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Abstract.

This article discusses the transformation from an organic to a mineral energy system from a Swedish historical perspective. Main arguments are that there was a dynamic interaction between the two systems during the Swedish industrialization process. For one, a diffusion of the mineral energy system contributed to opening previously inaccessible organic resources in the forest of northern Sweden. Secondly, the development of the pulp- and paper industry contributed to the switch from charcoal to coke in the iron industry. Thirdly, the development of hydropower, itself an organic source of energy, further contributed to the emergence of a mixed energy system. One can therefore see the Swedish transition from an organic to a mineral energy system as a shift from a traditional organic energy system to an industrialized organic energy system, which is to say an organic energy system which for its operation was depending on technologies and organizational structures of the mineral energy system.

KEY WORDS: Organic energy system, energy history, Sweden, forest history, firewood

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Introduction

Tony Wrigley argued already in the 1960's that the early modern economy saw the scale of its energy flows being limited by the acreage available for food and firewood production.[1] This is so since photosynthesizes, the bio-chemical, solar energy based process by which plants transform atmospherical carbon dioxide to carbon hydrates and cellulose, the fabric of plants, is depending on land. Photosynthesizes was therefore the basis for most energy flows in the organic energy system, including fuels for industrial and domestic purposes along with nutrition for humans and draught animals. The limits to growth imposed by the energy system, also known as the organic economy or the biological regime, where eventually overcome by coal as there were no areal limitation on the size of the fossil fuel energy flows. The rise of the coal based energy system, in Wrigley's terminology 'the mineral economy' was therefore a key factor in Kenneth Pomeranz' explanation of 'the great divergence' implying that a transformation of the energy system was at the heart of the industrial revolution.[2]

If a tentative factor analysis of early modern Sweden during the biological regime is carried out, one notices that the country had a good supply of fuel and hydropower.[3] Sweden may therefore at a first glance appear as a relatively blessed country during the pre-fossil fuel era as far as energy resources are concerned. With the exception of the southernmost parts of the country, forest was a dominant feature of the landscape. Inland Norrland, a significant part of the country's land area, was to an even higher degree dominated by woodlands, yet largely inaccessible to economic exploitation of any scale. Significant organic energy resources were therefore not assets in an economic sense, which paradoxically was a consequence of the organic energy system itself. How the organic energy system limited access to organic resources is a main theme in this article.

Around three quarters of the Swedish land area is found in the boreal coniferous forest, or taiga. A short growing season meant that the supply of productive

[1] Wrigley, E. A. (1962). The Supply of Raw Materials in the Industrial Revolution, *Economic History Review* 15, 1–16.

[2] Pomeranz, K. (2000). *The Great Divergence: China, Europe, and the Making of the Modern World Economy*. Princeton: Princeton University Press.

[3] For an introduction to the concepts of organic and mineral energy systems see Wrigley, E. A. (1988). *Continuity, Chance and Change: The Character of the Industrial Revolution in England*. Cambridge: Cambridge University Press; Wrigley, E.A. (2010). *Energy and the English Industrial Revolution*. Cambridge: Cambridge University Press.

agricultural land was limited in comparison to Western European countries. The exception was the southern parts of Sweden, with agricultural conditions more similar to Denmark or Germany, however noticing that there are evidence for agricultural surpluses in the Mälardal region from the 17th century.[4] The inadequate farming conditions, mainly determined by the country's northern location, in turn explains the low population density, which in turn explains the relatively abundant supply of timber but also hydropower. Sweden was additionally endowed with significant mineral resources, mainly iron and copper ore located in the mid-central districts known as Bergslagen. Since the conditions for agriculture in these districts were not fully satisfactory, but since the surplus in the Mälardal region could be used for supporting miners and iron workers, there was also enough man power for the development of an iron and copper industry.[5] It was therefore the favorable mix of mineral resources, hydropower, and decent agricultural conditions and nearby boreal forests, which allowed the metal industry to develop.

The value chains of the metal industries were kept within the country in the spirit of the mercantilist economic doctrine. Thus ore exports were prohibited until the mid-1800s. In the early modern European trading system, Sweden was a country specializing in metal products and forest products such as tar, utilizing its special factor endowments. The domestic economy was prior to the agricultural revolution from the 1750s and onwards based on agriculture with a limited capacity to support a larger population.

Northern Sweden and its factors of production

The above outline shows that in order to understand the transition from an organic to a mineral energy system in a specific country, it is, as a first step, important to consider the factor mix. This is plain to see when northern Sweden is focused. In this part of the country there were large areas of forests, especially old-grown spruce with high-quality, dense saw timber. The high quality depended on the slow rate of growth in the harsh climate. When Carl von Linneus undertook his expedition to Lapland in

[4] Se Myrdal, J. (1999) *Det svenska jordbrukets historia. [Pt 2], Jordbruket under feodalismen : 1000-1700*, Natur och kultur

[5] Jonsson, Kristina (2001), *Järnhanteringen i norra Västergötaland. Arkeologiska undersökningar i Essunga, Främmestad, Istrum, Ledsjö, Lerdala, Vättlösa och Älgerås socknar*, Jernkontorets Bergshistoriska Utskott, H 71: Stockholm. p 89-91.

