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The Danish Agricultural Revolution in an Energy Perspective: A Case of Development with Few Domestic Energy Sources[1]

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Abstract: We examine the case of Denmark - a country which historically had next to no domestic energy resources - for which we present new historical energy accounts for the years 1800-1913. We demonstrate that Denmark's take off at the end of the nineteenth century was relatively energy dependent. We relate this to her well-known agricultural transformation and development through the dairy industry, and thus complement the literature which argues that expensive energy hindered industrialization, by arguing that similar obstacles would have precluded other countries from a more agriculture-based growth. The Danish cooperative creameries, which spread throughout the country over the last two decades of the nineteenth century, were dependent on coal. Although Denmark had next to no domestic coal deposits, we demonstrate that her geography allowed cheap availability throughout the country through imports. On top of this we emphasize that another important source of energy was imported feed for the cows.

Keywords: Coal, Denmark, energy transition, agriculture

JEL codes: N5, Q4

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We examine the case of Denmark[3] within the context of the debate about the role of energy and energy transitions for development, in particular through the construction of new energy accounts for the years 1800-1913[4]. As is well known, Denmark did not so much industrialize but rather experienced a rapid transformation of her agricultural sector in the second half of the nineteenth century.[5] This process truly revolutionized Danish agriculture, and seems fit for the epithet 'agricultural revolution'[6]. From being a grain exporter she became a highly efficient producer of processed foods, exporting butter and bacon to the UK. Growth in this leading sector in particular allowed the Danish economy to grow quickly, reaching levels of GDP per capita rivalling the richest countries in the world, a position which has since been maintained.

Previous work has emphasized in part what might be described as the demand side of this story, in particular the importance of supplying the growing industrializing cities of northern England. On the supply side, the role of the spread of superior institutions, i.e. the cooperative creameries, and technology, i.e. the steam-driven cream separator, have been discussed (see Henriksen et al 2011). Building on this, O'Rourke (2007) argues that the cultural homogeneity of the Danes allowed them to form successful cooperatives, in stark contrast with Ireland, and Henriksen, Hviid and Sharp (2012) demonstrate that the cooperatives also relied on legal institutions which were particularly beneficial in an international context. The role of energy has, however, not previously been emphasized.

On the face of it, Denmark might in fact appear to be an example of a successful alternative to the energy-intensive development path of the coal-rich countries. She had few natural

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[3] Please note that with 'Denmark' we mean Denmark proper or the Kingdom of Denmark as it was known. This constituted all of present day Denmark except for the area of southern Jutland which once formed the northern part of the Danish Duchy of Schleswig, which was lost to Prussia in 1864, but became part of Denmark again after the First World War. Thus this work does not consider the Duchies of Schleswig and Holstein before 1864, or Norway before 1814, even though they were under the Danish monarchy. Likewise, we do not consider other former or present Danish overseas territories: the Faroe Islands, Greenland, Iceland, and the Danish West Indies.

[4] Most earlier work on energy consumption for Denmark is patchy and goes back only to 1870 at the earliest, see Bjerke and Ussing (1958). See however also Sørensen (2011).

[5] Here we stick with the traditional interpretation of Danish history that saw butter production as part of the agricultural sector (see for example Hansen 1984) – the cooperative creameries were after all owned by the farmers. This has recently been questioned by for example Larsen et al (2010), who provide new national accounts from 1896 with the creameries in the industrial sector.

[6] Although of course we are aware that there are other uses of the term 'agricultural revolution', see for example Bjørn (1998). But this revolution was more specifically a *Danish revolution*, and was at least as transformative. Moreover, it mirrored the Industrial Revolution in Britain in terms of supplying the food to the factory workers.

energy resources. Her land had been largely deforested over the preceding centuries, she had practically no coal, and she did not even enjoy the fast flowing water which was to be so important for the hydropower of her fellow Scandinavian countries. However, as we will demonstrate, Denmark's use of energy increased early on for a coal-poor country, and this was based on a rapid transition from traditional energy sources to coal. In particular, Danish agriculture was actually a large consumer of coal, which was used to fuel the machinery in the cooperative creameries and to a lesser extent the related slaughterhouses for the pork industry. Indeed, this coal was not even simply incidental to the development. The automatic cream separator, a centrifuge, relied almost exclusively on steam power from coal to function (at least until electrification in the twentieth century), a point made clear during the First World War when imports of coal were difficult, and creameries were forced to rely on alternatives such as locally sourced peat to run the machinery, which proved very unsatisfactory and expensive (Bjørn 1982). In addition, the country's vast (in per capita terms) dairy herds required huge imports of energy as feed, particularly concentrates.

We demonstrate that although coal was not available in Denmark, the rapidly falling transportation costs of the late nineteenth century meant that Denmark was particularly well placed to receive cheap imports from Newcastle: both of course because of her physical proximity, but also because of her geography. Denmark is a country consisting of one peninsular and hundreds of islands – nowhere is more than a few miles away from the coast. It was thus relatively cheap to import coal into any part of the country, and this allowed the rapid spread of the cooperative dairy system. Similar factors aided imports of feed, combined with Denmark's policy of free trade, which she maintained throughout this period at a time when other continental European countries were returning to agricultural protection.

Thus, aside from the new data, the present work proceeds to make two main contributions. First, we demonstrate both how and why energy was important for Danish development, something which has not previously been emphasized by economic historians. Second, we make the more general point that even if countries follow a non-industrial, more agricultural development path, energy is still crucial. Thus, we can complement the literature which argues that expensive energy hindered industrialization, by arguing that similar obstacles would have prevented other countries from more agriculture-based growth.

We provide a wealth of statistical evidence, both on the macro-level, and on the level of the individual creamery, showing the importance of coal for production, and we demonstrate that coal was available more cheaply in Denmark than almost any other European country. Moreover, using a new database of energy consumption by source we demonstrate that coal was the major energy source behind the Danish 'agricultural revolution'. On top of this we emphasize that another important source of energy was imported feed for the cows. Clearly, having few domestic energy sources was in fact not necessarily a barrier to economic development, as has sometimes been argued in the literature[7], even before the age of oil and electricity.

In the next section, we survey the literature on the importance of energy and coal in particular for development. In section II, we introduce the new energy accounts for Denmark, which reveal that there was a transition to coal in the second half of the nineteenth century. Departing from the standard approach, which only includes energy for working animals, we also calculate the energy consumption of cows, arguing that this was large in comparison with other countries and of particular importance for the Danish economy. In section III, we discuss the role of energy in Danish dairying, which was very energy intensive. In section IV, we explain how such energy dependence was possible for Denmark, due to her particular geography and free trading relationship with the UK, which made imports of both feed and coal extremely cheap in a European context, as well as her relatively high wages, which made the transition to more capital intensive forms of production more desirable. Section V concludes.

I

The debate about the role of energy for nineteenth century development is essentially a debate about the role of coal. This can be summed up in what Fernihough and O'Rourke (2014) have termed, in the excellent survey of the literature included in their paper, the *growth* and the *location* hypotheses, both of which they test and find to be important in a European context. The first – associated with the work of Deane (1965), Landes (1965),

[7] Fernihough and O'Rourke (2014, p. 6) explain in their literature survey that an 'argument traditionally made about coal is that *local supplies of coal* were essential, or at least highly desirable, if a region was to industrialize during the 19th century' (our emphasis).

Braudel (1973), Cipolla (1962) and particularly Wrigley (1988, 2010) – states that the transition from a low energy and organic economy to a high energy and fossil fuel economy is a necessary, albeit not sufficient, precondition for industrialization. Without coal, the amount of energy required for an Industrial Revolution would have required the felling of unrealistically large acreages of forest. Recently, Kander et al (2013) have taken a broader perspective on the role of energy for European economic growth. They take a slightly stronger standpoint than Wrigley, and view the transition from organic to fossil fuels as both a necessary condition for and a factor that induces modern economic growth. They explain that the European economy was heading towards an energy crisis from 1650 to 1800 with population doubling, and food and firewood prices growing, since energy supply was not enough to meet demand. This was however avoided when coal become available. They do not therefore believe that an Industrial Revolution as we understand it would have been possible without coal, because the structure of industry and the economy as a whole were strongly shaped by fuel costs and the development of associated skills. This is similar to the argument put forward by Kjærgaard (1994), who describes how Denmark by the early nineteenth century was in a serious ecological crisis, due to the disappearance of forests, sand drift etc. He argues that Denmark developed for two reasons: the introduction of new and improved varieties of plants in agriculture, and the transition from wood to coal and iron.

The second hypothesis – associated with the work of Pollard (1981), Mathias (1983), Pomeranz (2000), and most recently Allen (2009) – states that the location of nineteenth century industry was strongly determined by the location of coalfields. Allen argues that a critical factor for British development was the availability of cheap domestic sources of energy, in particular coal, as well as high wages, which made investment in labour saving technologies desirable. Pollard (1981) sees early regional industrialization as an imitation of the British Industrial Revolution, which was only possible for regions with similar factor endowments to England, such as Belgium or the Ruhr. Kander et al (2013) explain that coal was crucial for European industrialization, but regional specialization was affected by energy costs. The fall in the price of freight with the transportation revolution made coal increasingly available in Europe, but the impact of this depended on geography.

However, there are scholars who have argued that coal was not so important, for example Mokyr (1990, 2002, 2009), McCloskey (2011), and Clark and Jacks (2007). They maintain that the use of coal was more a symptom of technological progress which came about due to changes happening in society. Coal was an advantage, everything else equal, but it is not what made the Industrial Revolution: the transition to fossil fuels was not even necessary, since coal could be substituted by traditional sources of energy such as wood, peat, wind or water; or alternatively, countries could have developed through specialization in less energy intensive industries. Both alternatives argue against the growth hypothesis. Moreover, they argue that location cannot have mattered so much, since coal could be transported, and even if this was costly, it was only a small fraction of total costs for leading industries.[8]

In order to shed light on this debate, scholars have increasingly turned to country studies. Much of this literature has argued that high energy costs delayed the industrialization of many coal poor economies in Europe. These countries generally followed similar patterns: they diverged from the early industrializers, had a late transition to fossil fuels and had to wait for the age of electricity and oil for their catch up to occur. Italy is one such example, where expensive coal was a serious disadvantage for manufacturing until the First World War. Bardini (1997) argues that Italy´s lack of competitiveness in relation to England could not be solved through the use of hydro-power or cheap labour, since steam acted as a General Purpose Technology (GPT) for the most advanced industrial sectors. Thus, Italian factor endowments led her to avoid the industrial sectors where steam acted as a GPT. The use of relatively more electricity only constituted an advantage in a few backward sectors, since it was merely used as a substitute for generic power. The Italian catch-up only occurred later, when the unit drive meant greater advantages of electricity. Similar findings have been made for Spain (see Sudrià 1995).

