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# *The Danish agricultural revolution in an energy perspective: a case of development with few domestic energy sources*[†]

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This article examines the case of Denmark—a country which historically had next to no domestic energy resources—for which new historical energy accounts are presented for the years 1800–1913. It demonstrates that Denmark's take-off at the end of the nineteenth century was relatively energy dependent. This is related to Denmark's well-known agricultural transformation and development through the dairy industry, and thus the article complements 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, this article demonstrates that Danish geography allowed cheap availability throughout the country through imports. On top of this it emphasizes that another important source of energy was imported feed for cows.

This article examines the case of Denmark[1] 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.[2] As is well known, Denmark did not so much industrialize as experience a rapid transformation of its agricultural sector in the second half of the nineteenth century.[3] This process truly revolutionized Danish agriculture, and seems fit for the epithet

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[1] Please note that by '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.

[2] Most earlier work on energy consumption for Denmark is patchy and goes back only to 1870 at the earliest: see Bjerke and Ussing, *Studier*. However, see also Sørensen, *History of energy*.

[3] Here we stick with the traditional interpretation of Danish history that saw butter production as part of the agricultural sector (see, for example, Hansen, *Økonomisk vækst*)—the cooperative creameries were after all owned by the farmers. This has recently been questioned by, for example, Larsen, Larsen, and Nilsson, 'Landbrug og industri', who provide new national accounts from 1896 with the creameries in the industrial sector.

'agricultural revolution'.[4] Denmark changed from being a grain exporter to being 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 that rivalled 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.[5] On the supply side, the role of the spread of superior institutions (that is, the cooperative creameries) and technology (that is, the steam-driven cream separator) have been discussed.[6] Building on this, O'Rourke argues that the cultural homogeneity of the Danes allowed them to form successful cooperatives, in stark contrast with Ireland,[7] and Henriksen, Hviid, and Sharp demonstrate that the cooperatives also relied on legal institutions which were particularly beneficial in an international context.[8] However, the role of energy has not previously been emphasized. This is perhaps not surprising. Denmark had few natural energy resources. Its land had been largely deforested over the preceding centuries, it had practically no coal, and it did not even enjoy the fast-flowing water which was to be so important for the hydropower of its fellow Scandinavian countries.

However, a large body of literature (surveyed in the next section) has stressed the importance of proximity to coal for economic development. For example, as Fernihough and O'Rourke explain, 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'.[9] On the face of it, Denmark might therefore in fact appear to be an example of a successful alternative to the energy-intensive development path of the coal-rich countries. However, as this article 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 highly unsatisfactory and expensive.[10] In addition, the country's vast (in per capita terms) dairy herds required huge imports of energy as feed, particularly concentrates.

[4] Of course we are aware that there are other uses of the term 'agricultural revolution'; see, for example, Bjørn, ed., *Agricultural revolution*. 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 food to the factory workers.

[5] See, for example, Henriksen, 'Transformation', p. 156; Lampe and Sharp, 'Greasing'.

[6] See, for example, Henriksen, Lampe, and Sharp, 'Role of technology'.

[7] O'Rourke, 'Culture, conflict and cooperation'.

[8] Henriksen, Hviid, and Sharp, 'Law and peace'.

[9] Fernihough and O'Rourke, 'Coal', p. 6 (emphasis added).

[10] See, for example, the survey of Danish cooperative creameries in MDS, 'Danmarks Mejeri-Drifts-Statistik' (1918).

 

This article demonstrates that although coal was not available in Denmark, the rapidly falling transport costs of the late nineteenth century meant that Denmark was particularly well placed to receive cheap imports from Newcastle: both of course because of its physical proximity, but also because of its geography. Denmark is a country consisting of one peninsula 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 it 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, it demonstrates both how and why energy was important for Danish development, something which has not previously been emphasized by economic historians. Second, it makes the more general point that even if countries follow a non-industrial, more agricultural development path, energy is still crucial. Thus, it complements the literature which argues that expensive energy hindered industrialization (see below), by arguing that similar obstacles would have prevented other countries from more agriculture-based growth.

The article provides 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 demonstrates that coal was available more cheaply in Denmark than almost any other European country. Moreover, using a new database of energy consumption by source, it is demonstrated that coal was the major energy source behind the Danish 'agricultural revolution'. On top of this, it is emphasized 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, even before the age of oil and electricity.

The next section surveys the literature on the importance of energy and coal in particular for development. Section II introduces 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, the energy consumption of cows is also calculated, and it is argued that this was large in comparison with other countries and of particular importance for the Danish economy. Section III discusses the role of energy in Danish dairying, which was very energy intensive. Section IV explains how such energy dependence was possible for Denmark, due to its 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 its 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 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.[11] The first—associated with the work of Deane,[12] Landes,[13] Braudel,[14] Cipolla[15] and particularly Wrigley[16]—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. have taken a broader perspective on the role of energy for European economic growth.[17] 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 the population doubling, and food and firewood prices growing, since energy supply was not enough to meet demand. This was however avoided when coal became 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, who describes how Denmark by the early nineteenth century was in a serious ecological crisis, due to the disappearance of forests, sand drift, and so on.[18] 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,[19] Mathias,[20] Pomeranz,[21] and most recently Allen[22]—states that the location of nineteenth-century industry was strongly determined by the location of coalfields, since coal was bulky and costly to transport. 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 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.[23] Kander et al. explain that coal was crucial for European industrialization, but regional specialization was affected by energy costs.[24] The fall in the price of freight with the transport revolution made coal increasingly available in Europe, but the impact of this depended on geography.

[11] Fernihough and O'Rourke, 'Coal', p. 2.
[12] Deane, *First industrial revolution*, pp. 100–14, 129–33.
[13] Landes, *Unbound Prometheus*.
[14] Braudel, *Capitalism*.
[15] Cipolla, *Economic history*.
[16] Wrigley, *Continuity*; idem, *Energy*.
[17] Kander, Malanima, and Warde, *Power*.
[18] Kjærgaard, *Danish revolution*.
[19] Pollard, *Peaceful conquest*.
[20] Mathias, *First industrial nation*.
[21] Pomeranz, *Great divergence*.
[22] Allen, *British industrial revolution*.
[23] Pollard, *Peaceful conquest*, pp. 84–141.
[24] Kander et al., *Power*.