1732, he noted the potential of the huge forest resources, but also pointed out that the forest stood there, "in vain and to no benefit".[6] The timber did not have any commercial economic value. Linneus argued that if the right spirit was there to cultivate the forest, there were enormous riches to be gained. While the continental powers fought over oversea colonies, Sweden had its own colony within its own borders. The idea of an internal colonization was not at all new in the 1700s.[7] In 1555, Olaus Magnus cites already then old authorities giving voice to the same idea. Northern Sweden had several small coastal towns that had been established in the middle ages, unclear exactly how. There was a population in the area before the Swedish government had put the coast under its jurisdiction. For long, historians have tried to understand who the true identity of the mysterious Kvaener as well as the emergence the Birkarlar in the 14th century.[8] The latter may have been a then new term for the indigenous non-sami population who earned their living in a combination of agriculture, fishing, hunting and trade, and who, after the area was put under the jurisdiction of the Swedish crown in the 14th century, also came to function as state officials and tax collectors. Northern Sweden, not the least the interior parts, was also populated by the Sami people, with an economy based on reindeer nomadism, fishing and to some extent hunting and trade. The settlements in the interior were during the 1600s very small, obviously a reflection of the harsh climate, most notably a short growing season with a persistent risk of crop failure. Basically, proper farms were found along the river valleys in the coastal area, while the inland presupposed hunting. From a biological perspective, Northern Swedish agriculture was highly dependent on dairy farming, since the short but intense growing season was relatively the most favorable for grass. The Sami reindeer herding utilized non-cultivated fodder, lichens, in areas were agriculture was practically impossible. The forest was used for domestic building material and fire wood, but not for commercial purposes of any important degree. An important factor explaining this was the low population density and therefore an inadequate labor supply.

[6] Linné, C. *Carl von Linnés lappländska resa: Caroli Linnæi Iter* Lapponicum, Stockholm: Natur och Kultur, 1969
[7] Sörlin; S. *Framtidslandet. Debatten om Norrland och naturresurserna under det industriella genombrottet*. Stockholm: Carlssons, p 24
[8] Harrison, D. (2002) *Jarlens sekel: En berättelse om 1200-talets Sverige*, Stockholm: Ordfront. p. 741 ff.

In the northern parts of the country the existence of huge iron ore deposits were known from 1642.[9] A large part of the deposits certainly had a too high phosphorous content to be utilized with contemporary technology. Sufficiently large low-phosphorous deposits were however discovered for advancing industrial exploitation. The problem in the northernmost parts were at the least twofold. For one, the population base in northern Lapland was even smaller than in other parts of Norrland and, secondly, the forest supply was at the best limited. The industrial strategy therefore included the transportation of iron ore to the ironworks situated in the coast areas. The transport network, depending on rain deer sledge transports during the winter where, however, not successful, due to low economies of scale. A main reason for allocating iron works along the Norrland coast was to counteract the fuel shortages in the central Swedish iron districts. Instead, ore to the Norrland ironworks was transported from the Stockholm archipelago. The examples from northern Sweden illustrates why it was so difficult to realize the vision of the large-scale colonization of inland Norrland: the major biological energy resources and the comparatively rich material resources were not extractable until there was a sufficiently large population. Basically, this could not happen before the interior Norrland was integrated in the growing international economy, something that only happened decades after the Industrial Revolution. The importance of the combination of factors of production in northern Sweden also shows why Greg Clarke's counterfactual thought experiment about an industrial revolution in England based on the Nordic and Baltic wood is not based on realistic assumptions. Before we return to the specific features of the Swedish energy transition, it is however motivated to look more closely at the hallmark machine of the industrialization, the steam engine, and how it was diffused to Sweden, thereby significantly linking the Swedish economy to the mineral energy system.

[9] Kengis was granted privileges in 1643 see: Norberg, P. (1958), *Forna tiders järnbruk i Norr- och Västerbotten*, Stockholm: Almqvist & Wiksell.

Sweden on Steam

An example of the importance of the combination of production factors, this time including know-how embedded in technology and real capital is the Dannemora mine steam engine project of 1728.[10] Already a decade after Newcomen had built his first steam engines in England there was a desire to evaluate the technology in Sweden. Here we see the importance of the institutional setting. It was the powerful Royal Board of Mining that initiated the project. The basic problem was the same as in England; hydrological conditions created problems with flooding mines. After the plans had first surfaced in 1715, just three after Newcomen's first engine, a Newcomen engine "a fire and air machine" was built in Dannemora in 1728 under the auspices of the Swedish engineer Mårten Triewald. It turned out, however, that the machine consumed large amounts of valuable firewood. The opportunity cost were high, since the wood had an alternative use as charcoal for use in the nearby blast furnaces, foundries and forges. This opportunity cost did not exist in England, where the engines were set up at the mouth of the coal pit. The costly fuel consumption simply meant that the machine was not profitable, which in turn deterred from resolving the remaining technical problems which, among other things, included that it did not operate well under winter conditions. High energy costs caused not only diminishing returns, but negative returns. The production factor missing at Dannemora was coal, not know-how nor basic economic incentives, and accordingly, and just as economic theory would predict, the project was shelved.[11]

The Watt steam engine came to Sweden with the British engineer Samuel Owen, a Leeds based engineer who moved to Stockholm in 1804 on initiative from his Swedish business contacts, who had previously bought British steam engines for two breweries, one textile industry and one flour mill.[12] In Stockholm, Owen constructed his first steam engines for industrial use, as well as small steamers such as "The Witch of Stockholm". Not without reason it is often considered that Owen played an important role in the establishment of a modern engineering industry in Sweden. One of his apprentices, Carl Gerhard Bolinder, did for instance start Bolinders Mekaniska Verkstäder (Bolinder's mechanical workshop) in Stockholm, a company

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[10] Lindqvist, S. (1984). *Technology on trial. The Introduction of Steam Power Technology into Sweden, 1715 – 1736.* Uppsala studies in history of science 1. Uppsala: Avd. för vetenskapshistoria.

[11] There is a 1:10 scale model of the machine on display in Stockholm's Technical Museum.

[12] Rye Margareta, red (2009). *Dædalus: Tekniska museets årsbok. Årg. 77(2009), Samuel Owen : teknik- och ångbåtspionjär*. Stockholm: Stockholmia.