However, it has also been noted that some countries did manage to industrialize without coal. Kunnas and Myllyntaus (2009) use the case of Finland to demonstrate that industrialization is possible using renewable sources if it is accompanied by technological change. Finland made use of wood and water-power for industry and at the same time improved the efficiency of household stoves and reduced the dependence on slash-and-burn cultivation, thus freeing up wood for industrial needs. Her neighbour, Sweden is another

[8] See also Weil (2009, p. 468).

country without coal. Kander and Stern (2014) find that substitution from traditional to modern energy carriers was a leading factor behind faster rates of economic growth from the 1890s, but wood and charcoal remained important in the early periods of industrialization[9]. Rydén (2005) shows how English technology and organizational processes in the iron industry were successfully adapted to charcoal, and then, according to Schön (2010), when increases in the price of charcoal and wood put heavy industry in a difficult position, there was the incentive to exploit hydropower, which became one of the main foundations of twentieth century Swedish industrialization.

Many studies have therefore emphasized that take off in the late nineteenth century was impossible without an energy intensive leading sector based on coal. Although others have stressed the possibility of substitution to alternative energy sources, in this context Denmark is of particular interest, since as we discussed above, she possessed neither the forests nor the rivers which would have allowed for this. So on the face of it, the Danish case might seem to present a potential argument against the role of coal, i.e. that a large increase in energy consumption is not needed for development, since specialization in non-energy intensive activities, perhaps agriculture, can solve the energy trap. The compilation of energy accounts for Denmark, which we turn to now, reveals that this is not the case.

II

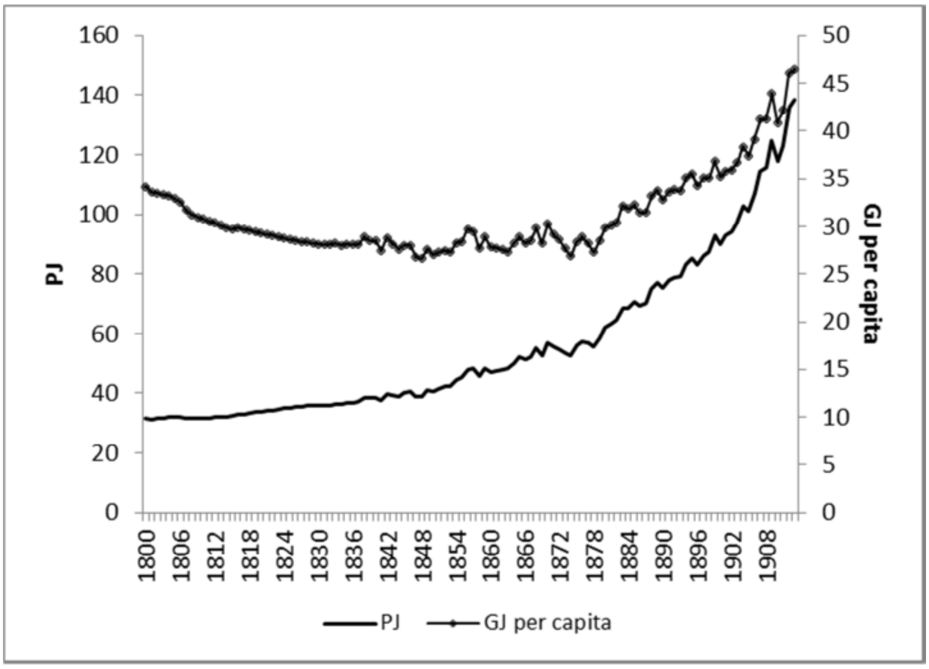
Before it is possible to get any idea of the role of energy for the development of Denmark, it is necessary to gather the available information on energy consumption. Taking a similar methodological approach as previous studies[10], we first construct a new energy series for Denmark that includes, besides modern energy carriers (coal, oil and primary electricity), traditional forms of energy such as muscle energy (human and animal), wind and water energy use, and peat and firewood consumption. The sources and assumptions behind this are discussed in detail in the appendix.

[9] Partly due to the colder climate, which meant that firewood was important.

[10] See for example Kander (2002), Rubio (2005), Malanima (2006), Gales et al (2007), Warde (2007), Henriques (2009) and Kander et al (2013).

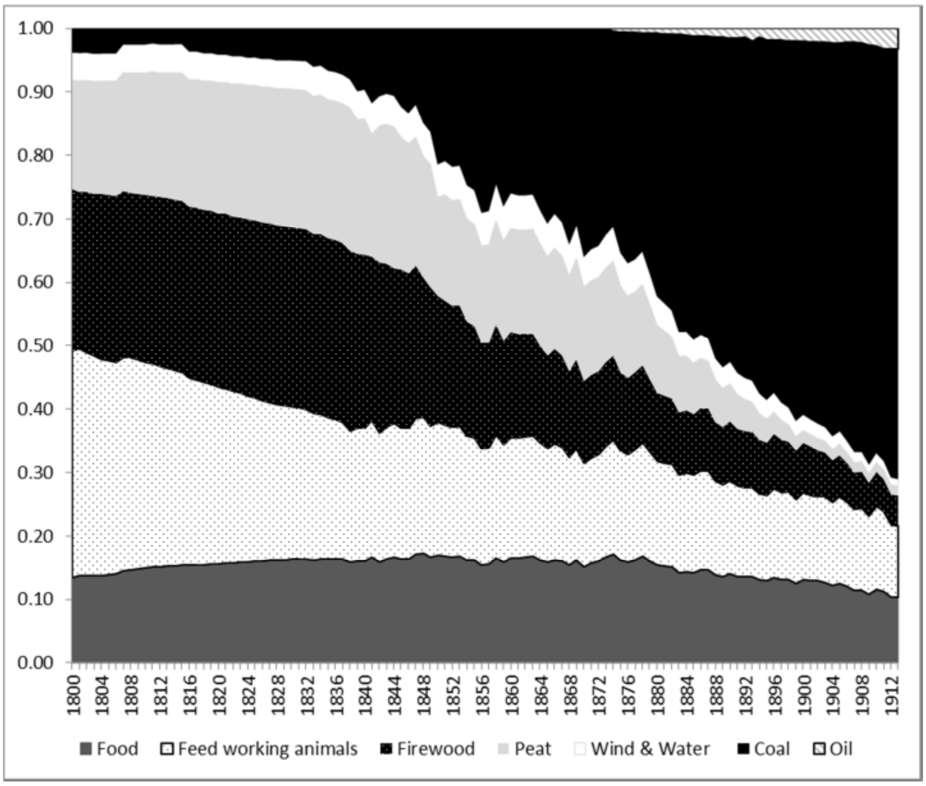
We rely on a combination of official statistics, secondary sources, and assumptions which are common in the literature. While fossil fuels were exclusively imported, which means it is possible to rely on official trade statistics, information on other sources is more patchy. The feed consumption of draft animals can be estimated by information on the number of animals and their plausible weight and working effort level (see Kander and Warde 2011). We assumed that the Danish population was particularly well fed, with a consumption of about 3000-3100 kcal per person per day, which is suggested by a mixture of household surveys, official reports, and national and urban estimations based on agricultural production and trade. Data on firewood and peat consumption is scarce, as for most countries, at least prior to the twentieth century, although in particular a consumption tax levied on fuel coming into towns provided some detailed information. For wind and water, a negligible part of the energy consumption, we rely on numbers of windmills, watermills and sail ships as well as assumptions on their power, frequency of use, and efficiency. Figures 1 and 2 illustrate our results.

Figure 1: Danish Energy Consumption, total (PJ) and per capita (GJ)



Source: See appendix.

Figure 2: Danish Energy Consumption by source (%)



Source: See appendix. Primary electricity (hydro and wind power, and net imports) has been calculated but excluded from the graph, since it is insignificant.

The two figures demonstrate clearly that the energy transition, in terms both of quantities and the change from organic to fossil fuel sources, was occurring in the Danish economy during the nineteenth century. Primary energy[11] consumption rose from circa 30 PJ[12] in 1800 to 140 PJ in 1913, a fourfold increase. However, much of this growth seems at first sight mostly simply to accommodate significant population growth. In per capita terms, Denmark's primary energy consumption actually declined from 34 GJ[13] per capita in 1800 to 30 GJ in 1880. This decrease can be explained by two factors. First, there was a reduction in the number of draft animals per capita (feed decreased from 12 GJ per capita in 1800 to 5 GJ in 1880), which was the result of the transition from an arable to a dairy based agriculture. Second, Denmark must have experienced some reduction in energy consumption at the

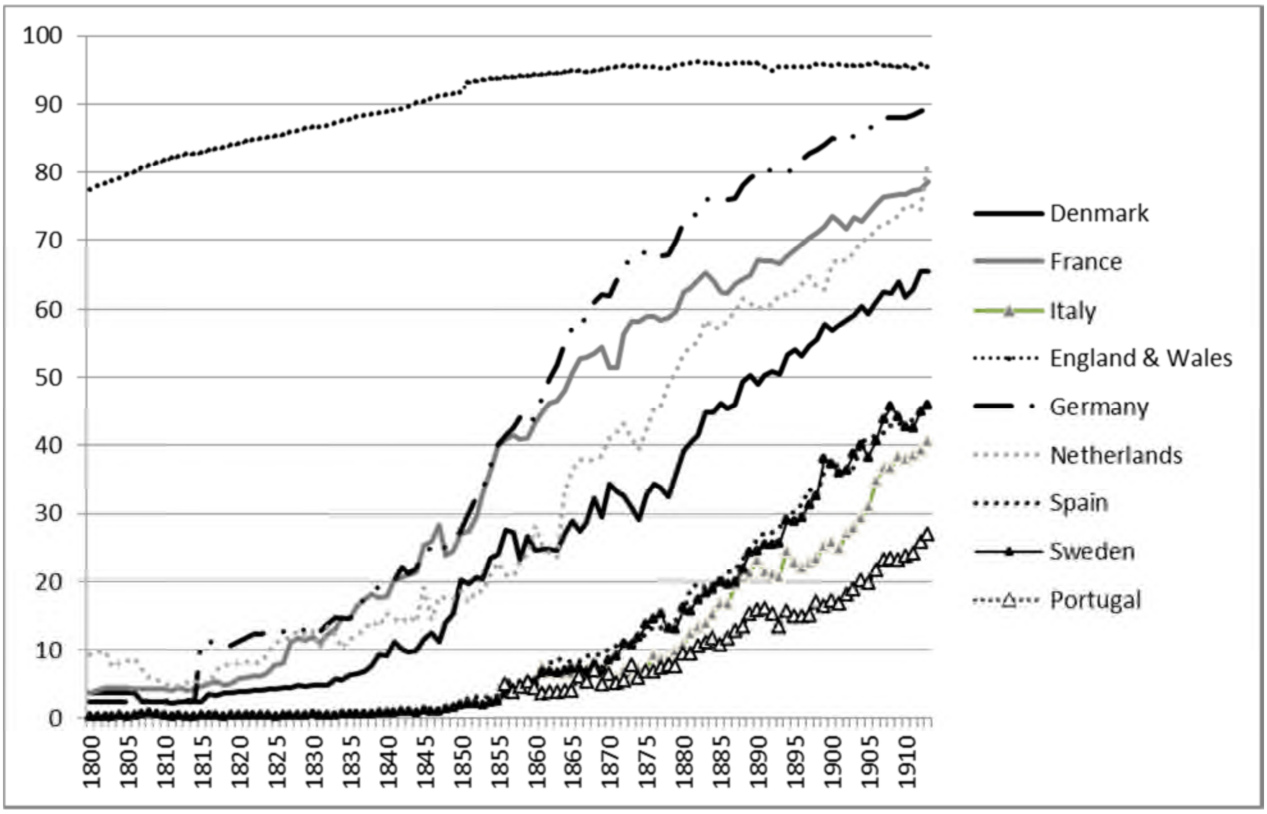
[11] Energy found in nature that has not been converted, i.e. raw fuels.
[12] 1 petajoule = 10^{15} joules, the international unit of energy.
[13] 1 gigajoule = 10^{9} joules.