However, there are scholars who have argued that coal was not so important, for example, Mokyr,[25] McCloskey[26] and Clark and Jacks.[27] 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.[28]

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.[29] Italy is one such example, where expensive coal was a serious disadvantage for manufacturing until the First World War. Bardini 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.[30] Thus, Italian factor endowments led Italy 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.[31]

However, it has also been noted that some countries did manage to industrialize without coal. Kunnas and Myllyntaus use the case of Finland to demonstrate that industrialization is possible using renewable sources if it is accompanied by technological change.[32] 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. Its neighbour, Sweden, is another country without coal. Kander and Stern find that substitution from traditional to modern energy carriers was a leading factor behind faster rates of economic growth from the 1890s,[33] but wood and charcoal remained important in the early periods of industrialization.[34] Rydén shows how English technology and organizational processes in the iron industry were successfully adapted to charcoal,[35] and then, according to Schön,[36] when

[25] Mokyr, *Enlightened economy*, pp. 100–5.
[26] McCloskey, *Bourgeois dignity*.
[27] Clark and Jacks, 'Coal'.
[28] See also Weil, *Economic growth*, p. 468.
[29] See Betrán, 'Natural resources'; Henriques, *Energy transitions*.
[30] Bardini, 'Without coal'.
[31] See Sudrià, 'Energy'; Nadal, *El fracaso*.
[32] Kunnas and Myllyntaus, 'Postponed leap'.
[33] Kander and Stern, 'Economic growth'.
[34] Partly due to the colder climate, which meant that firewood was important.
[35] Rydén, 'Responses'.
[36] Schön, *Sweden's road to modernity*, pp. 206–10.

 

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 discussed above, it possessed neither the forests nor the rivers that 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, that is, 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, to which we turn 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,[37] 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 online appendix S1.

We rely on a combination of official statistics, secondary sources, and assumptions that 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.[38] We assumed that the Danish population was particularly well fed, with a consumption of about 3,000–3,100 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 are 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.

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

[37] See, for example, Kander, *Economic growth*; Rubio, 'Energía, economía y $CO_2$'; Malanima, *Energy consumption*; Gales, Kander, Malanima, and Rubio, 'North versus south'; Warde, *Energy consumption*; Henriques, *Energy consumption*; Kander et al., *Power*.

[38] See Kander and Warde, 'Energy availability'.

 

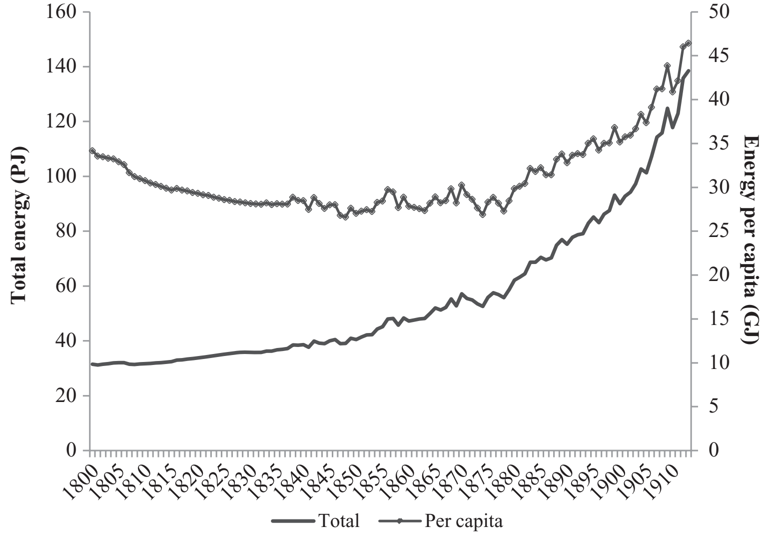


Figure 1. *Danish energy consumption, total (PJ) and per capita (GJ)*
*Notes:* 1 petajoule (PJ) = 1,015 joules, the international unit of energy. 1 gigajoule (GJ) = 109 joules.
*Source:* See online app. S1.

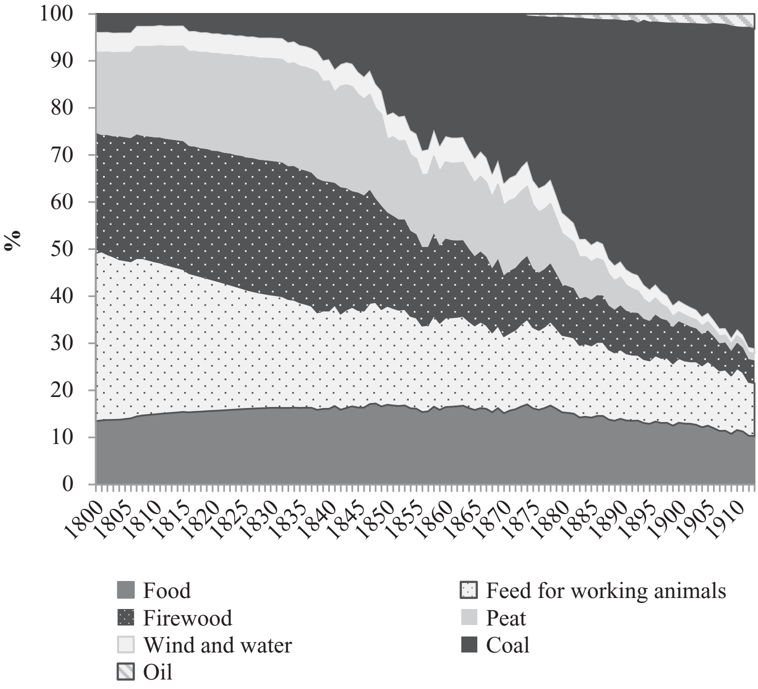


Figure 2. *Danish energy consumption by source (%)*
*Notes:* Primary electricity (hydro and wind power, and net imports) has been calculated but excluded from the graph, since it is insignificant.
*Source:* See online app. S1.