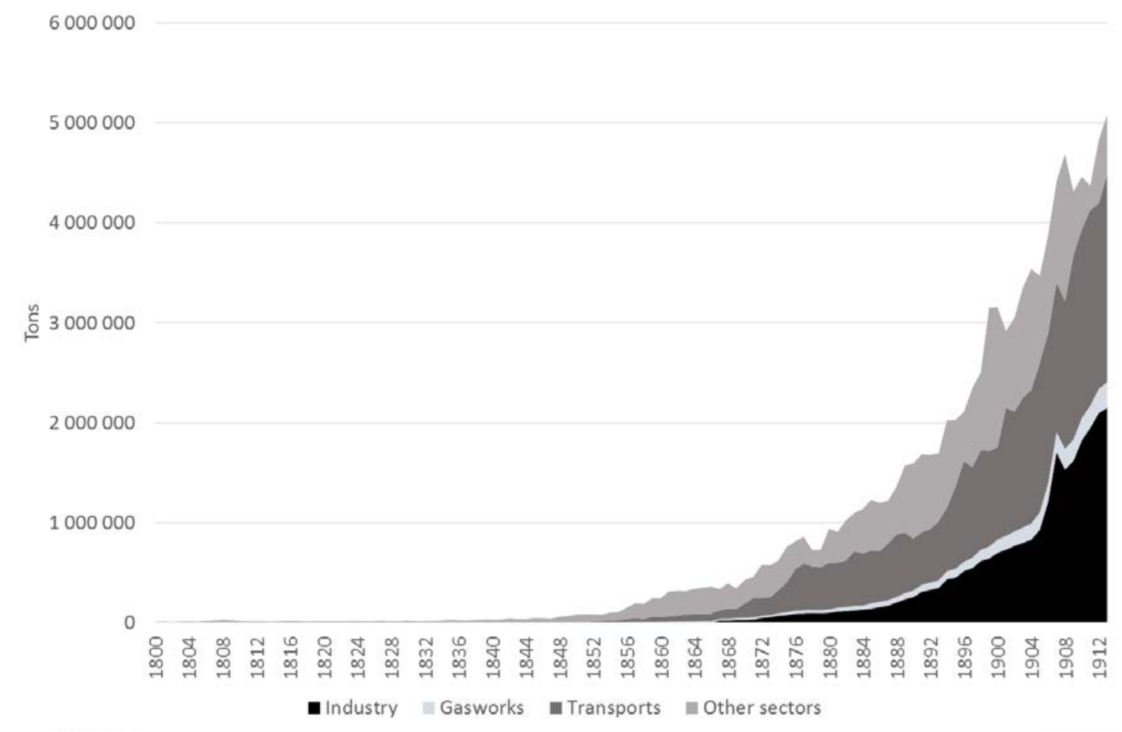
which is today part of the Volvo Group. Atlas Copco, today a global engineering company specializing in compressed air technology, was also co-founded by one of Owen's students. Owen's business operations may from an organizational perspective be seen as part of the transition from the biological to the mineral-based energy system in Sweden. Owens, and his Swedish business partners, transferred a critical know-how from Britain to Sweden. Seen from a human capital perspective, Owen additionally exemplifies a transfer or reinforcement of a values stemming from his devoted involvement in the Wesleyan Methodism. Not only coal came with the steam engine, but also liberal and egalitarian ideas held by the class of people to which Owen belonged. For instance, Owen was the first president of the Swedish temperance movement. Even though Owens role as an individual should not be exaggerated, the picture emerges of the energy transition as complex, multi-level process which was not limited to coal as such. The transition went hand in hand with business innovations and economic transformation, which probably strengthened certain evangelistic and liberal values, perhaps even bourgeois virtues, which came to form an ideological backbone in the institutional renewal of the state during the 1800's. Of course, Owen was not the sole bearer of liberal ideas or technological know-how, there were also a number of Swedish-born industrialists and businessmen with similar attitudes and skills. We dare however to speculate that the steam engine, coal and the formation of human capital, the latter including technological know-how and values, were strengthened in a symbiotic, co-evolutionary process with successful business, ultimately manifested in profitable investments.

The origins of the demand for coal

The railways constituted an important role in the energy transition, not only in terms of steam and coal, but from an institutional perspective as well. This is so because the railways required a new state. The overall organization was based on state support for the construction of trunk lines, of which the first was completed in 1856. Individual businesses were responsible for local and industrial sidings. Also in this part of the energy transition, it is important to consider the complexity that lies behind the changes in order to avoid an overly technologically-reductionist interpretation. To begin with, railway construction required a new form of government, very different from the mercantilist military state that had first emerged in the 1500s, making railway construction part of the extensive liberal reforms that took place in Sweden from about 1840. The state of the energy transition era borrowed money on international financial markets to finance investments in communications and railway networks. As railways directly contributed to the increased use of coal, the national railway project was one of the most important measures behind the Swedish energy. The locomotives, originally of British or German designs were intended to run on coal. As a matter of fact coal hold much better qualities for steam engines as compared to biofuels such as wood or peat. This is especially so concerning locomotives, with high demands on power and limited size. Here lies some important, but not seldom overlooked technical circumstances which are important to consider. First, coal has a significantly higher energy content in relation to its weight than biofuels. If volume is instead considered, which is some respects is more important than weight, the difference becomes even more striking. One cubic meter of wood is in energy terms equivalent to approximately 0.17 tons of coal. As the density of coal is about twice as that of wood, this means that one cubic meter of coal weighs around two tons, which in energy terms corresponds to around 10 cubic meters of wood. A steam locomotive such as model SJ Litt. B., a Swedish design from 1909, had a fender with a coal storage capacity of 6 tons, corresponding to around 35 cubic meters of wood. Furthermore, as locomotives need to develop significant amounts of power, there is a close relationship between performance and the boiler capacity, measured in tons of steam per hour. One important factor affecting the boiler capacity is the rate at which the fuel can be burned, which gives how much energy that can be transferred to the water in the boiler per hour. Since the area of the firebox correspond to how much fuel that can be combusted and since that area is imitated in a steam locomotive, running the engine on biofuels rather than coal reduces the boiler capacity and, thus, the locomotive's power, by approximately 50 percent. Locomotives were therefore designed to run on coal, even if other fuels could be used in cases of emergency. Coal was also the preferred fuel for stationary industrial steam engines, even though it possible to keep up the boiler capacity by simply constructing a large boiler and extending the combustion area of the firebox. Even in this case, a larger boiler would be needed if biofuels were used. Adding to these disadvantages of biofuels, peat and even firewood also contain some amount of water, which means that energy is spent on drying the fuel itself.[13] Steam engines therefore induced a demand for coal, not fuel in general.