household level, as a result of an improvement in household stoves and substitution to fossil fuels. Similar declines in per capita consumption are also reported to have occurred in other northern European countries, such as Finland, Sweden, and Norway (see Kunnas and Myllyntaus 2009, Kander 2002, and Lindmark 2007).

This fact does not hide completely the important shifts that were taking place. Around 1800, Denmark was still an organic economy, with her primary energy consumption being divided into firewood (26%) and peat (17%), mostly for household needs, and feed (36%) and food (13%) for muscle power. Coal consumption was still relatively insignificant (4%), that is at the level of wind and water (4%). Without doubt, the most important feature of the Danish energy transition was the relatively quick switch to coal, beginning around the middle of the nineteenth century, and accelerating from the 1870s. This largely crowded out peat and firewood consumption, which become insignificant by the late 1880s.

Just how rapid the Danish transition was, and how important coal was as a source of energy, can be seen in Figure 3, which compares the percentage of energy coming from coal to that in other countries. By the late 1880s more than 50 per cent of energy consumption came from coal, and its proportion would increase to almost 70 per cent in 1913. Denmark is clearly more in the club of relatively coal-dependent and rich countries, than it is together with laggards such as Italy, Spain, Sweden, and Portugal, where coal failed to reach a 50 per cent share of consumption on the eve of World War I.

Figure 3: Percentage of Energy Consumption from Coal for Selected Countries, 1800-1913



Sources: Henriques (2009), Gales et al (2007), Warde (2007), Kander et al (2013), and see the appendix.

Denmark's transition from traditional energy carriers to coal was not only fast, but seems to have covered all the important sectors of the economy. At the household level, coal quickly substituted wood and peat. Almost all the Danish towns of more than 3000 inhabitants were covered by gas networks around 1870, although manufactured gas from coal had a late appearance in the country, in the 1850s (Hyldtoft 1994). In manufacturing, steam dominated from the 1870s, representing 80 to 90 per cent of the power in use. In common with other countries, railroads and steamships spread across the country (Generaldirektoratet for Statsbanerne 1947, Møller 1998).

Coal was thus an important energy source for Denmark. Another important source of energy for Danish agriculture was, however, feed, much of which was imported. As is standard in the energy history literature, the accounts presented above include the energy consumption of working (draft, i.e. horses, oxen, mules and donkeys) animals, but not that of other animals, for example milch cows. One reason for so doing is that meat and dairy products are included in the calculation for human consumption, but this is of course an oversimplification, since the primary energy necessary to feed those animals is always much higher. The second reason is that non-working animals do not produce mechanical power per se, so they should not be included in the strictest definition of energy (for heat, light and power). The system boundaries are however not completely clear, since all the feed consumption of draught animals and humans (and not only the share of energy used in mechanical use) is included in the standard historical accounts. One can argue, however, that although other agricultural animals do not produce mechanical power, it is relevant to account for their feed consumption from a resource perspective, especially because feed competes with other uses of land, i.e. forests[14].

Moreover, for a country such as Denmark, which specialized in dairy production for export, the normal procedure is even less relevant, since it obscures the increasing importance of feed in the energy system. Thus, in the same way as coal was necessary to run the steam engines which produced the world's industrial products, so agriculture was dependent on feed to sustain a herd of animals. Thus, the change from a 'vegetable based' agriculture to a 'meat based' agriculture will always have implications for a country's energy system. In the case of Denmark, the vast majority of the production of agricultural produce was exported, and what fed the cows were feedstuffs, in particular concentrates[15]. These were as much a necessary energy input to dairying as coal was to the factories in the UK. Thus, to get an impression of the importance of this for the Danish economy, and after deducting the share of animal products from food consumption, we add the energy consumption of non-working oxen and cows to the standard energy accounts (see Figure 4), partially drawing on methodologies proposed by socio-ecologists (see i.e. Kraussman and Haberl 2002)[16].

Clearly, this was a large part of the total energy consumption, rising from 20 per cent in 1800 to 35 per cent in 1880, being surpassed by coal only at the end of the period, and is complimentary to the traditional story of Danish agriculture maintaining a free trade stance

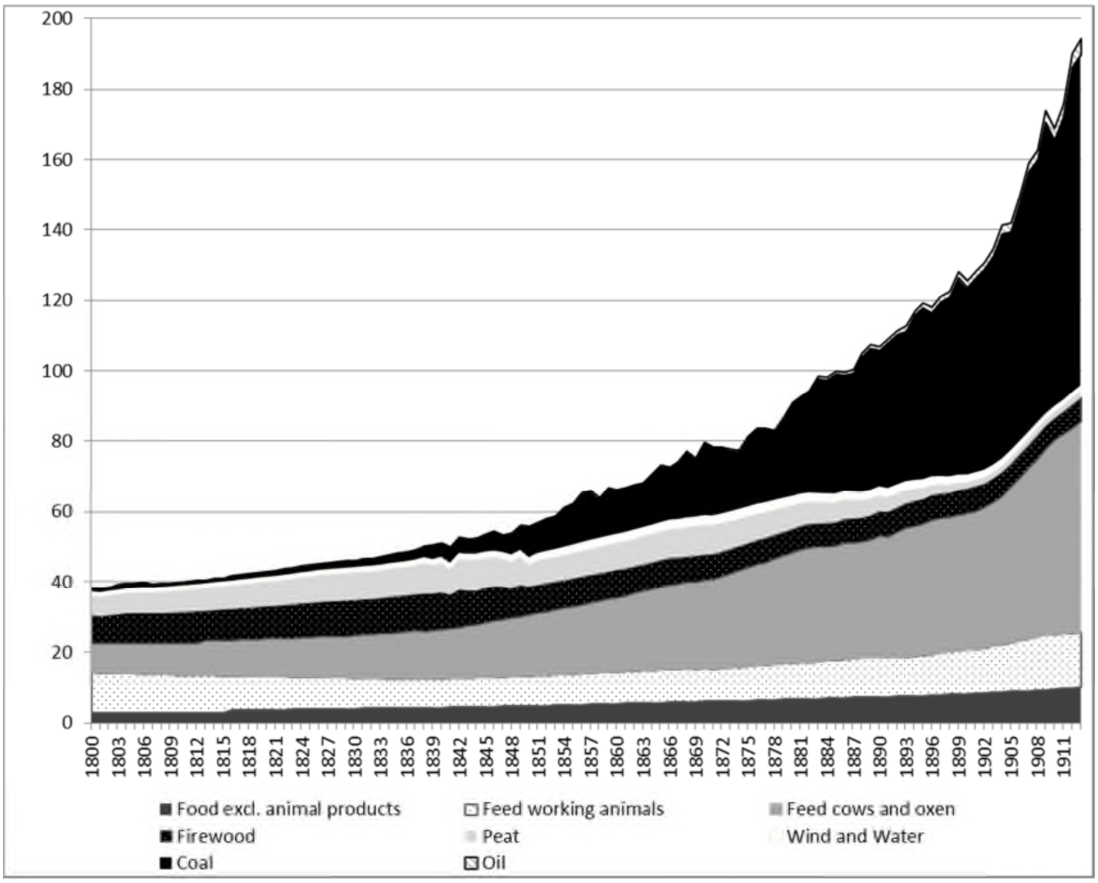
[14] The inclusion of feed for non-working animals in the historical energy accounts can be roughly compared with the standard inclusion of non-energy uses of oil and natural gas (15-30% of present fossil fuel consumption, the bulk of that employed in the production of fertilizers and other chemicals) in the modern energy balances.

[15] See Lampe and Sharp 2015 for more on the importance of feeding.

[16] Kraussman and Haberl's (2002) socio-metabolic approach proposes to quantify as primary energy the biomass (crops, pastures, and forestry) used by humans and domesticated animals regardless of the purpose of its use. Our figure only provides the feed consumption from cows and oxen. In this period, the consumption of pigs was also important, but a significant proportion of its feed was composed by dairy products, i.e. the waste products from producing butter. We differ from Kraussman and Haberl (2002) as we do not include wood for construction purposes.

and enjoying cheap imports of grain to feed the animals (Henriksen 1992). The proportion of grain and concentrate imports in the total feed consumption of cows, oxen and horses rose from two per cent in the 1880s to about 20 per cent in the 1910s[17]. Around 60 per cent of the growth in feed consumption during this period was met by imports.

Figure 4: Including feed in the energy accounts, 1800-1913, PJ



Source: See appendix. In order to avoid double counting, we reduce the total food consumption by 30 per cent, in order to avoid including energy from meat and dairy products both under food and under feed for cows and oxen.