Danish economy during the nineteenth century. Primary energy[39] consumption rose from circa 30 PJ[40] in 1800 to 140 PJ in 1913, a more than fourfold increase. However, much of this growth seems at first sight simply to accommodate significant population growth. In per capita terms, Denmark's primary energy consumption actually declined from 34 GJ[41] 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 arable to dairy-based agriculture. Second, Denmark must have experienced some reduction in energy consumption at the 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.[42]

This fact does not hide completely the important shifts that were taking place. Around 1800, Denmark was still an organic economy, with its primary energy consumption being divided into firewood (26 per cent) and peat (17 per cent), mostly for household needs, and feed (36 per cent) and food (13 per cent) for muscle power. Coal consumption was still relatively insignificant (4 per cent), that is, at the level of wind and water (4 per cent). 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 became 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 clearly belongs more in the club of relatively coal-dependent and rich countries than among laggards such as Italy, Spain, Sweden, and Portugal, where coal failed to reach a 50 per cent share of consumption on the eve of the First World War.

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 was quickly substituted for wood and peat. Almost all the Danish towns of more than 3,000 inhabitants were covered by gas networks around 1870, although manufactured gas from coal made a late appearance in the country in the 1850s.[43] 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.[44]

Coal was thus an important energy source for Denmark. Another important source of energy for Danish agriculture was, however, feed, much of which was

[39] Energy found in nature that has not been converted, that is, raw fuels.
[40] 1 petajoule = $10^{15}$ joules, the international unit of energy.
[41] 1 gigajoule = $10^{9}$ joules.
[42] See Kunnas and Myllyntaus, 'Postponed leap'; Kander, *Economic growth*; Lindmark, 'Estimating'.
[43] Hyldtoft, *Den lysende gas*, pp. 224–8.
[44] Generaldirektoratet for Statsbanerne, *De Danske Statsbaner*; Møller, *Med korn og kul*.

 

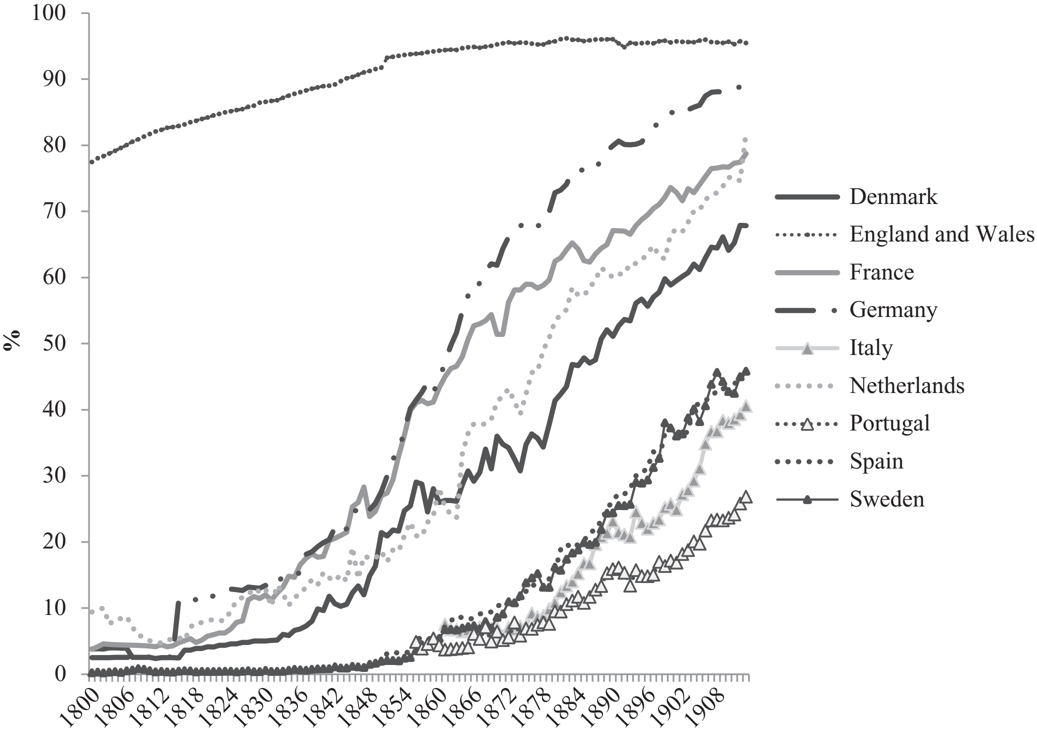


Figure 3. *Percentage of energy consumption from coal for selected countries, 1800–1913*
*Sources:* Henriques, *Energy consumption*, p. 90; Gales et al., 'North versus south', p. 224; Warde, *Energy consumption*; Kander et al., *Power*, pp. 131–58; and see online app. S1.

imported. As is standard in the energy history literature, the accounts presented above include the energy consumption of working (draught, that is, horses, oxen, mules, and donkeys) animals, but not that of other animals, such as milch cows. One reason for doing this 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. It can be argued, 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, such as forests.[45]

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

[45] 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.