In quantitative terms, Swedish coal imports began to increase from 1840. Lindmark and Olsson-Spjut have in an upcoming paper shown that the rise can largely be explained by the increasing steam motive power in the industry, the development of steamship tonnage, the recorded railway fuel consumption and the coal consumption in gasworks (see figure 1).

Fig 1. The Swedish coal consumption after sector. 1800-1913.



Source: Lindmark & Olsson Spjut (2017 forthcoming) *Industrialization and the transformation of the organic energy system. Sweden 1800-1913.* Dept. of economic history, Umeå University

Only minor parts of the coal imports may therefore have been used for domestic heating and other premises. Lindmark and Olsson-Spjut therefore conclude that the increasing demand for coal was linked to the leading economic sectors of the industrialization of Sweden, despite the country's considerable assets in the form of

[13] As such, the SJ Litt. B. spent 100-120 kg of coal for heating one cubic meter of water to a pressure of 12 bar and a temperature of 187 C. At top speed 90 km/h this amounts to 9 cubic meters and one ton of coal per hour. Under ideal conditions, the SJ Litt B. could produce 25 tons of steam per hour, which corresponds to a three storage high industrial steam engine. Interview with steam engine and locomotive expert Michael Carlsson, Solberga Station AB 2017-02-16

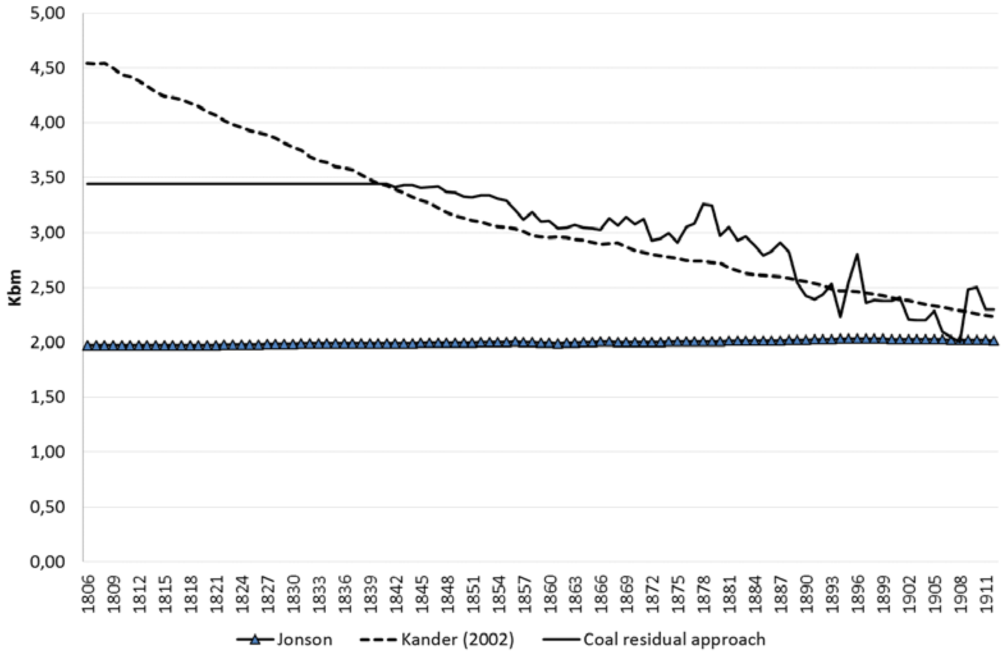
wood. It was the mechanization of transports and manufacturing that drove the energy transition. Still, the Swedish energy transition was characterized by a dynamic interaction between changes in both the organic energy system and the mineral system, which create synergies between both systems. The expansion of the saw mill industry along the Norrland coast initially utilized mechanical hydropower. Steam power did, however, grow in importance from the 1850's, not the least since steam made it possible to allocate the mills to locations more suitable for shipping. Specific for this industry was the possibility to utilize the main waste product, sawdust, as a main fuel for the engines. These synergies are the distinguishing feature of the Swedish energy history in the 1800s and well into the 1900s. However, we should first look into the energy transition from a rural point of view before we devote industry further attention.