Denmark was not of course unique in having a change towards a more animal based agricultural production, which in part reflected changing relative prices, and the shifts in demand with high income and industrialization which led to this. Thus, many countries had

[17] Total obtained converting the net imports of grain and concentrates from Henriksen and Ølgaard (1960) into PJ and comparing them with the estimated feed for horses, oxen and cows.

large herds of cows, although in Denmark this seems to have been more significant than in most others. To make a rough comparison, we start with the work of Kander and Warde (2009, 2011), who calculated the energy availability (feed intake) from working animals (horses, oxen, mules and donkeys) for seven European countries (France, Germany, Sweden, Italy, Spain, the Netherlands, and England and Wales), and we add Portugal (Henriques 2009). They took into account historical variations in the weight of livestock, giving the weight of oxen as 350 kg in 1870 in Spain and Italy, increasing to 400 kg in 1913, and 450 kg for other European countries in 1870, increasing to 500 kg in 1913. We use these figures to perform a calculation of the impact of including feed for non-working cattle (mostly cows) in the totals of each country. From Mitchell (2007) we obtain the number of cattle (oxen and cows) for 1880, 1900 and 1913. Assuming that a cow consumes ¾ of the energy of an ox[18], we get the new totals for animal energy reported in Table 1.

Table 1: Estimated GJ animal energy per capita

	Feed for draught animals in agriculture								
	Denmark	France	England & Wales	Germany	Italy	Netherlands	Portugal	Spain	Sweden
1880	5	3	2	3	2	2	3	5	5
1900	5	3	2	3	3	2	3	4	5
1913	5	2	1	3	3	2	3	4	5
	Feed for draught animals in agriculture, including non-working cattle								
	Denmark	France	England & Wales	Germany	Italy	Netherlands	Portugal	Spain	Sweden
1880	21	10	6	9	4	10	4	7	14
1900	21	11	6	10	4	9	3	6	15
1913	25	11	5	10	5	10	3	6	16

Source: Own calculations based on the method by Kander and Warde (2009, 2011). The data is taken from Kander and Warde (2009, 2011), Mitchell (2007), Barciela et al (2005), Henriques (2009).

Including animal energy for cows increases the total for all countries by a factor of between two and five (the latter is for the Netherlands, which was also a dairying country), but what

[18] Proportion in line with what is observed for Denmark for the period in question; Kraussman and Haberl (2002) also indicate similar values. Cows are reported to be smaller than oxen, but consume more feed per kg of body weight.

stands out about Denmark is the GJ per capita of animal energy, which we estimate at 21 GJ per capita in 1880 and 25 GJ per capita in 1913. This is roughly double that of any western country, including the Netherlands. The only country approaching this is Sweden, which, in the south, followed a similar agricultural development to Denmark, and otherwise made greater use of draft animals than other European countries. Denmark is, however, still substantially higher.

Tying this all together, we can proceed to compare total energy consumption in Denmark with the same countries, both with and without the contribution of non-working animals. The results are given in Table 2.

Table 2: Total energy per capita in GJ

	Excluding non-working cattle								
	Denmark	France	England & Wales	Germany	Italy	Netherlands	Portugal	Spain	Sweden
1880	30	35	142	43	18	40	19	19	39
1900	35	49	146	74	19	45	21	22	51
1913	46	60	162	97	24	63	23	25	64
	Including non-working cattle								
	Denmark	France	England & Wales	Germany	Italy	Netherlands	Portugal	Spain	Sweden
1880	44	41	145	48	18	47	19	20	47
1900	49	55	150	80	19	51	21	23	59
1913	65	67	165	102	24	70	23	28	75

Source: Henriques (2009), Gales et al (2007), Warde (2007), Kander et al (2013), and see the appendix. Food for humans was reduced by 30 per cent to take into account the consumption of animal products.

Excluding feed to non-working cattle, Denmark is somewhat in the middle of the distribution – clearly consuming more energy than southern European countries, but rather less than countries like France, the Netherlands and Sweden, and far less than the industrial powerhouses of the UK and (in the later years) Germany. Figure 3 demonstrated, however, that Denmark distinguished herself through a relatively large proportion of her energy coming from coal, a point we will take up in more detail in the next section. Including feed for cows changes the picture somewhat, however. Denmark is more on a par with France, the Netherlands and Sweden, with the obvious implication that, seen in this way, Danish development was similarly dependent on energy, making the country less obviously an outlier compared to her relative success in terms of increasing income.

III

Clearly, Danish development was greatly dependent on energy – and yet Denmark did not experience the usual pattern of industrialization in the late nineteenth century. Instead, as discussed briefly above, she specialized in an export-based and high value added form of agriculture. This Danish agricultural revolution was remarkable by any measure. At a time when satisfying the demand from the rapidly growing cities of the north of England was the goal of agricultural exporters worldwide (see the literature on the grain invasion from the United States and other New World suppliers, for example O'Rourke and Williamson 1999), Denmark rapidly captured these markets for animal products, increasing her share of the UK market for butter from 15 per cent to over 40 per cent by 1900, and from 1 per cent to 50 per cent of the UK market for bacon over the same period (Henriksen 1992). Historical rivals, such as Ireland and the Netherlands, were outcompeted both in terms of volumes and the prices received (Lampe and Sharp 2014).

We have already suggested that Danish agriculture was a large consumer of energy embodied in feed, but coal was also a large part of this story. The cooperative creameries, the first of which was founded in 1882, with the whole country covered by 1890, are commonly held to be the main reason for Danish success, and produced the vast majority of the butter. These were formed by peasants in order to raise the capital necessary to invest in a new technology, the automatic cream separator (Henriksen, Lampe and Sharp 2011). Although the basis of this invention can be traced to Germany in 1864, the crucial refinements were made in the formerly Danish duchy of Holstein in 1876. This had been the heartland of the Danish dairy industry, and the place from which best practice spread over the course of the nineteenth century (Lampe and Sharp 2015). The duchy was however lost to Prussia in 1864. Separators based on this design were then launched by rival Danish and Swedish firms in 1878/79 (Pedersen 1999, p. 51). These quickly replaced existing technologies, since they allowed for production on a larger scale, the extraction of more cream from the milk, and the immediate separation of cream from milk which had been transported over long distances. This much is well known. What has, however, to our knowledge been almost completely ignored in the literature is the fact that the cooperatives relied heavily on access to coal, which was used to power the machinery, mostly the separator, but from the mid-1880s also for heating and steam for pasteurization, and from the mid-1890s for cooling machines (van der Vleuten 1998, p. 42).

Evidence on the use of energy for mechanical power by the creameries compared to other industrial activities comes from the 1897 Danish Industrial Census which gives a comprehensive portrait of the horsepower (HP) installed in factories[19]. We use this to construct Table 3, which gives an idea of the HP per worker in various industries. Clearly, the creameries were relatively capital intensive, with an HP/worker of 1.41 in 1897, slightly higher than in the spinning mills, another largely mechanized industry.

[19] The Danish industrial census recorded companies of any size; the historical literature has however not recorded consistently the results of the census, which leads to an underestimation of the total HP employed by the dairies.

Table 3: HP per worker for the main branches of Danish industry, 1897

	All Factories		Mechanized factories		Total	HP/	HP/ worker
	number	workers	% of total	workers	HP	worker	(mechanized)
Food,bv & t.	11301	30517	41	19660	19151	0.6	1
Creameries	1233	4391	96	4283	6173	1.4	1.4
Slaughterhouses	3180	3351	2	1086	1173	0.4	1.1
Textiles	4358	12533	6	8762	4962	0.4	0.6
Spinning mills	111	636	98	635	807	1.3	1.3
Weaving mills	3061	6613	3	6131	3580	0.5	0.6
Clothing	23557	28291	0.2	2369	293	0	0.1
Construction, furniture	19781	42389	1	4957	3294	0.1	0.7
Wood	4896	8119	12	4659	3722	0.5	0.8
Leather	227	1227	31	857	310	0.3	0.4
Nonmetallic minerals	1757	13700	17	9872	5833	0.4	0.6
Metals	9383	27302	5	16402	4665	0.2	0.3
Chemicals	602	4061	29	2992	1497	0.4	0.5
Paper	82	2057	45	1721	1690	0.8	1
Others	1248	5358	16	3290	677	0.1	0.2
All	77192	175554	9	75541	46093	0.3	0.6

Source: Own elaboration from Statistics Denmark (1899).

Notes: [a] Includes factories with wind and water power. [b] Excludes reserve machinery, wind and water power. [c] Excludes gas and electric utilities.

Table 4 supplements the above with information from the two subsequent industrial censuses, from 1906 and 1914, in order to give an impression of the HP from steam in creameries as a proportion of the total in industry. In 1897, 92 per cent of total horsepower was from steam, and this level was maintained more or less until the First World War (Hyldtoft and Johansen, p. 135).

Table 4: HP in creameries, and the total HP from steam machines in industry

	No. of creameries	Total workers	HP (from steam)	HP / worker	HP total from steam in industry	HP in creameries as % of total
1897	1,233	4,391	6,115	1.4	41,436	15%
1906	1,366	4,945	7,975	1.6	85,321	9%
1914	1,462	4,904	12,300	2.5	132,636	9%

Source: Statistics Denmark (1899, 1908, 1917).

Thus, in less than two decades, the HP/worker in creameries almost doubled. Part of this was due to the growing use of automatic butter churners, refrigerators, and electric lighting (Hyldtoft 1984, pp. 358-9). Moreover, there was an increasing tendency to have more than one centrifuge per creamery (Statistics Denmark 1909).

Even more dramatic developments can be seen in the related pork industry, which developed based on the use of by-products from butter production to feed pigs. According to Hyldtoft (1984, p. 361), in 1897 there were 74 slaughterhouses and sausage factories with six or more employees with 1,383 workers using 805 HP, i.e. just 0.58 HP/worker, increasing in 1914 to 113 slaughterhouses with 2,658 workers using 4,704 HP, i.e. 1.77 HP/worker.

On the micro-level we can demonstrate how important the consumption of coal was for butter production in particular. We use information on butter production for the period 1890-1905 (Bjørn 1982) and combine it with estimates of the amount of coal required to produce a kilogram of butter from individual creameries. Our best estimate is from 1903, since a national survey of 523 cooperative creameries corresponding to 49 per cent of butter production is available (MDS 1903[20]). The use of coal was widespread with only 3 per cent of the cooperatives reporting the use of other fuels (mostly peat). From this, and using the average of the prices paid by creameries in 1903 recorded by Birk (1904, pp. 8-9, see also below), as the consumption of coal is given in terms of its value, we find a coal (kg) to butter (kg) ratio of 1.1, and a total consumption by the creameries of circa 110 thousand metric tons, or 6 per cent of total coal consumption.

[20] A digitalized version of this was kindly made available to us by Morten Hviid.