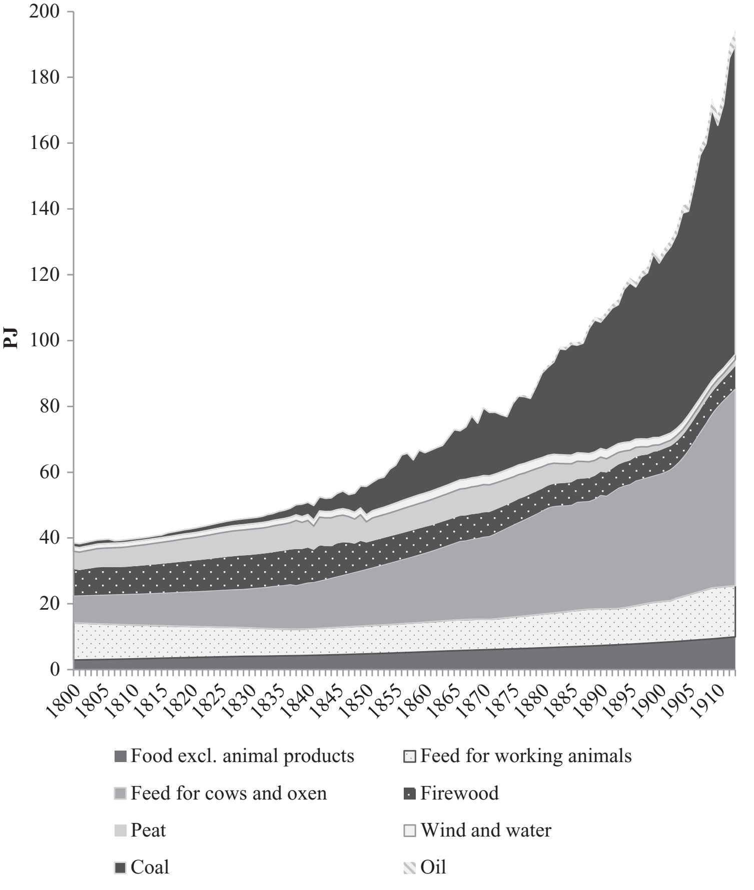


Figure 4. *Including feed in the energy accounts, 1800–1913, PJ*
*Note:* In order to avoid double counting, we reduce the total food consumption by 30%, in order to avoid including energy from meat and dairy products both under food and under feed for cows and oxen.
*Source:* See online app. S1.

increasing importance of feed in the energy system. Thus, in the same way that 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 'vegetable based' agriculture to 'meat based' agriculture will always have implications for a country's energy system. In the case of Denmark, the vast majority of agricultural produce was exported, and what fed the cows were feedstuffs, in particular concentrates.[46] 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),

[46] See Lampe and Sharp, 'Just add milk', for more on the importance of feeding.

partially drawing on methodologies proposed by socio-ecologists such as Krausmann and Haberl.[47]

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 complementary to the traditional story of Danish agriculture maintaining a free trade stance and enjoying cheap imports of grain to feed the animals.[48] The proportion of grain and concentrate imports in the total feed consumption of cows, oxen, and horses rose from 2 per cent in the 1880s to about 20 per cent in the 1910s.[49] Around 60 per cent of the growth in feed consumption during this period was met by imports.

Denmark was not of course unique in experiencing a change towards 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 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, 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),[50] and we add Portugal.[51] 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 for each country. From Mitchell, we obtain the number of cattle (oxen and cows) for 1880, 1900, and 1913.[52] Assuming that a cow consumes three-quarters of the energy of an ox,[53] we get the new totals for animal energy reported in table 1.

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 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

[47] Krausmann and Haberl's ('Process of industrialization') 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 their feed was composed of dairy products, that is, the waste products from producing butter. We differ from Krausmann and Haberl, as we do not include wood for construction purposes.

[48] Henriksen, 'Transformation'.

[49] Total obtained by converting the net imports of grain and concentrates from Henriksen and Ølgaard, *Danmarks Udenrigshandel*, pp. 74–5, into PJ and comparing them with the estimated feed for horses, oxen, and cows.

[50] Kander and Warde, 'Number, size and energy consumption', pp. 23–4; idem, 'Energy availability', pp. 23–6.

[51] Henriques, *Energy consumption*, pp. 144–5.

[52] Mitchell, *International historical statistics*, pp. 368–9, 371–2, 383–4, 386–7, 397, 399–400, 403.

[53] This proportion is in line with what is observed for Denmark for the period in question; Krausmann and Haberl, 'Process of industrialization', p. 189, also indicate similar values. Cows are reported to be smaller than oxen, but consume more feed per kg of body weight.

 

Table 1. *Estimated GJ animal energy per capita*

*Feed for draught animals in agriculture*

| | Denmark | England and Wales | France | Germany | Italy | Netherlands | Portugal | Spain | Sweden |
|---|---|---|---|---|---|---|---|---|---|
| 1880 | 5 | 2 | 3 | 3 | 2 | 2 | 3 | 5 | 5 |
| 1900 | 5 | 2 | 3 | 3 | 3 | 2 | 3 | 4 | 5 |
| 1913 | 5 | 1 | 2 | 3 | 3 | 2 | 3 | 4 | 5 |

*Feed for draught animals in agriculture, including non-working cattle*

| | Denmark | England and Wales | France | Germany | Italy | Netherlands | Portugal | Spain | Sweden |
|---|---|---|---|---|---|---|---|---|---|
| 1880 | 21 | 6 | 10 | 9 | 4 | 10 | 4 | 7 | 14 |
| 1900 | 21 | 6 | 11 | 10 | 4 | 9 | 3 | 6 | 15 |
| 1913 | 25 | 5 | 11 | 10 | 5 | 10 | 3 | 6 | 16 |

*Sources:* Own calculations based on the method by Kander and Warde, 'Number, size and energy consumption'; eisdem, 'Energy availability'. The data are taken from ibid.; Mitchell, *International historical statistics*, pp. 368–9, 371–2, 383–4, 386–7, 397, 399, 403; Barciela, Giráldez, Grupos de Estudos de História Rural, and López, 'Sector agrário y pesca', p. 316; Henriques, *Energy consumption*, pp. 144–5.

