose of achieving control of the trade in the Baltic Sea, Sweden in the period 1560-1660 - in continuing warfare with Russia, Denmark, Poland/ Saxony and the Habsburg Empire - established its Baltic Empire as shown in the map, Figure 9. This development was almost entirely based on the revenues of the metal industry, which was supported in an energy perspective, by the forest [10]. The Empire was successfully defended up to the first decades of the eighteenth century.

Most insightful and comprehensive assesments of the role of the forests in various human societies are presented by Cottrell [1] and Perlin [5] describing the development of civilization from ancient Mesopotamia to the struggle for independence of the New England states in North America. The Swedish Baltic Empire parallels the theme of their books: Wood-Energy-Wealth-Power. For a forester, these books are most fascinating readings.

When the era of fossil fuels comes to an end, the forests will again capture a key role for the supply of energy. It is already now appropriate to recognize such a probable scenario and to act accordingly. Foresters, used to thinking and acting in a long time perspective, should now strengthen their lead and efforts for restoring the productivity of harmfully exploited forest resources and to curtail still ongoing wasteful destruction.

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