For earlier periods, estimates are fraught with uncertainty, but some rough calculations can be made. From 1888 the Danish journal *Mælkeritidende* published accounts from individual creameries, some of which give information on the amount of coal used, usually in terms of costs, or occasionally in terms of the actual quantities used. For the period 1888 to 1893 we found accounts of 72 individual dairies, twelve of which recorded both the volume of coal used as well as the volume of butter produced, and the rest which recorded the volume of butter produced, but only the monetary value of the coal. For the twelve for which we have the amount of coal used, the average was 1.8 kg coal per kg of butter, with a minimum of 1.3 kg and a maximum of 2.5 kg[21]. To increase the size of the sample, we converted the values of coal into quantities of the remaining dairies assuming that the coal price was 25 per cent above the coal price in the gasworks in Copenhagen (Københavns Belysningsvæsen 1932)[22]. The mean is also 1.8 kg coal/butter[23], suggesting that there were large improvements in the efficiency of production between the late 1880s and 1903 (when the ratio was 1.1 as reported above)[24]. Assuming that this coal/butter ratio is representative, we estimate that creameries represented nine per cent of total coal consumption in a period where the proportion of HP in industry was probably at its highest[25]. Considering that probably more than half of the coal was used to produce gas for lighting, to fuel steamships and trains and for domestic heating, this was not an insignificant amount[26]. Moreover, the creameries were totally dependent on this supply of coal.

Outside animal production, the rest of agriculture also became increasingly mechanized. In 1897, from the 64,905 HP installed in steam boilers in use in both industry and agriculture – 11,295 HP were used in creameries and 6,509 HP in agriculture (Statistics Denmark 1899).

[21] The reason for the high variation in the coal/butter ratio is probably related to the differing efficiencies of equipment across creameries (different acquisition dates) and some differences in the production process (for example, cheese production or pasteurization). This variation was not related to price differences since neighboring dairies could register strong variations in coal consumption per butter, see Hertel (1903).

[22] As we will demonstrate in Section IV this is a plausible assumption. Prices in the twelve creameries for which we have information vary from 5% to 25% of the Copenhagen gas price.

[23] The standard deviation is 0.8.

[24] This is consistent with an increase in the efficiency of steam engines for the period 1880 to 1900 (see Ayres and Warr 2010), but could also indicate improvements in the organizational process.

[25] There were already 6400 HP of steam installed in dairies and agricultural activities in 1890 compared with 7100 HP in 1900, and the growth was probably slower than the rest of industry, see Christensen (1996).

[26] In 1913, 40% of coal was used in industry, 16% in railroads, 15% in gasworks, 3% in electric utilities and 27% in domestic heating (Statens Kulfordelingsudvalg 1921); roughly assuming similar proportions for the industry in 1890-1894 and 1900-1904 would result in a 20% industrial share in 1890-1894 and 15% in 1900-1904, slightly above its HP share, which could be explained by a relatively higher use for heating.

There was an increasing use of steam driven threshers, roughly one sixth of those used according to a survey of machines in agriculture conducted in 1907 (Statistics Denmark 1910), although since they were heavy and rather clumsy, steam was rapidly phased out in agriculture outside dairying in the twentieth century in favour of internal combustion engines.

Coal was therefore an important factor in Denmark's rapid development. On top of this is the contribution of feed, as discussed in the previous section, which fed the cows which provided the milk for the creameries. Table 5 attempts a simple approximation of the proportion of total energy going to butter production. From an estimate of the amount of milk used based on milk/butter ratios and information on average milk yields we can estimate the number of cows used in butter production, and thus, using the quantities of feed necessary to feed the cows as described above, we reach an estimate of the feed used in butter production.

Complicating this calculation is however the point that, as mentioned above, the vast majority of the by-products of butter production, i.e. the skim milk and the buttermilk, were used to fatten pigs. Thus the output of the 'butter cows' was not only butter but also pigs. Table 5 might thus be interpreted as an estimate of the proportion of energy used for butter and pig production, but then it is an underestimate of this, since the majority of the feed given to pigs was grain and concentrates. Moreover, we do not account for labour input for example.

Table 5: Energy in dairying, 1890-1913

	1890-1894	**1900-1904**	**1910-1913**
Butter production, tons	68,000	97,000	110,000
kg of coal per kg of butter	1.8	1.1	1.1
Total Coal for butter production (PJ)	3.6	3.2	3.5
kg milk per kg of butter	27	26	25
ton milk per cow	2.0	2.3	2.8
Butter cows, thousands	924	1100	1016
Feed per cow (GJ)	21	22	25
Total Feed embodied in milk delivered to the dairies (PJ)	19.6	24.3	24.9
Total Energy, Dairying	23.2	27.5	28.4
in (%) of total Energy (including cows)	21%	21%	16%

Sources: Butter production is from Bjørn (1982, p.124). Kg of coal per kg of butter: 1890-1894, own calculations (see the text), for 1900-04, MDS (1900); for 1910-13, MDS (1914). Kg of milk per kg of butter: for 1890-94, Henriksen et al (2011); for 1900-04, MDS (1900); for 1910-13, MDS (1914). Metric tons of milk per cow comes from Wade (1981), using linear interpolation. Feed per cow as in the appendix.

Clearly energy was an important factor for Denmark's leading sector, dairying, at around 20 per cent of total energy consumption. In this context it might also be noted that this in turn promoted the expansion of domestic industry (supplying for example cream separators and refrigerators) and services (especially shipping) – see Henriksen (1992). As is well known from the literature, the grain was available cheaply due to Denmark's commitment to free trade during the American grain invasion. But given that the lack of local supplies of coal has been considered such a serious impediment to development for other countries, how do we explain the dependence on coal for a country with practically no domestic reserves?

IV

Denmark's agricultural revolution – and her economic development in general – was to a large extent based on the rapid spread of centrifuges and cooperative creameries. The reasons why cooperatives spread faster in some countries than others has been much debated (see for example Fernández 2014), but here we concentrate on the technology rather than the institution. We have so far demonstrated that this technology led to the cooperative creameries being relatively energy intensive, and also that Danish agriculture more generally took an energy intensive development path before the First World War. However, the question remains as to what it was about Denmark which allowed this to happen.

Perhaps surprisingly, given that Denmark had next to no coal, and is often considered to be closer to the poor periphery of Europe than the industrial core before the end of the nineteenth century, we look to the hypothesis presented by Allen (2009) as to what gave rise to the Industrial Revolution in England. His hypothesis rests on the finding that a couple of factors made Britain unique in the nineteenth century: wages were very high, while coal and energy were cheap. This created a demand for labour saving, energy intensive technology, and on the supply side, the high wages made it easier to respond to this challenge. Wages were high in Britain because of the foreign trade boom in the seventeenth and eighteenth centuries. Energy was cheap because of the vast and easily accessible reserves of coal located particularly in north-western England. Our basis for appealing to Allen's hypothesis for the case of Denmark rests on two points. First, despite the lack of deposits in Denmark, her geography and openness nevertheless made access to coal relatively inexpensive. Second, Danish incomes were fairly high before the agricultural revolution, and rapidly increasing during it.

Regarding geography, Denmark had few natural energy resources, and was largely deforested by the 1700s (Kjærgaard 1994). Denmark had peat, and a little coal on the island of Bornholm (Christensen 1996), but it was to be imports of coal that were to be of greatest importance. These were relatively cheap, in two senses. First, they were cheap when compared with the price of firewood and peat. Between 1730 and 1800 firewood and peat prices in Copenhagen measured in silver increased by a factor of 2 and 3 (Friis and Glamann, 1958), selling at about 8-11 silver grams per million BTU in 1800, placing Copenhagen among the European cities with expensive firewood[27]. Around the late eighteenth century, coal was being sold in Jutland at a price that was already about the same or cheaper than firewood and peat in Copenhagen[28]. This price differential increased in the second half of the

[27] Our calculations from the price series of firewood (favn) and peat (læs) from Friis and Glamann (1958); 1 peat læs = 500 Kg= 5.25 GJ and 1firewood favn =2.2 m3 = 17.2 GJ. Prices in Copenhagen were at the level of Amsterdam in 1800, another city with a fast transition to coal (Allen 2009).

[28] Comparison in GJ based on the prices of peat and firewood from Friis and Glamann (1958) and the prices of coal from Andersen and Pedersen (2004), p. 640-642.

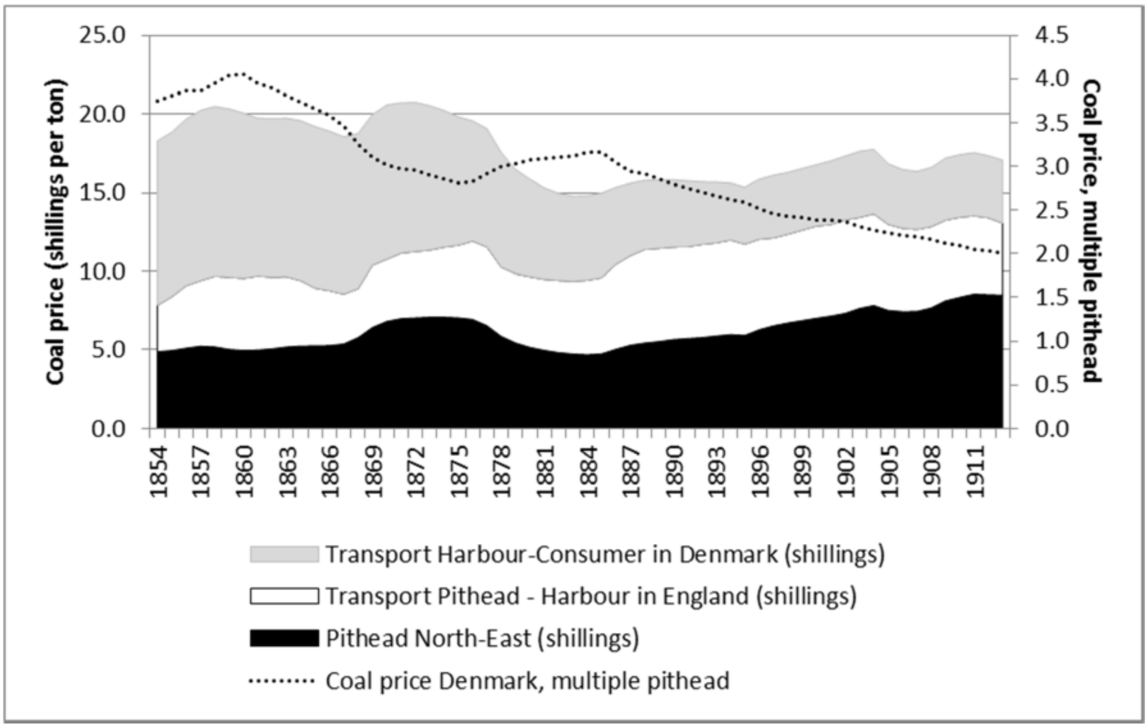
nineteenth century, with wood and peat costing three to four times more than coal[29]. Clearly, there was a great incentive to switch to coal.