Table 2. *Total energy per capita in GJ*

*Excluding non-working cattle*

| | Denmark | England and Wales | France | Germany | Italy | Netherlands | Portugal | Spain | Sweden |
|---|---|---|---|---|---|---|---|---|---|
| 1880 | 30 | 142 | 35 | 43 | 18 | 40 | 19 | 19 | 39 |
| 1900 | 35 | 146 | 49 | 74 | 19 | 45 | 21 | 22 | 51 |
| 1913 | 46 | 162 | 60 | 97 | 24 | 63 | 23 | 25 | 64 |

*Including non-working cattle*

| | Denmark | England and Wales | France | Germany | Italy | Netherlands | Portugal | Spain | Sweden |
|---|---|---|---|---|---|---|---|---|---|
| 1880 | 44 | 145 | 41 | 48 | 18 | 47 | 19 | 20 | 47 |
| 1900 | 49 | 150 | 55 | 80 | 19 | 51 | 21 | 23 | 59 |
| 1913 | 65 | 165 | 67 | 102 | 24 | 70 | 23 | 28 | 75 |

*Note:* Food for humans was reduced by 30% to take into account the consumption of animal products.
*Sources:* Henriques, *Energy consumption*, p. 96; Gales et al., 'North versus south'; Kander and Warde, 'Number, size and energy consumption', p. 224; Kander et al., *Power*, pp. 131–58; and see online app. S1.

a similar path of agricultural development to Denmark, and otherwise made greater use of draught 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.

Excluding feed for 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 such as France, the Netherlands, and Sweden, and far less than the industrial powerhouses of the UK and (in the later years) Germany. Figure 3 demonstrates, however, that Denmark distinguished itself through a relatively large proportion of its energy coming from coal, a point we will address in greater detail in the next section. The inclusion of 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 its 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, it 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,[54] Denmark rapidly captured these markets for animal products, increasing its 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.[55] Historical rivals, such as Ireland and the Netherlands, were outcompeted both in terms of volumes and the prices received.[56]

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.[57] 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.[58] The duchy was, however, lost to Prussia in 1864. Separators based on this design were then launched by rival Danish and Swedish firms in 1878/9.[59] 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.[60]

[54] See the literature on the grain invasion from the US and other New World suppliers; for example, O'Rourke and Williamson, *Globalization and history*.
[55] Henriksen, 'Transformation', p. 156.
[56] Lampe and Sharp, 'Greasing'.
[57] Henriksen et al., 'Role of technology'.
[58] Lampe and Sharp, 'How the Danes discovered Britain'.
[59] Pedersen, *Teknologisk udvikling*, p. 51.
[60] van der Vleuten, 'Electrifying Denmark', p. 42.

 

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

| | *All factories* | | *Mechanized factories* | | | | |
|---|---|---|---|---|---|---|---|
| | *No.* | *Workers* | *% of total* | *Workers* | *Total HP* | *HP/worker* | *HP/worker (mechanized)* |
| Food, beverages, and tobacco, of which: | 11,301 | 30,517 | 41 | 19,660 | 19,151 | 0.6 | 1.0 |
| Creameries | 1,233 | 4,391 | 96 | 4,283 | 6,173 | 1.4 | 1.4 |
| Slaughterhouses | 3,180 | 3,351 | 2 | 1,086 | 1,173 | 0.4 | 1.1 |
| Textiles, of which: | 4,358 | 12,533 | 6 | 8,762 | 4,962 | 0.4 | 0.6 |
| Spinning mills | 111 | 636 | 98 | 635 | 807 | 1.3 | 1.3 |
| Weaving mills | 3,061 | 6,613 | 3 | 6,131 | 3,580 | 0.5 | 0.6 |
| Clothing | 23,557 | 28,291 | 0.2 | 2,369 | 293 | 0.0 | 0.1 |
| Construction, furniture | 19,781 | 42,389 | 1 | 4,957 | 3,294 | 0.1 | 0.7 |
| Wood | 4,896 | 8,119 | 12 | 4,659 | 3,722 | 0.5 | 0.8 |
| Leather | 227 | 1,227 | 31 | 857 | 310 | 0.3 | 0.4 |
| Non-metallic minerals | 1,757 | 13,700 | 17 | 9,872 | 5,833 | 0.4 | 0.6 |
| Metals | 9,383 | 27,302 | 5 | 16,402 | 4,665 | 0.2 | 0.3 |
| Chemicals | 602 | 4,061 | 29 | 2,992 | 1,497 | 0.4 | 0.5 |
| Paper | 82 | 2,057 | 45 | 1,721 | 1,690 | 0.8 | 1.0 |
| Others | 1,248 | 5,358 | 16 | 3,290 | 677 | 0.1 | 0.2 |
| **All** | 77,192 | 175,554 | 9 | 75,541 | 46,093 | 0.3 | 0.6 |

*Source:* Own elaboration from Statistics Denmark, 'Danmarks haandværk og industri', *Statistisk Tabelværk* VA,1.

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% |

*Sources:* Statistics Denmark, 'Danmarks haandværk og industri', *Statistisk Tabelværk*, VA,1; idem, *Statistisk Tabelværk*, VA,7; idem, *Statistisk Tabelværk*, VA,12.

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.[61] 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 1.4 in 1897, slightly higher than in the spinning mills, another largely mechanized industry.

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 HP was from steam, and this level was maintained more or less until the First World War.[62]

[61] 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.

[62] Hyldtoft and Johansen, *Teknologiske forandringer*, p. 135.

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.[63] Moreover, there was an increasing tendency to have more than one centrifuge per creamery.[64]

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, in 1897 there were 74 slaughterhouses and sausage factories with six or more employees with 1,383 workers using 805 HP, that is, just 0.58 HP/worker, increasing in 1914 to 113 slaughterhouses with 2,658 workers using 4,704 HP, that is, 1.77 HP/worker.[65]

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[66] 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.[67] 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[68] (see also below), as the consumption of coal is given in terms of its value, we find a volume ratio of coal to butter of 1.1 to 1, and a total consumption by the creameries of *c.* 110,000 metric tons, or 6 per cent of national coal consumption.