Firewood in the domestic sector

The Swedish energy consumption was during most of the 1800s dominated by domestic uses of fire wood in rural areas. Unfortunately, the source material for the 1800s is very sparse and from source critical point of view of low value. We can only make guesses about the development of fire wood consumption based on more reliable from the 1920s. It is also extremely difficult to make a distinction between fuel consumption for consumption purposes, mainly residential heating, and fuel consumption for production purposes because the typical farming household was an organizational unit for both production and consumption activities. What we know is that a huge percentage of 19th century fuel consumption occurred on rural farms. The urban fuel consumption, even counted per capita, was significantly lower, partly by overcrowding and since tile stoves were common in cities. Urbanization was therefore a factor that tended to reduce per capita energy consumption. Both the iron stove and the stove were innovations with a higher thermal efficiency than traditional fireplaces, but weather the new types of stoves actually reduced or even increased the per capita firewood consumption in rural areas is not known. The crux is to what degree improved heating efficiency was used for reduced firewood consumption or higher indoor temperatures in combination with an increased number of heated rooms.[14] It is also uncertain how much the rise of a landless rural working class in the 1800's, with accommodation in smaller crofts affected the aggregated fuel consumption per capita. An estimate that only takes into account population trends in different parts of the country, northern Sweden had a larger population growth and a higher per capita firewood consumption than the rest of the country, and population growth in the cities, gives that household and agricultural uses of firewood was about 5 million cubic meters in 1800, which roughly corresponds to the forest industry's raw material consumption in the mid-1860s. In this case, the annual per capita consumption is relatively constant at two cubic meters. Assuming instead relatively strong effects of improved technology, primarily stoves, gives a corresponding figure at 11 cubic meters in total during the early 1800's, equivalent to the forest industry's raw material consumption around 1890. In this scenario, there is falling per capita consumption from around five to two cubic meters per person and years until the early over the 19th century. Figure 2 shows scenarios of household firewood consumption. The first series (Jonson) demonstrates a scenario in which efficiency gains were totally offset by increased temperatures and heated space. The second series is Kander's (2002) estimate with a high net-effect of diffusion of tile stoves especially up to the 1850's. The third series assumes mainly substation effects from increased coal consumption, using the coal residual from figure 1 to adjust the back-cast of Jonson's 1923 bench-mark. We will shortly explain why it is important which of these scenarios closest to the truth.

Fig 2. Estimates of domestic per capita firewood consumption 1805-1913

[14] This problem is discussed in Lindmark & Andersson (2010) Household Firewood Consumption in Sweden during the Nineteenth Century, *Journal of Northern Studies*, 14, 55-78



Source: Jonson (1923); Kander (2002) Lindmark & Olsson-Spjut (forthcoming 2017)

The forest industry was one of the important pillars in the Swedish industrialization process and the period 1840 to 1890 saw a tenfold increase of the timber consumption in the sector; from about one million cubic meters per year to 11 million cubic meters.[15] At the same time the total manufacturing industry biofuel consumption has been estimated to increase from approximately 4.7 million cubic meters to 6.5 million cubic meters.[16] Manufacturing industry value added, the sectoral contribution to GDP, increased sevenfold from 30 million to over 225 million SEK in 1913 constant current prices over the same period.[17] This exercise demonstrates a considerable productivity gain in terms of firewood efficiency during the initial phase of Swedish industrialization. This effect was mainly due to a more efficient use of charcoal in the iron industry. Evidence for substitution effects, coal replacing firewood or more specifically charcoal can only be found after 1900, when the first iron works started to use coke.

[15] Sven Gaunitz' estimate. From Lundgren, N-G. (1984) *Skog för export. Skogsarbete, teknik och försörjning i Lule älvdal 1870-1970*, (Diss.) Umeå studies in Economic History 6, Umeå, Umeå University p 223 f.
[16] Lindmark & Olsson-Spjut (2017) forthcoming *From Organic to Fossil and in between. New estimates of energy consumption in the Swedish manufacturing industry 1800 to 1913*
[17] Krantz & Schön (2007) *Swedish Historical National Accounts*.

It was approximately from the 1850s that forest resources in interior northern Sweden could first be utilized on commercial scale. The expansion of the forest industry, the so-called timber frontier had its origin in the Oslo area already in the 1700s. By the 1840's, the frontier had reached the city of Sundsvall and twenty years later northern Västerbotten and, finally, Norrbotten by the mid-1870's.[18] An important driver was the demand for large, old grown timber which became increasingly scarce as the saw mills expanded. This expansion coincided with a transformation of the agriculture in interior Norrland. Dan Bäcklund stated that the inland Norrbotten farms before 1870 could not even be characterized as subsistence farming, if one, by referring to subsistence farming means a farm with some surplus production capacity that can be sold in exchange for basic necessities.[19] Farming conditions were simply too poor, something that became painstakingly clear during the frequent crop failures, such as the famine in the late 1860s. Bäcklund therefore chose to label this type of agriculture "subsistence small farming". Still, this form of agriculture in which grassland farming on outlying, marginal land such as moors was essential supported the sparse population. It was the expansion of the sawmill industry along the northern Swedish coast that boosted demand for labor in the hinterland. For instance, Nils-Gustav Lundgren has estimated that about 350,000 cubic meters annually harvested in Jokkmokk area in Norrbotten around the turn of the century required approximately 2,700 forestry workers.[20] Owing to the high demand for labor, there was also an increased element of wage labor. In the 1880s, about 70 percent of smallholders depend on wage income, equivalent to around 200 SEK per year, which in turn is equal to more than 100 days of payments for an agricultural worker.[21] As forestry expanded outfield farming was gradually abandoned, it created a structural change within Norrland agriculture. Another effect was that the increased male labour in the forest required more women's work in the agriculture. In parallel, there were substantial investments in transport networks. Streams were cleared from rocks and other obstructions to allow for timber floating,

[18] Bunte, R., Gaunitz, S., Borgegård, L-E. (1982) *Vindeln. En Norrländsk kommuns ekonomiska utveckling 1800-1980*. Lund. p. 135
[19] Bäcklund (1988). *I industrisamhällets utkant. Småbrukens omvandling i Lappmarken 1870-1970*. Umeå Studies in Economic History 8, Dept. of economic history, Umeå University, p 39-41
[20] Lundgren, N-G. (1984) *Skog för export.*
[21] Jörberg, L. (1972) A History of Prices in Sweden 1732-1914, Lund, CWK Gleerup. p 714.

while timber transportation on the lakes depended on steam tugs.[22] The road network was expanded at the same time while the railway came to reach Norrbotten in the 1890s. Along with coastal steam shipping from the 1840s, this provided the backbone of a distribution system forest companies. This distribution system provided fodder for horses and food for the lumbers. This is, in short, how the interior Norrland, with its vast forest resources, was drawn into the market economy. The utilization of the forest therefore depended on Sweden's integration into the world economy. In short sawn timber exported to the European markets, while food distribution to the hinterland. The role of coal was its role in the transportation networks and in the engineering industry that build the machines for the saw mills.