Second, the price of imported coal was relatively cheap for a country without domestic resources. One obvious reason for this is the relatively short distance from Newcastle to Denmark. Not only were coal freights to Copenhagen very low in European terms, but Denmark also benefited from the fact that Newcastle pithead prices were lower than those in Cardiff, the other significant coal supplier to Europe, during most of the nineteenth century. Another key point for a successful coal trade rests on ensuring cargo for the home journey. Between 1828 and 1857 the number of Danish ships visiting British harbours increased by a factor of six. These were largely carrying exports of grain, and they returned with coal to the provincial harbours. Copenhagen, on the other hand, was largely supplied by British ships which were on their way to the Baltic. Thus, a commentator in 1843 noted that coal was cheaper in Copenhagen than in Berlin and that generally freight rates to the Baltic were very low (Møller 1998, p. 66). This process continued as steamships made the connection more regular and Denmark's agricultural exports expanded in the 1870s and 1880s (Møller et al 1998, p. 94).

An analysis of the coal prices faced by a big consumer (the gasworks in Copenhagen) is presented in Figure 5. In the 1860s coal was sold at a price of 3.5-4 times the pithead prices in Newcastle, but a significant decline in coal freights due to the increasing use of steam shipping decreased market prices in Copenhagen to the value of twice the pithead price in 1913.

[29] Comparison based on the on the prices of peat of Hansen (1984) 1858-1870 and the coal prices of the gasworks Københavns Belysningsvæsen (1932) for the same period.

Figure 5: Coal prices in Denmark, 1854-1913 (9 year moving averages)



Sources: Pithead prices calculated from Church (1986) and Mitchell (1984). Construction of the main components with the freight and price series comes from Københavns Belysningsvæsen (1932). For the early years they are constructed from Klovland (2010) and Annual Statement of Trade (several years).

Of course, with this level of prices, Denmark could never specialize in the coal intensive industries of the First Industrial Revolution. This was reserved for regions with coal mines, such as the UK, Germany, Belgium or even France. However, Denmark compared very well with other coal importers. International comparisons at the port level show an early advantage in coal import prices in relation to other coal-poor regions such as Italy, Spain and Portugal. This advantage seems to have been significant during the 1870s and the first half of the 1880s, although it diminished subsequently as shown in Table 6.

Table 6: Coal prices at the pithead and ports in current shillings per ton, 1850-1900

	United Kingdom Pithead	Germany Pithead	France Pithead	Italy Imports	Denmark Imports	Spain Imports	Portugal Imports
1850s	5.3				15-18		18
1860s	5.6			32	16-20	31-41[a]	19
1870-72	6.5			29	19	28	23
1879-81	5.4			24	13	21	20
1884-86	5.1	5	9	21	13	18	17
1889-91	7.5	7	10	25	15	21	16
1899-01	9.2	9	12	29	14	24	18

Sources: UK, Italy (from 1870), German and French prices come from Bardini (1997). Prices in the UK from the 1850s and 1860s come from Clark and Jacks (2007). For Italy in 1860 they are from ISTAT (1958). Spain prices are from Coll and Sudrià (1987) and refer to an average of three coastal locations Bilbao, Cádiz and Barcelona; [a] for 1860s (1865) the lower price refers to Cádiz and the higher price to Barcelona. Portugal import prices come from INE, Comércio Externo. Denmark CIF prices (from 1870s) come from Henriksen and Ølgaard (1960), and for the period 1850s-1860s the lower bound refers to an index of coal prices for the Copenhagen gasworks (Københavns Belysningsvæsen 1932) which is connected with the CIF prices. The higher bound is constructed by adding the average of FOB prices for Denmark reported in the British *Annual Statement of Trade* (1850-1869) to the coal freights Tyne-Copenhagen from Klovland (2010).

These figures only tell a small part of the story, however. The important point was not how cheaply coal arrived at a particular port, but how cheaply it arrived to a particular consumer. For example, coal was sold almost as cheaply in Lisbon as in Copenhagen in the late 1880s, but lack of land infrastructure made coal extremely expensive inland in Portugal where it was sold at ten times the pithead price (Henriques 2011). Big differences in coal prices were also apparent in Spain and Finland (Coll and Sudrià 1987, Kunnas and Myllyntaus 2009). Even in countries endowed with coal, there was similar variation – in 1880 it was sold in London or landlocked parts of Germany at 2-3 times the domestic pithead prices (Kander et al 2013). Denmark, by contrast, has a particular geography, as we will discuss below, which played a very important role for easing the diffusion of steam technology to all parts of the country.

The earliest information we have on the regional dispersion of coal prices in Denmark is from Birk (1904, pp. 8-9). He surveys coal prices faced by 34 creameries around the country in 1903. Apart from two outliers[30], these vary between 16 kroner/metric ton (in north central Jutland, but located close to Mariager Fjord to the east and Limfjord to the west) to 21.6 kr/ton (in Faaborg, a harbour in the south of the island of Funen). The maximum value is thus only 35 per cent higher than the lowest price. The same year, the prices paid by two large consumers, the Gasworks in Copenhagen and the Danish State Railways (DSB) were 15 kr/ton and 17.8 kr/ton respectively (Generaldirektoratet for Statsbanerne 1930, pp. 178-9). The average price paid by creameries was 19 kr/ton which is only 27 per cent above the gas price and 7 per cent above the railway price. Why was there such a lack of regional variation compared to other countries?

With the loss of the Duchies of Schleswig and Holstein to Prussia in 1864, Denmark was a very small country, with nowhere further from the coast than 52km (32 miles). Jevons (1865) mentions in his seminal book, *The Coal Question*, that about one third (135 ports) of the European ports involved in the coal trade with Britain were Danish. The port in Copenhagen, supplemented with another large port in Esbjerg from 1874, together with local provincial harbours[31] meant that coal could be transported cheaply by sea to the whole country.

This easy access to coal was crucial for Danish butter production since dairies were situated in the countryside. Had they not had this, perhaps the Danish Agricultural Revolution could never have reached the heights that it did, or Danish development might have proceeded very differently. Exactly the contribution of cheap coal to the viability of the cooperative production form is impossible to assess. The cooperatives were owned by individual farmers, each with a small number of cows. The typical contract stipulated that they were to be paid according to the volume of the milk they delivered (and from 1887, after the control centrifuge was invented, sometimes by the fat content). The proceeds from the production of butter, minus the money already paid for the milk and the operating expenses of the creamery (typically around 6 per cent according to Henriksen et al 2012), were then also distributed among the farmers. The true profitability would, however, require knowledge of all operating expenses on the farm. However, what we can see from the earliest accounts published in *Mælkeritidende* described above from the late 1880s, was that coal constituted

[30] 12.8 kr/t and 26 kr/t. Both are in the north of the island of Funen, but located to the east and the west of Odense Fjord, respectively.
[31] See Fransen (1996) for a detailed account of the interplay between railroads and ports on the island of Funen.

around 25 per cent of expenses[32], around the same as the share spent on wages (most of the rest going on the cost of transporting milk from the suppliers). The share of expenses on coal fell over time (to around 10 per cent by 1900), but in the early days in particular, more expensive coal would have made the creameries less profitable. Moreover, without the quick diffusion of steam technology to the dairies, there would not have been any incentive to initiate the cooperatives, since there would have been no reason to supply a central creamery (Jespersen 2011).

Turning now to income, it is already apparent from Maddison's estimates of GDP/capita that Denmark was already relatively rich among 'peripheral' agricultural economies, even before her agricultural transformation: see Table 7. By the First World War, Denmark was even catching up with the industrial core.

Table 7: GDP/capita (1990 int. GK$) for selected European countries, 1870-1913

	Belgium	Denmark	France	Germany	Italy	Neth.	Portugal	Spain	Sweden	UK
1870	2692	2,003	1,876	1,839	1,542	2,755	975	1,207	1,345	3,190
1880	3065	2,181	2,120	1,991	1,589	2,927	947	1,646	1,480	3,477
1890	3428	2,523	2,376	2,428	1,690	3,186	1,128	1,624	1,635	4,009
1900	3731	3,017	2,876	2,985	1,855	3,329	1,302	1,786	2,083	4,492
1910	4064	3,705	2,965	3,348	2,176	3,783	1,228	1,895	2,543	4,611

Source: Bolt and Van Zanden (2013).

Comparisons of national income per head mask, however, the fact that real wages in agriculture in Denmark were extremely high, at least compared to her immediate neighbours and to other agricultural exporters in Europe. As Henriksen (1992) notes, our knowledge of agricultural wages for Denmark before the twentieth century is very limited. There is however evidence that the rural/urban wage gap was rather small, which might be taken as evidence of the relatively high productivity of agricultural labour. Moreover, migration from the country to the cities was slower than elsewhere, and emigration was far lower – in fact agricultural labourers from especially Germany and Sweden immigrated to

[32] This is a quite high energy cost share, comparable to energy-intensive industries. See Balderston (2010) for a discussion on the importance of coal in the low energy intensive cotton sector.

Denmark. Van Zanden (1991) also places Denmark in 1870 in the 'core' of Europe and at the efficiency frontier in agriculture together with the UK, the Netherlands, Belgium, and France. Moreover, Denmark differentiated herself from other countries through having a high share of labour in her agricultural workforce compared to her productivity.