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, 12 of which recorded 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 12 for which we have the amount of coal used, the average was 1.8 kg of coal per kg of butter, with a minimum of 1.3 kg and a maximum of 2.5 kg.[69] To increase the size of the sample, we converted the values of coal into quantities for the remaining dairies assuming that the coal price was 25 per cent above the coal price in the gasworks in Copenhagen.[70] The mean is also 1.8 kg coal/butter,[71] suggesting that there were large improvements in the efficiency of production between the late 1880s and

[63] Hyldtoft, *Københavns industrialisering*, pp. 358–9.
[64] Statistics Denmark, 'Produktionsstatistik', pp. 49–50.
[65] Hyldtoft, *Københavns industrialisering*, p. 361.
[66] Bjørn, 'Dansk mejeribrug', p. 124.
[67] MDS, '*Danmarks Mejeri-Drifts-Statistik*' (1903). A digitalized version of this was kindly made available to us by Morten Hviid.
[68] Birk, *Kul til mejerierne*, pp. 8–9.
[69] 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 neighbouring dairies could register strong variations in coal consumption per butter; see Hertel, 'Mejeridriften', p. 501.
[70] Københavns Belysningsvæsen, *Københavns Gasværker*, p. 327. As we will demonstrate in section IV, this is a plausible assumption. Prices in the 12 creameries for which we have information vary from 5% to 25% of the Copenhagen gas price.
[71] The standard deviation is 0.8.

 

Table 5. *Energy in dairying, 1890–1913*

| | *1890–4* | *1900–4* | *1910–13* |
|---|---|---|---|
| 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 of milk per kg of butter | 27 | 26 | 25 |
| Tons of milk per cow | 2.0 | 2.3 | 2.8 |
| Butter cows, thousands | 924 | 1,100 | 1,016 |
| 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 (PJ) | 23.2 | 27.5 | 28.4 |
| in (%) of total energy* | 21% | 21% | 16% |

*Note:* * Total energy includes feed for oxen and cows.
*Sources:* Butter production is from Bjørn, 'Dansk mejeribrug', p. 124. Kg of coal per kg of butter: for 1890–4, own calculations (see text); for 1900–4, MDS, *Danmarks Mejeri-Drifts-Statistik* (1906), p. 248; for 1910–13, idem (1914). Kg of milk per kg of butter: for 1890–4, Henriksen et al., 'Role of technology', p. 483; for 1900–4, MDS, *Danmarks Mejeri-Drifts-Statistik* (1900); for 1910–13, idem, *Danmarks Mejeri-Drifts-Statistik* (1914). Metric tons of milk per cow comes from Wade, *Institutional determinants*, p. 323, using linear interpolation. Feed per cow as in online app. S1.

1903 (when the ratio was 1.1 as reported above).[72] Assuming that this coal/butter ratio is representative, we estimate that creameries represented 9 per cent of total coal consumption in a period when the proportion of HP in industry was probably at its highest.[73] 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.[74] Moreover, the creameries were totally dependent on this supply of coal.

Outside animal production, the rest of agriculture also became increasingly mechanized. In 1897, of 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.[75] 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,[76] 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 lies the contribution of feed, as discussed in the previous section, which was supplied to the cows that provided the milk for the creameries. Table 5 attempts a crude 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 obtain an estimate of the

[72] This is consistent with an increase in the efficiency of steam engines for the period 1880 to 1900 (see Ayres and Warr, *Economic growth engine*, p. 102), but could also indicate improvements in the organizational process.

[73] There were already 6,400 HP of steam installed in dairies and agricultural activities in 1890 compared with 7,100 HP in 1900, and the growth was probably slower than the rest of industry. See Christensen, *Det moderne projekt*, pp. 195–200.

[74] 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, *Kulforholdene*, p. 34); assuming roughly similar proportions for the industry in 1890–4 and 1900–4 would result in a 20% industrial share in 1890–4 and 15% in 1900–4, slightly above its HP share, which could be explained by a relatively higher use for heating.

[75] Statistics Denmark, 'Danmarks haandværk og industri', *Statistisk Tabelværk*, VA,1, p. 52.

[76] Statistics Denmark, 'Anvendelsen af landbrugsmaskiner', p. 21.

 

number of cows used in butter production. This, multiplied by the average quantity of feed consumed by a cow, gives us an estimate of the feed used in butter production.[77]

Clearly energy was an important factor for Denmark's leading sector, dairying, at around 16–21 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). Moreover, grain was available cheaply due to Denmark's commitment to free trade during the American grain invasion.[78] However, 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 its 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,[79] 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 that 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 as to what gave rise to the industrial revolution in England.[80] 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, its geography and openness nevertheless made access to coal relatively inexpensive. Second, Danish incomes were fairly high before the agricultural revolution, and rapidly increased during it.

[77] We only include the feed consumed by milch cows. Feed for oxen and cows which were not producing milk at the time is not accounted for, even though these animals were an indispensable part of the production process. We also do not take into account the energy embodied in the human labour that went into feeding the cows, collecting the milk, and producing the butter. Finally, it must be noted that butter production gives rise to some by-products, such as skim milk and buttermilk (which were used mainly for feeding pigs), so not all of the energy content of whole milk is incorporated in the final product, butter.

[78] Henriksen, 'Transformation'.

[79] See, for example, Fernández, 'Trust'.

[80] Allen, *British industrial revolution*.

Regarding geography, Denmark had few natural energy resources, and was largely deforested by the 1700s.[81] Denmark had peat, and a little coal on the island of Bornholm,[82] 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 two and three,[83] selling at about 8–11 silver grams per million BTU[84] in 1800, placing Copenhagen among the European cities with expensive firewood.[85] 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.[86] This price differential increased in the second half of the nineteenth century, with wood and peat costing three to four times more than coal.[87] 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, for 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.[88] This process continued as steamships made the connection more regular and Denmark's agricultural exports expanded in the 1870s and 1880s.[89]

An analysis of the coal prices faced by a major consumer (the gasworks in Copenhagen) is presented in figure 5. In the 1860s coal was sold at a price of 3.5–4.0 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.