The charcoal consumption in the Iron Works

As previously pointed out, the charcoal consumption of the ironworks was significant. Estimates suggest that 21 million hectoliters of charcoal was consumed by the ironworks around the year 1800, equivalent to approximately 2.5 million cubic meters of wood. Although this is significant amounts of wood, the figure is, however, dwarfed in comparison to even modest estimates of the household consumption. The charcoal consumption meant that the ironworks required a hinterland for both a supply of energy and labor. The area dependence meant that the localization pattern of the ironworks, mainly situated in the iron ore-rich central parts of Sweden, was clearly decentralized. This was not only a reflection of the area dependence of the organic energy system, but also due to the difficulties in transporting charcoal long distances without the charcoal shaking down into a powder. The production of charcoal was also strictly regulated. To start with, there was a "pre-emption obligation" within the mining district.[23] A Yeoman who wanted to sell charcoal was obliged to first ask the local iron work team if they wanted to "to a useful price". Only if they turned down the offer, it was possible to sell charcoal outside the mining district Bergslagen. This regulation was abolished in 1850. The charcoal market outside Bergslagen was liberated in 1846, motivated by by the elimination of the

[22] Törnlund, E. (2003). "Flottningen dör aldrig". *Bäckflottningens avveckling efter Ume- och Vindelälven 1945-1970*. Umeå Studies in Economic History 27, Dept. of economic history, Umeå University

[23] Olsson (2007), *Järnhanteringens dynamik. Produktion, lokalisering och agglomerationer i Bergslagen och Mellansverige 1368-1910*. Umeå Studies in Economic History 35, Dept. of economic history, Umeå University, p. 43

Forging Ordinance the same year. This means that market prices for charcoal only exists from 1850.

The localization of ironworks, huts and hammers was administered by the crown, through the Swedish Board of Mines, which set productions allowances and conceded privileges for different parts of the iron production process. This was both an expression of the mercantilist state and of resource management of limited forest and hydropower assets.[24]

By the second half of the 19th century, the iron industry was in a process of rationalization with extensive closures. At the same time, however, iron production increased, which shows that there was a concentration to larger units.[25] The transformation pressure was due in turn to the lower iron prices which originated as a result of the increased supply of British iron, which in turn ultimately depended on the increased production capacity and high productivity provided by coke-fired blast furnaces. Price changes in markets result from shifts in supply and demand, not from changing cost of inputs and factors of production. Changing prices will, in turn, signal a need for shifting inputs or economizing of some certain input. The transformation of the organic economy in Sweden could, theoretically, be the expected of relative price shifts, as the price of coal fell relative to wood and charcoal prices. Before we attempt an analysis of the relative price movements it is important to realize that saw timber did not have an alternative use as firewood or charcoal. The saw mill industry simply used different timber dimensions as compared to the dimensions used for fuels. Sawmills used old grown timbers, often with diameters of around 90 centimeters, for two reasons. First, a large dimension log is not as likely to sink when floated as compared to a smaller log. Second, debarking a large dimension log is more labor efficient per cubic meter as compared to debarking a smaller log. Both these reasons are due the geometrics of the cylinder; how surface area is related to volume. Thirdly, the saw dust waste is smaller when sawing larger logs. Waste wood and small dimensions were therefore used for charcoal and firewood. It is more convenient to handle small dimensions, not the least to split the log, which is necessary if it is to be used as a fuel. The fact that old grown dimensions and young dimensions are not close substitutes explains why many companies often combined iron production with

[24] Olsson (2007), *Järnhanteringens dynamik* p. 39-42.
[25] Attman, Artur (1986), *Swedish Iron and Steel, 1800-1914*, Jernkontorets bergshistoriska skriftserie, 21: Stockholm.

sawmilling operations. This was especially the case along the coats, while the iron companies in central Sweden usually had a smaller sawmill production. It was due to the difficulty of transporting sawmill products to the coast, a problem basically solved with the railways. It is another example of how organic resources in the organic economy were not always accessible in the economic sense.

There is reliable information on the development of coal prices in Sweden from mid-1860, while a compilation coal prices for earlier dates have not been made. The prices published as Swedish prices are, as shown by Fredrik Olsson instead series from the Danish historical national accounts, which in turn are British export prices.[26] The prices from 1866 have been collected from the State Railways[27]. Calculated per Joule charcoal prices were approximately 5 to 15 percent lower than coal prices until 1880, when charcoal became approximately 20 percent more expensive than coal. This price relation lasted throughout the 1880's and early 1890's. This means that if coal and charcoal were perfect substitutes, coal ought to have replaced charcoal in the iron industry no later 1880. Since that was not the case, the two fuels cannot have been perfect substitutes. Therefore, a falling relative price of coal would have caused a decreased demand for charcoal. A more pronounced relative price shift did however occur during the period from 1894 and onwards. By the year 1900 charcoal was 50 percent more expensive than coal, and by 1910 charcoal was three times as expensive. There were two reason for this. First, technical change had given rise to an alternative use of spill wood and small timber dimensions as pulpwood. When demand for small-sized timber increased, prices rose, which in turn drew up the charcoal prices. Secondly, industrialization itself caused an increased demand for labor, which caused rising wages also among the coalers. Charcoal production was relatively labor intensive, which shifted the cost structure especially for charcoal. The combination of the expansion of the pulp and paper industry from especially the 1890s and more rapidly increasing wages from the same decade, explain the late switch from charcoal to coke in Swedish blast furnaces, where the first coke fired furnace was started in 1905. In short, it seems as if the major price-wise reason to switch to coke happened when increased demand for small wood also made charcoal more expensive. Simultaneously with the changeover to coke there was also an increased tendency of concentration in the iron industry into fewer but larger units, with a climax in the so

[26] Olsson, F. (2007). *Järnhanteringens dynamik*
[27] Lindmark & Olsson-Spjut (2017 forthcoming)

called iron-work death in the 1920s crisis.[28] This crisis virtually wiped out charcoal fired blast furnaces. The bottom-line is that coke enabled increased economies of scale in the iron industry. This is consistent with the hypothesis that an earlier switch to coke had resulted in a significant destruction of capital. Mill owners decided against doing so as long as the relative prices did not make the switch necessary.