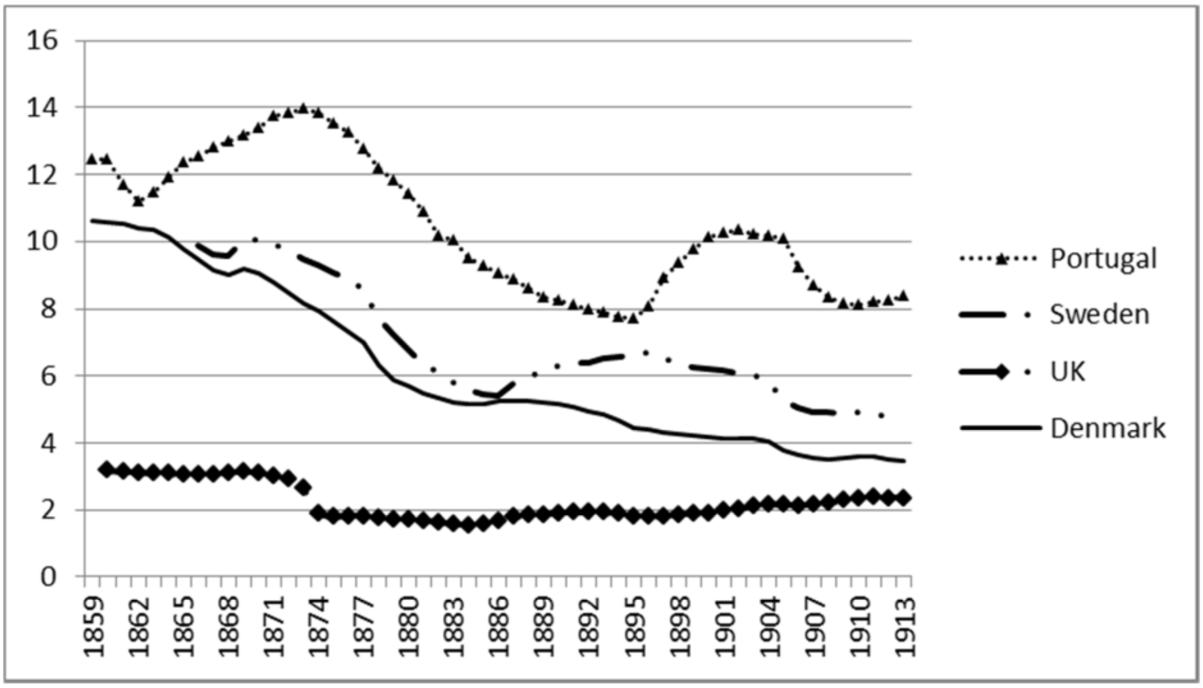
Contemporaries also noted Denmark's relatively high rural wages. Rainals (1860), the British Vice-Consul in Copenhagen, noted that 'The Danish farm labourer is generally well off and while he is without family is able to save part of his wages as is sufficiently proved by the large sums of money placed in the savings banks by this class' (p. 290). He also noted other features of the wealth of Danish agriculture, such as the immigration from abroad, and the fact that oxen were not generally used for draught (p. 306).

Khaustova and Sharp (2014) have taken some of the available evidence there is on agricultural wages in Denmark, and converted them to real wages using the methodology described by Allen (2001). Their ongoing work suggests that on the eve of the agricultural revolution, unskilled agricultural labourers could afford almost one and a half times Allen's respectability basket of goods, and unskilled labourers in Copenhagen could afford around two and a half times. This puts Copenhagen higher than Amsterdam in 1875, well above other European cities such as Madrid and Florence, where workers could afford less than one respectability basket, although of course somewhat below London labourers, at over two times. Danish workers were thus relatively well-off by any measure, and we might note that agricultural labourers probably did not represent much of Danish agriculture, which was based on small scale self-owning peasant agriculture earning rents from the land rather than from their labour.[33]

Finally, in the spirit again of Allen (2009), we illustrate in Figure 6 the coal price to wage ratio for the UK (coal endowed), and for Sweden, Denmark and Portugal (coal poor countries). This ratio can be interpreted as an incentive to adopt steam technology.

[33] Interestingly, hand separators, i.e. centrifuges operated by hand rather than by steam power, although manufactured in Denmark, were not used in Danish creameries. They were however used widely elsewhere, including in southern Sweden. This also seems to be striking support for the idea that labor-saving technologies were prioritized.

Figure 6: Coal price (ton) ratio to wages (day) in Denmark, the UK, Sweden and Portugal (9 year moving averages)



Sources: Denmark: Average male urban wages from Christensen (1975) for 1870-1913, and Hansen (1984) for 1858-1870; coal prices from Københavns Belysningsvæsen (1932). Portugal: Wages from Martins (1997), simple average of 14 urban and industrial tasks; coal prices from INE, Comércio externo. For Sweden: Average industrial wages from Prado (2010); coal prices from Ljungberg (1990) after 1890 and a revised coal series 1866-1889 based on railroad costs kindly provided by Astrid Kander. UK: Builders' wage refers to south-eastern England and is taken from Clark (2004). Pithead coal prices are taken from the *Digest of Welsh Historical Statistics: Coal 1780-1975*.

This figure confirms Allen's story that coal to wage ratios were drastically lower in Britain than in any other country in the second half of the nineteenth century. In England, 1 metric ton of coal was equivalent to the daily wages of 3 men in the late 1860s, while in Denmark, Sweden and Portugal it was equivalent to between 8 and 13. Still, when compared with other coal-poor countries it is possible to argue that Denmark had the greatest incentives to mechanize. Not only were the levels of the coal/wage ratio significantly higher than in Portugal, and relatively higher than in Sweden in 1860, but they also fell more sharply over the period 1860-1913. On the eve of the First World War, 1 metric ton of coal was equivalent to the wages of 3 men in Denmark, but about 5 in Sweden, and 8 in Portugal. The evolution of the coal to wage ratio in those three countries supports Allen's view on the spread of the Industrial Revolution first to high wage countries and later to low wage countries. Coal surpassed wood and peat in Denmark as early as 1854, while in Sweden low firewood prices coupled with relatively lower wages meant that the transition had to wait until 1906. Portugal, as a very low wage country, would fail the transition to coal altogether. Coal was never the main energy carrier in that country, and she would have to wait for the cheap oil prices after the Second World War before she could catch up with the European Core (Henriques 2011).

V

The present work, through the compilation of new energy accounts and evidence from the micro level, reveals that Denmark was relatively heavily dependent on energy during her period of economic catch up. We find that Denmark seems to have enjoyed the combination of relatively expensive labour and, largely owing to her geography, relatively inexpensive coal, which could stimulate the sort of development process suggested by the work of Robert C. Allen. In addition, the energy perspective gives us another important insight: that the cows had to be fed with vast amounts of domestically produced and imported energy, in the form of feed. This was cheap owing to Denmark's decision to remain a free trader throughout the first era of globalization.

More expensive energy might not have made the creameries unprofitable, but it would have reduced the incentives to invest in them. For example, a hand-driven alternative to the large stream-driven centrifuges was also developed, and if Denmark had not adopted steam technology, then perhaps farmers would have adopted the cheaper technology, remained small-scale, and less export oriented. Denmark would have developed anyway, but not in the same way. More generally, our analysis allows us to explore the argument sometimes made that energy and coal are not crucial for development. We find support for both the growth and location hypotheses. Denmark's initial conditions (high wages, and an ideal geographical location) constituted an early advantage vis-à-vis other equally coal-poor countries. This favoured both an early transition to coal and laid the road for subsequent development. One might also argue, however, that Denmark can be considered to support the idea that countries do not need natural resources to be rich as long as they can import cheaply from elsewhere (and deliver equally cheaply to the final consumer). That coal was vital for Denmark's development is, however, without question.

Appendix: Danish Primary Energy, 1800-1913

Table A1: Danish Energy Consumption by Type in PJ, 1800-1913

	Food	Feed working animals	Firewood	Peat	Wind &Water	Coal	Oil	Primary Electricity (wind, water, imports)	Total	Feed for cows and oxen	Total including cows
1800	4.2	11.3	8.1	5.4	1.4	1.2			31.5	8.3	39
1810	4.7	10.3	8.4	6.1	1.4	0.8			31.7	9.5	40
1820	5.3	9.4	9.3	7	1.5	1.4			33.9	10.6	43
1830	5.8	8.6	10.2	7.8	1.6	1.8			35.8	11.9	46
1840	6.2	8.1	10.6	8.3	1.8	3.7			38.6	14.1	51
1850	6.9	8.5	8.1	6.3	2.1	8.7			40.5	17.3	56
1860	7.8	9.0	7.9	7.7	2.6	12.3			47.2	21.1	66
1870	8.6	9.4	7.4	8.4	2.7	20.6			57.1	25.0	80
1875	9	9.6	7	7.6	2.9	19.4	0.3		55.9	28.0	81
1880	9.5	10.2	6.7	6.7	2.8	25.7	0.5		62.1	31.4	91
1885	10	10.8	6.9	5.6	2.6	33.7	0.8		70.5	32.3	100
1890	10.5	11.1	7	4.4	2.6	38.4	1.1		75.2	34.7	107
1895	11	11.5	7.2	3.1	2.5	48.3	1.6		85.2	37.3	119
1900	11.8	12.4	7.1	1.7	2.2	53	1.8		90.1	38.9	125
1905	12.7	13.9	6.6	1.7	2.1	62	2.3		101.3	44.2	142
1910	13.6	15.5	6.4	1.7	1.7	75.5	3.3	0.02	117.8	55.1	169
1911	13.9	15.5	6.4	1.7	1.6	80.2	3.6	0.02	122.9	56.7	175
1912	14.1	15.5	6.6	1.9	1.6	92.1	3.9	0.02	135.8	58.4	190
1913	14.3	15.5	6.7	2	1.6	93.9	4.5	0.02	138.5	60.0	194

Sources: See below. Note that, in Figure 4, in order to avoid double counting, we reduced the amount of energy on food by 30 per cent in order to exclude meat and dairy products, and thus allow us to include feed for non-working animals, which is the final column in this table, and not included in the total given. See also the notes to Figure 4.

1. Food

The Danish population was particularly well fed during this period. There are only partial statistics that can give an idea of the living standards of the Danish population in the nineteenth century. Thestrup (1971) uses municipal taxes to determine the average calorie intake of an inhabitant of Copenhagen in the period 1730-1800. The calorie consumption is estimated to vary between 2600-2900 kcal/day during the 1730s and 1750s to 3100-3200 in the 1790s and 1800s. Using the available agricultural statistics of the period, Jensen (1985) estimates that there was about 3000 kcal of available food per individual for the early 1800s, perhaps 1700 kcal in grain, 600 kcal in beer and 700 kcal in dairy products.

Some studies on the kcal implied by the food expenses of urban and rural workers were conducted in 1897 and 1909 (Heiberg and Jensen 1910, Bjørum and Heiberg 1914, Statistics Denmark 1900, 1901 and 1912). These reveal that in 1897 Danish urban workers (adult males) had an average daily food consumption of 3350 kcal/day in Copenhagen, 3153 kcal/day in the provincial towns, and 3600-3700 kcal/day in the rural districts (Heiberg and Jensen 1910, p. 101-16). A similar study conducted in 1909 gives 3250 kcal in Copenhagen, 3368 kcal in the provincial towns, and 3800-5000 kcal/day in rural areas. These surveys thus point to a small rise in the per capita consumption in the rural areas of the country.

In order to account for women and children, we lowered the average food consumption in the period from 1800-1897 to 3000 kilocalories a day, assuming a linear increase to 3100 kcal by 1910. This latter figure is based on a national retrospective study on food consumption 1914-1948 which was published by Statistics Denmark in 1949. This shows that the availability of food before the outbreak of the war amounted to 3150 kcal/day.