Of course, with prices at this level, 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.

[81] Kjærgaard, *Danish revolution*, p. 18.

[82] Christensen, *Det moderne projekt*, pp. 182–92.

[83] Friis and Glamann, *History of prices*, pp. 315–18, 322–32.

[84] British Thermal Units (BTU), 1 BTU = 1.055 GJ.

[85] Our calculations from the price series of firewood (*favn*) and peat (*læs*) from Friis and Glamann, *History of prices*, pp. 315–18, 322–32. 1 peat (*læs*) = 500 kg = 5.25 GJ and 1 firewood *favn* = 2.2 $m^3$ = 17.2 GJ. Prices in Copenhagen were at the level of Amsterdam in 1800, another city with a fast transition to coal; Allen, *British industrial revolution*, p. 99.

[86] Comparison in GJ based on the prices of peat and firewood from Friis and Glamann, *History of prices*, pp. 613–17, and the prices of coal from Andersen and Pedersen, *History of prices*, pp. 640–2.

[87] Comparison based on the prices of peat for the years 1858–70 from Hansen, *Økonomisk vækst*, p. 310, and the coal prices at the gasworks from Københavns Belysningsvæsen, *Københavns Gasværker*, p. 326, for the same period.

[88] Møller, *Med korn og kul*, p. 66.

[89] Møller, Dethlefsen, and Johansen, *Sejl og damp*, p. 94.

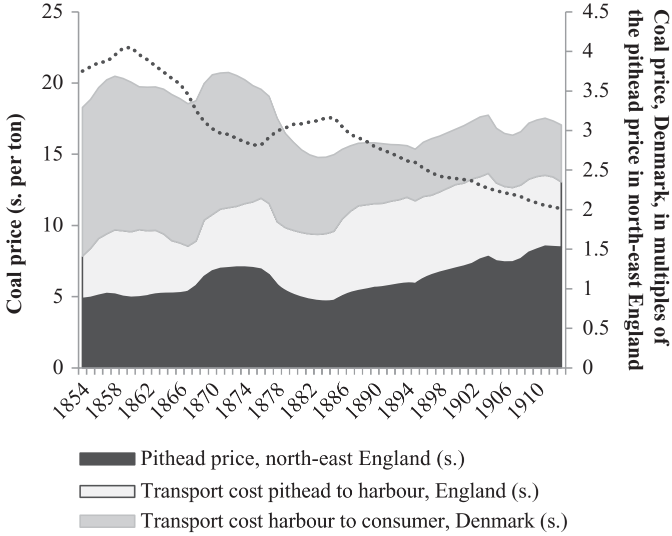


Figure 5. *Coal prices in Denmark, 1854–1913 (nine-year moving averages)*

*Sources:* Pithead prices calculated from Church, *History of the British coal industry*, pp. 58–9; Mitchell, *British historical statistics*, p. 248. Construction of the main components with the freight and price series comes from Københavns Belysningsvæsen, *Københavns Gasværker*, pp. 326–7, 331. For the early years they are constructed from Klovland, 'Repeat sailings index', pp. 34–7; HMSO, *Annual Statement* (1854–1913).

Table 6. *Coal prices at the pithead and ports in current shillings per ton, 1850–1900*

| | *UK 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 |
| 1870–2 | 6.5 | | | 29 | 19 | 28 | 23 |
| 1879–81 | 5.4 | | | 24 | 13 | 21 | 20 |
| 1884–6 | 5.1 | 5 | 9 | 21 | 13 | 18 | 17 |
| 1889–91 | 7.5 | 7 | 10 | 25 | 15 | 21 | 16 |
| 1899–1901 | 9.2 | 9 | 12 | 29 | 14 | 24 | 18 |

*Notes: a* For the 1860s (1865) the lower price refers to Cádiz and the higher price to Barcelona.

*Sources:* UK, Italian (from 1870), German, and French prices come from Bardini, 'Without coal', p. 636. Prices in the UK from the 1850s and 1860s come from Clark and Jacks, 'Coal', p. 44. For Italy in 1860, they are from ISTAT, *Sommario di statistiche storiche italiane*, p. 194. Spanish prices are from Martin and Sudrià, *El carbón en España*, pp. 474–82, and refer to an average of three coastal locations: Bilbao, Cádiz, and Barcelona. Portuguese import prices come from INE, *Comércio externo* (1850–1900). Danish cost, insurance, and freight (CIF) prices (from the 1870s) come from Henriksen and Ølgaard, *Danmarks udenrigshandel*, pp. 98–9; and for the period 1850s–60s the lower bound refers to an index of coal prices for the Copenhagen gasworks (Københavns Belysningsvæsen, *Københavns Gasværker*, pp. 326–7) which is connected with the CIF prices. The higher bound is constructed by adding the average of free on board (FOB) prices for Denmark reported in the British *Annual Statement* (1850–69) to the coal freights Tyne-Copenhagen from Klovland, 'Repeat sailings index', pp. 34–7.

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.