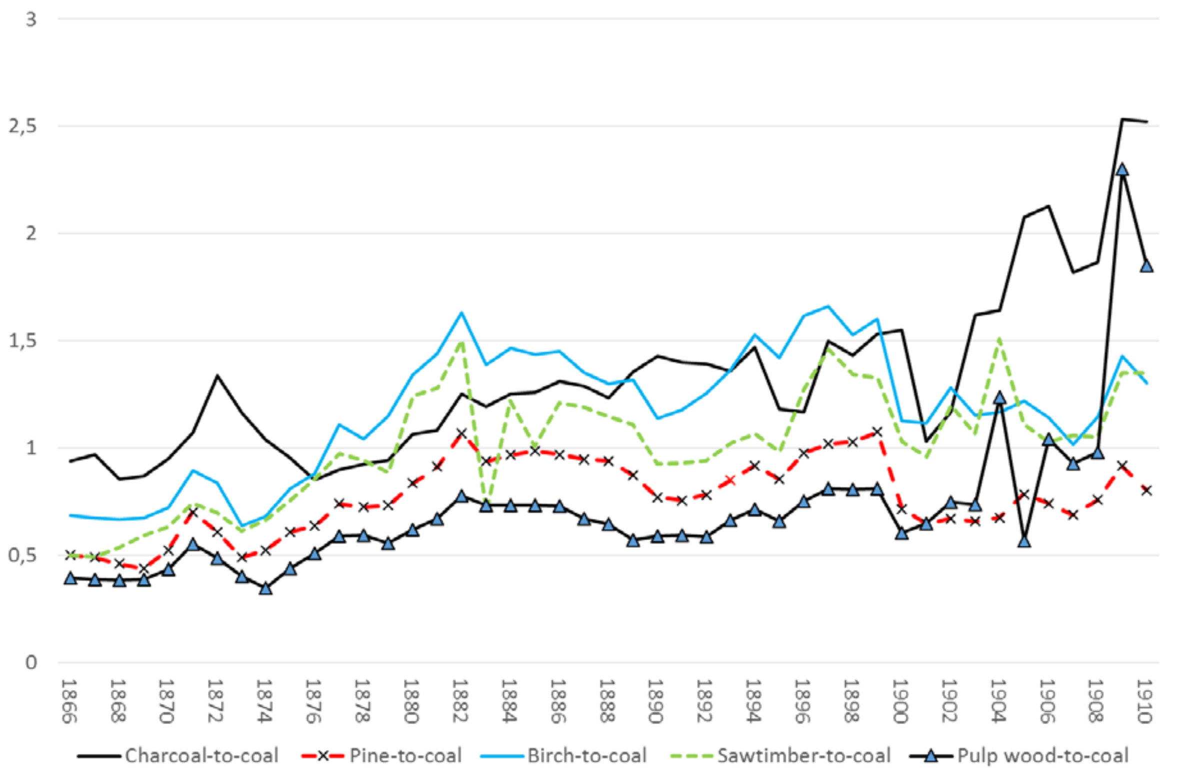
It was actually the development of a wood based pulp and paper industry that propelled the final stages of the transformation of the organic energy system in Sweden. First, the pulp and paper industry's demand for small timber caused rising prices which altered the relative prices between coal and coke and, through these developments, the cost structure in the iron industry. At first only spurce was used for pulp, but as pine also became available for the pulp manufacturing process, the competition with charcoal manufacturing became harder. Secondly, and as noticed previously, the slender timber dimensions were more inclined to sinking than saw logs if floatation was attempted. The forest industry's cleansing of natural streams for timber floatation, investments in steam powered tugs, as well as railways, made it possible to secure supplies of raw materials to the pulp industry around the turn of the century. Finally, while the raw material used in the pulp manufacturing process was organic, the pulp and paper mills were in themselves highly depending on coal. In 1913, the first year for which reliable data on the sectoral coal consumption in Sweden exists, the pulp and paper industry stood for around 30 percent of the manufacturing industry's total coal consumption. Steam engines were not the least used for driving generators, providing electricity for machines. It is therefore not surprising to learn that the pulp and paper industry's share of the total installed engine power of the Swedish manufacturing industry was also the around 30 percent in 1913. The pulp and paper industry also changed forestry itself as smaller timber dimensions became more valuable.[29] First, thinning of the forests became profitable, thereby improving the growth of large trees intended for saw timber. Secondly, a shorter turn-around time meant that less capital was sunk in growing forests. This improved the profitability of forest companies and probably facilitated the emergence of sustainable forestry and practices that stood in sharp contrast to the 19th century

[28] Söderberg, E. Wretblad, P.E. (1957*), Fagerstabrukens historia, Nittonhundratalet*, vol. 3 Uppsala: Almqvist & Wiksell.
[29] Heckscher, E.F. (1941). *Svenskt arbete och liv. Från medeltiden till nutid*, Stockholm: Albert Bonniers förlag

forest tycoons, not seldom associated with illegal logging, land grabbing, unethical business methods and deforestation.