2. Feed for working animals

The first animal census is from 1800 and can be found in Falbe Hansen (1888). From 1838 there are national registers of horses (*Kreaturtælling* 1837, 1861, 1866, 1871, 1876, 1881, 1888, 1893, 1898, 1903, and 1909). After deducting for foals and colts, we assumed that all horses worked in either transportation or agriculture. The annual requirement of feed depends on the weight of the animal and its working effort. Kander and Warde (2011) provide a guideline of weights and working effort for estimating animal energy in various European Countries. We have assumed that Danish horses had the same energy requirements as those indicated for Northern Europe.

3. Firewood and Peat

Firewood and peat consumption are reported for the period 1900-1914 in a retrospective on the energy balance of Denmark which was published by Statistics Denmark in 1960. Estimations of peat and firewood consumption are based on records for extraction in peat bogs and forests.

For the nineteenth century there is scattered but rich information on the urban consumption of firewood and peat, as both fuels were recorded on entry to Copenhagen and market towns for taxation purposes. Using this it is possible to reconstruct the supply of firewood and peat to the city of Copenhagen for the period 1800-1880 for firewood, and from 1800-1850 for peat. See Morville (1798), Begtrup (1803), Olufsen (1811), Thaarup (1796, 1819, 1825), *Kollegial-Tidende* (1798), Bergsøe (1847), Müller (1881), Rubin (1892), Nathanson (1832, 1836) and the *Statistiske Tabelværk* (Statistics Denmark 1838-1851). Firewood consumption in the capital was 1.6 m^3 per capita/year in 1756-1770; 1.3 m^3 per capita/year from 1795-1804; 0.72 m^3 per capita/year in 1840; and 0.42 m^3 per capita/year in 1880. Peat consumption increased from 110 kg per capita/year in the early 1800s to about 250-300 kg per capita/year in the period 1830s-1850s.

For the market towns, there are figures from the toll registers for the period 1838-1850 (*Statistics Tabelværk* 1838-1850). During the early part of the period (1838-1841) market towns consumed about 3.4 kg/day of fuel, half in peat and half in firewood. In the later part of the series (1848-1850) consumption is down to 2.7 kg/day, with firewood decreasing at a much higher rate than peat. There were no significant regional variations in the total fuel consumption and shares of peat/wood. In 1841, wood and peat totalled 11.3 GJ per capita/year in Funen, 13.9 in Jutland and 13.4 in Zealand. The proportion of peat to firewood in calorific terms was 53 per cent in Funen, 48 per cent in Jutland and 51 per cent in Zealand, which indicates the wide use of peat across the country. Market towns were small at that time (700-10,000 inhabitants), so consumption can be assumed to be of the same magnitude across the rural areas as well.

To derive the totals for early years, we have assumed that per capita consumption and the share of wood and peat in rural areas and market towns was constant for all the period 1800-1838. Our assumption matches well with the educated guesses of contemporary authors. Morville (1798) indicates an amount of 8 m^3 of firewood of wood or alternatively about 8 *læs* of peat was the norm for a small family of farmers (3-4 people). Olufsen (1811) suggests that an annual consumption of 1.8 m^3 of beech firewood per capita/year (other fuels included) would be enough to satisfy (with the technology of the time) the heating needs of the Danish population: 1.8 m^3 of beach firewood equivalent (including peat) is exactly the reported consumption around 1838-1840.

After 1850 we have assumed different trends for consumption of the two fuels. Firewood consumption per capita was assumed to decline linearly from 1850 to 1880 to a level that matches a national estimation of wood production based on a wide sample of the forest area by the forest engineers Peter Müller for 1881 and A. Opperman for 1896 (see Müller 1881 and Opperman 1896-1902).

Peat consumption was assumed to be stable in absolute terms in the capital[34] and at a per capita level in the other parts of the country. After 1870 we have assumed a rapid replacement of peat by coal, which started to be transported by railroads to the rural areas (Müller 1881)[35].

4. Wind and Water

The major users of mechanical wind energy were sail ships and mills (flourmills, farm mills and factories). In order to calculate wind energy we need to estimate the number, power, efficiency and intensity of use of the converting machines. For sail ships, Mitchell (2007) reports the tonnage of Danish vessels for the period 1829 to 1913 and Warming (1913) has benchmarks for 1800 and 1824. We use the method proposed by Lindmark (2007) who calculates the power of vessels to be approximately 0.6 kW per ton, already accounting for 50 per cent of energy losses in the sails. We assumed a coefficient of use of 3,650 hours per year in order to obtain the primary energy from wind.

The best benchmark for windmills is found in 1907. At that date there were about 7,000-8,000 windmills in Denmark: 4,714 were farm windmills and 2,541 were commercial windmills. Commercial windmills were of the Dutch type and total power was reported to be about 41,000 HP, or 16 HP per windmill (Ølgaard 1979). Numbers of commercial windmills are available for some selected years (1830, 1897, 1908 and 1914) and the HP per mill can be assumed to be the same. Before 1830 we estimated HP by the population growth from 1800-1830.

Farm mills were of the post-mill type and they were generally smaller. We estimated that they had a maximum of 1.5 HP per machine. Before 1907 there is no information on the

[34] Firewood supply in absolute terms stabilized after 1840.
[35] Hansen (1970) also made an estimation of peat production for 1818-1900 with a basis on similar assumptions, but with only one year of information (1840) for Copenhagen and the market towns.

number of farm mills. However, we know that until 1862 it was a royal privilege to run a windmill, so farm mills started to be erected only around 1865-1875.

Our estimation on the power of windmills points to 12 GW in 1800, 21 GW in 1850 and 34 GW in 1900. Using this procedure it is also necessary to estimate the time and the efficiency at which these turbines were operating. Nowadays, in Denmark, modern wind turbines are operating only 16 to 20 per cent of the time, or a maximum of 1,800 hours over the course of the year. Considering that the wind blows mostly during the night, that is outside of working hours, and that many mills and factories used auxiliary power, we estimate that a use of 1000 hours per year in the nineteenth century is quite plausible. Regarding efficiency, we know that Dutch windmills, the dominant type during the nineteenth century, had only 6 per cent efficiency. We have assumed that efficiency started to increase after 1860, when other types of mills entered the market to reach a total efficiency of 16 per cent by 1913[36].

Water was much less important than wind in Denmark. Numbers of watermills are available for several years (1830, 1897, 1906 and 1914) from Lampe (1984). Warming (1913) writes than in 1906 there was approximately 10,000 HP installed in watermills, or 16 HP per mill. HP per watermill was probably less than half that of 100 years before[37]. It is difficult to know how many hours those mills were operating, so intensity of use was set to 3000 hours/year, based on the usual industrial week at the time. Efficiencies were low due to the absence of high heads. In 1830 most of the wheels were undershot (30 per cent efficiency). We assume a rise in efficiency to reach 55 per cent in 1897, 60 per cent in 1906, and 65 per cent in 1914, as turbines started to be introduced in the second half of the nineteenth century. Water power is estimated for the period 1800-1830 based on population growth. In primary energy terms, water power represents only 5 per cent of the direct use of water and wind.

5. Modern Energy: Coal, Oil and Primary Electricity

Nineteenth century production of brown coal was insignificant, and was therefore not recorded. Danish trade statistics on coal start in 1844. Unfortunately, there are some

[36] In 1921-1924 there was a study that indicated that the average efficiency of the dominant Danish turbines at the time was 17 per cent.

[37] Hyldtoft (1996) reports the mechanical power of watermills for industrial uses (textiles, paper, big flourmills, and iron and other metal industry) for several years (1855, 1872, 1882, and 1897). They increase from 16 HP in 1855 to 32 HP in 1897. Other mills were generally smaller.

inconsistencies in the Danish trade statistics, due to, among other factors, variations in how to include the Duchies of Schleswig and Holstein before they were lost to Prussia in 1864. We have thus used the exports of coal to Denmark reported in the British Trade statistics from 1830 to 1873. Early imports of coal are based on the scattered information in Nüchel and Thomas (1966)[38]; Thaarup (1796), *Kollegial Tidende* (1798) Rubin (1892), Kjærgaard (1994), Edington (1813) and Taylor (1848). From these sources we know that imports of coal to Denmark amounted to 30-40 thousand metric tons from 1792-1796, 40 thousand tons just before the Napoleonic wars and 25 thousand tons in 1811, with Copenhagen taking about 50-60 per cent of all imports. In 1828, imports were already 60,000 tons. We have assumed that they increased linearly from 25,000 in 1815 (a time of peace) to 61 thousand tons in 1828.

Imports of oil and coal from 1874-1899 are taken from Henriksen and Ølgaard (1960). From 1900 to 1913, coal, oil and an insignificant amount of primary electricity is reported by Statistics Denmark (1960).

6. Feed for non-working animals: Cows and Oxen

In addition to what is common in the literature, we also present an estimation of the energy in the feed given to non-working cows and oxen for the period 1800-1913. For oxen, we use the same feed requirements indicated by Kander and Warde (2009, 2011) for Northern Europe. For cows, weight approximations and suggestions on feed requirements are abundant in the literature. Larsen (1942) mentions that in the first decades of the 1800s cows were small and had a daily intake of 3 FU[39]. Lampe and Sharp (2015b) have compiled information on feed consumption by cow at the level of the dairy. Their figures suggest that milk cows had on average a daily intake of 4.7-5.0 FU over the period 1880-1900. Our estimated value of 5.4 FU in 1913 derives from the fact that a normal cow weighed about 400-500kg (Bjørn 1982) and that each 1 kg of milk should be equivalent to 0.33 FU (Larsen 1942). Feed for cows can only be added to the energy series if animal protein food consumption by humans is deducted from the totals. Food surveys from the 1900s show that animal protein (excluding fish) represented about 22-28 per cent of the daily intake (Heiberg

[38] Nüchel and Thomas' (1966) figures in pounds sterling were converted to metric tons using the export fixed prices that can be calculated from Mitchell (1962). The correlation between the value in pounds and tons exported from the British Statistics is 0.91.

[39] 1 Fodder Unit = 3000 Kcal

and Jensen 1910, Bjørum and Heiberg 1914, Statistics Denmark 1900, 1901, 1912, and 1949). We have taken the conservative approach of deducting 30 per cent of the total of the food consumption for the whole period in question, risking of course underestimation for the early years.

7. Conversion factors used

kilo (k) = 10^3; Giga (G) =10^9**;** Peta (P) =10^{15}

1 favn firewood = 2.2 m^3

1 m^3 firewood = 0.625 t

1 peat læs = 0.5 t

1 ton imported coal = 29.31 GJ

1 ton peat = 10. 5 GJ

1 ton firewood = 12.5 GJ

1 calorie = 4.19 Joule

1 horse-power (hp) = 0.746 kW

1 watt-hour (Wh) =3600 J

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