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 at 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 10 times the pithead price.[90] Large differences in coal prices were also apparent in Spain and Finland.[91] Even in countries endowed with coal, there was similar variation—in 1880 it was sold in London or landlocked parts of Germany at two to three times the domestic pithead prices.[92] 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.[93] He surveys coal prices faced by 34 creameries around the country in 1903. Apart from two outliers,[94] these vary between 16 kroner (kr) per 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. In 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.[95] The average price paid by creameries was 19 kr/ton, which is only 27 per cent above the gasworks 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 52 km (32 miles). Jevons mentions in his seminal book, *The coal question*, that about one-third (135) of the European ports involved in the coal trade with Britain were Danish.[96] The port in Copenhagen, supplemented by another large port in Esbjerg from 1874, together with local provincial harbours, meant that coal could be transported cheaply by sea to the whole country.[97]

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. The contribution of cheap coal to the viability of the cooperative production form is impossible to assess exactly. 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.), were then also distributed among the farmers.[98] Measuring the true prof-

[90] Henriques, *Energy transitions*, p. 149.
[91] Martin and Sudrià, *El carbón en España*, pp. 474–82; Kunnas and Myllyntaus, 'Postponed leap', p. 178.
[92] Kander et al., *Power*, p. 206.
[93] Birk, *Kul til mejerierne*, pp. 8–9.
[94] 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.
[95] Generaldirektoratet for Statsbanerne, *Beretning om driften*, pp. 178–9.
[96] Jevons, *Coal question*, p. 148.
[97] See Fransen, 'Varetransport', for a detailed account of the interplay between railroads and ports on the island of Funen.
[98] Henriksen, Lampe, and Sharp, 'Strange birth', p. 781.

 

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, 'First update'.

itability 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 around 25 per cent of expenses,[99] 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.[100]

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

Comparisons of national income per capita, however, mask the fact that real wages in agriculture in Denmark were extremely high, at least compared to its immediate neighbours and to other agricultural exporters in Europe. As Henriksen notes, our knowledge of agricultural wages for Denmark before the twentieth century is very limited.[101] 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 Germany and Sweden in particular emigrated to Denmark. Van Zanden 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.[102] Moreover, Denmark differentiated itself from other countries through having a high share of labour in its agricultural workforce compared to its productivity.

Contemporaries also noted Denmark's relatively high rural wages. Rainals, 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

[99] This is a quite high energy cost share, comparable to energy-intensive industries. See Balderston, 'Economics of abundance', for a discussion of the importance of coal in the low energy-intensive cotton sector.
[100] Jespersen, *History of Denmark*, p. 158.
[101] Henriksen, 'Transformation'.
[102] van Zanden, 'First green revolution'.

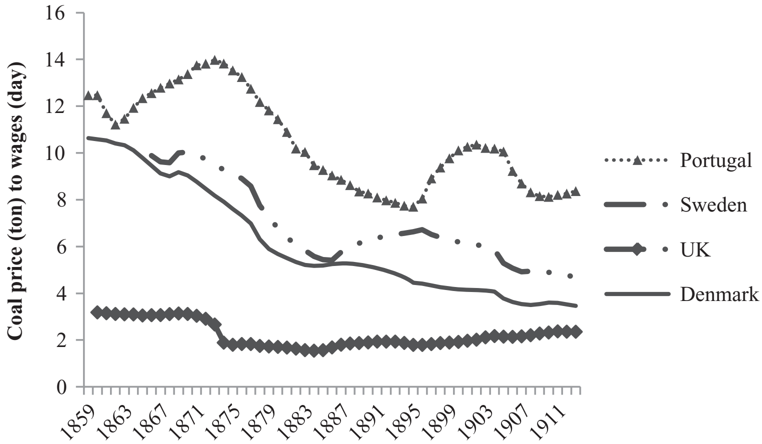


Figure 6. *Coal price (ton) ratio to wages (day) in Denmark, Portugal, Sweden, and the UK (nine-year moving averages)*

*Notes and sources:* Denmark: average male urban wages from Khaustova and Sharp, 'Note', for 1858–70; coal prices from Københavns Belysningsvæsen, *Københavns Gasværker*, pp. 326–7. Portugal: wages from Martins, 'Trabalho e condicões', pp. 533–5, simple average of 14 urban and industrial tasks; coal prices from INE, *Comércio externo* (1859–1913). For Sweden: average industrial wages from Prado, 'Nominal and real wages', pp. 510–11; coal prices from Ljungberg, *Priser*, p. 345, after 1890, and a revised coal series, 1866–89, based on railroad costs kindly provided by Astrid Kander. UK: builders' wage refers to south-eastern England and is taken from Clark, 'Condition of the working class', p. 1325. Pithead coal prices are taken from Williams et al., 'Digest'.

this class'. He also noted other features of the wealth of Danish agriculture, such as immigration from abroad, and the fact that oxen were not generally used for draught.[103]

Khaustova and Sharp have taken some of the available evidence on agricultural wages in Denmark,[104] and converted them to real wages using the methodology described by Allen.[105] 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 incomes from their land rents rather than from their labour.[106]

Finally, in the spirit again of Allen,[107] we illustrate in figure 6 the ratio of coal prices to wages for the UK (a coal-endowed country), and for Sweden, Denmark,

[103] Rainals, 'Report', pp. 290, 306.
[104] Khaustova and Sharp, 'Note'.
[105] Allen, 'Great divergence'.
[106] Interestingly, hand separators, that is, 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 southern Sweden. This also seems to provide striking support for the idea that labour-saving technologies were prioritized.
[107] Allen, *British industrial revolution*.

 

and Portugal (coal-poor countries). This ratio can be interpreted as an incentive to adopt steam technology.

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, one metric ton of coal was equivalent to the daily wages of three men in the late 1860s, while in Denmark, Sweden, and Portugal it was equivalent to between eight 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, one metric ton of coal was equivalent to the wages of three men in Denmark, but about five in Sweden, and eight in Portugal. The evolution of the coal/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 it would have to wait for the cheap oil prices after the Second World War before it could catch up with the European core.[108]

## V

The present work, through the compilation of new energy accounts and evidence from the micro level, reveals that Denmark's dependence on energy was relatively heavy during its period of economic catch-up. We find that Denmark seems to have enjoyed the combination of relatively expensive labour and, largely owing to its geography, relatively inexpensive coal, which could stimulate the sort of development process suggested by the work of 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, and would have 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 in comparison with other equally coal-poor countries. This both favoured an early transition to coal, and laid the road for subsequent development. One might also argue, however,

[108] Henriques, *Energy transitions*.

 

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.

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## Supporting information

Additional supporting information may be found in the online version of this article at the publisher's web-site:

**Appendix S1.** Danish primary energy, 1800–1913.