At this stage we are inclined to draw some tentative conclusions if we first can explain why the use of coal increased dramatically, in presence of an absolute price disadvantage in terms of cost per energy unit over firewood, while more dramatic changes in relative prices between biofuels (firewood and charcoal) and coal only happened at the turn of the century. The relative prices shown in figure 3 shows that coal was at all occasions more expensive than pine wood, measured in silver per Mega Joule, while less expensive than birch wood from 1876. This is after coal consumption had started to increase at a compound rate as previously shown in figure 1.

Fig 3. Relative prices for fuels and wood versus coal. Sweden 1866-1910.



Source: Coal: Statens Järnvägar, Bisos, 1866-1902; Kander (2002) 1903-1910
Charcoal: Olsson (2007), based on Jörberg (1972); Wood Pine: Jörberg (1972)
Wood birch: Jörberg (1972), pp 498ff, Skaraborg County; Pulp wood (Ljungberg 1988)

The difference in price level can be explained if coal and charcoal were not perfect substitutes in every respect. This was clearly so in the case of steam engines, especially so steam engines requiring a high boiler capacity, such as locomotives. Here, coal held a technical or qualitative advantage over biofuels due to its higher energy content per unit of volume, which made it possible to transfer more heat energy to water per time as compared to biofuels. Thus, we can conclude that the increased demand for coal was primarily derived from the demand for mechanical power provided by steam engines in the manufacturing industry and transport sectors. This explains why the coal consumption increased despite coal being more expensive than pine firewood in terms of energy and despite the fact that coal prices in comparison to biofuels remained fairly stable. In order to explain why the relative prices were stable we need to conclude that coal and firewood were close substitutes in low-end uses, such as residential heating. Coal had an edge over firewood, but only in cities with major coal imports for industrial uses.[30] Firewood therefore remained an important domestic fuel well after the period studied here.

Hydropower

Hydropower was also one of the important energy sources both before and after the Swedish industrialization. The first wave of saw mil expansion was based on mechanical hydro power, from the 1890's, the period for which there is official statistics on motive power, it is clear that the mechanical hydro power remained at the same level in the saw mills, while the steam engines increased. Hydro power was also of great strategical importance in the iron industry, and it has even been suggested that the search for more hydro power contributed to the spatial diffusion of the industry during the 19th century.[31] Indeed the total effect of mechanical hydropower in the manufacturing industry and mining was larger than that of steam power as late as 1900.[32] The official statistics reports approximately 250,000 horsepower in mechanical hydropower and 174,000 horsepower of steam engines. Hydropower therefore substituted for coal during the Swedish industrialization, even

[30] Lindmark, M. & Andersson, L.F. (2010) Household Firewood Consumption in Sweden during the Nineteenth Century, *Journal of Northern Studies*, 14, 55-78
[31] Eriksson, G. (1955*). Bruksdöden i Bergslagen efter 1850. Med särskild hänsyn till företag i Kolbäcksåns dalgång* Jernkontorets Bergshistoriska Skriftserie 15, Stockholm: Jernkontoret
[32] BiSOS Industrin 1900

if it is difficult to estimate the importance in terms of energy flows, since mechanical hydropower is not always admitted continuous operation throughout the year. At the turn of the century hydropower had already begun to be transformed as the second industrial revolution saw the emergence of electricity technology. At the turn of the century, about 13 percent of the mechanical water power was used for driving generators. The considerable differences between industries regarding the use of hydro powered generators is also an indicator of the structural transformation of the second industrial revolution. In the chemical industry more than 90 percent of the hydropower was used for generator operation. The dominant branches was in this respect manufacturing of chlorate, a chemical used in the matches and explosives industry, and the manufacture of calcium carbide used for the manufacturing acetylene gas for carbide lamps and welding. The use of calcium carbide in the steel industry concerned the purification of sulfur from steel.

Conclusions

Even though the Swedish industrialization to a high degree was depending on the organic energy system, the underlying mechanization with steam engines induced a demand for coal, which implies that also the Swedish industrialization was depending on the rise of the mineral energy system. The mineral energy system obviously provided Sweden with additional energy, mainly imported from England. In line with Tony Wrigley's arguments British coal removed some of the Swedish areal limitations to economic growth imposed by the organic energy system. Notice that coal substitutes for land in Wrigley's interpretation of the industrial revolution. It therefore hypothetically exists an area that corresponds to the coal volume consumed. That area is the forest land that is needed to produce the same amount of energy as provided by coal. In terms of area equivalents one could therefore think of Sweden as an importer of land created in British coal mines. Just as if coal mines did produce land. Having said this, it is important to recognize that coal and firewood were not perfect substitutes. Coal was, as argued in the article, a superior fuel for steam engines. Since the fuels were not perfect substitutes one should also be aware that the idea of an area equivalent for coal is not true in an absolute sense, but rather a parable. This is also compatible with the energy transformation as a dynamic process, including feedback loops between the organic and mineral energy systems.

The rise of the mineral energy system and industrialization did for instance open organic energy and material resources that hitherto had been inaccessible from an economic point of view. This included for instance forest in the Northern Swedish inland. Moreover, some of the changes in the organic energy system even encouraged a further diffusion of the mineral system, with the rise of the pulp and paper industry as the perhaps most adequate example. One can therefore see the transition from an organic to a mineral energy system as a shift from a traditional organic energy system to an industrialized organic energy system. This is to say that the Swedish industrialization also included a transformation of the organic energy system, not the least through technologies and organizational structures which were part of the mineral energy system. This transformation of the organic energy system included the shift in the use of wood, where the importance of wood as a fuel decreased as the demand for wood as a raw material increased, as well as the transformation of hydro power from mechanical hydro power to electricity generating systems, which created strong links emerging between the electricity, pulp and paper and chemical industries.

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