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ORIGINAL ARTICLE

Fuelling the English breakfast: hidden energy flows in the Anglo-Danish trade 1870–1913

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Abstract The 1870–1914 globalization period had profound impacts on the international division of labour, with coal-endowed countries specializing in the production of energy-intensive manufacturing goods and others in the production of agricultural goods. This study analyses the environmental consequences of this specialization, by quantifying the flows of energy and hidden energy embodied in the bilateral trade between the UK, the industrial workshop of the world, and Denmark, a coal-poor country with an agricultural economy. We show that the transformations that occurred in Danish agriculture to meet the growing demand for breakfast foods in the UK required significant quantities of feed and coal. Denmark was a net importer of energy throughout the period and a net importer of hidden energy in 1870. However, by the end of this wave of globalization, Denmark had become a significant net exporter of hidden energy to the UK. This was due both to an increase in its land productivity and to the import of coal, grain and fertilizers from abroad.

Keywords Denmark · UK · Embodied energy · Agriculture · Globalization · Nutrition transition

Introduction

China and other emerging economies are perceived today as the workshops of the world, manufacturing and exporting industrial energy-intensive goods to developed and service-based economies. Recent research shows that the hidden energy embodied in this international trade contributes to the trend of declining CO_2 emissions in post-industrialized economies (Peters and Hertwich 2008). There is reason to believe that in the late nineteenth and early twentieth century, trade had a similar effect in influencing the levels of energy consumption of trading partners.

The period before WWI has been compared with today's globalization in terms of the speed and scale of market, labour and capital integration (Bairoch and Kozul-Wright 1996). Between 1870 and 1913, exports increased from 4.6 to 7.9% of world GDP, aided by rapidly falling transportation costs, deepening the international division of labour and product specialization (World Trade Organization 2013). Differences in natural resource endowments remained a major factor in determining the paths of specialization taken by each country. This meant that the production of coal and coal-intensive manufactured goods was much more concentrated among a few countries than it is today. In 1870, the UK, Germany and the USA produced approximately 80% of the world's coal and three quarters of its pig iron and steel (Burnham and Hoskins 1943; Mitchell 2007). On the other hand, there was a massive inflow to industrializing European markets of hidden energy embodied in the products of the land, mostly grain but also meat, reflecting an improvement in diets (O'Rourke and Williamson 1999).

These developments meant that the environmental impacts of changes in the consumption of food and manufactured

The original version of this article was revised: An entry is missing from Table 6. Value 2.7 should be in row 2.1 (Feed (metabolizable)) under column (Eggs PJ)

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goods brought about by rising incomes were increasingly likely to be found outside the national borders of those countries where increasingly affluent consumers lived. For industrial regions specialized in energy-intensive manufactures, local air pollution due to fossil fuel combustion became a major concern. For agricultural regions, specialization in livestock production for exports impacts land use and its biodiversity, while animal wastes and excessive use of fertilizers can contribute to eutrophication and acidification of water and terrestrial systems (Smil 2013). But some of the impacts are truly global with both fossil fuel burning and livestock activities being major contributors to global warming.

Historical energy consumption, which usually takes in only energy carriers that are combusted or consumed within a country's borders, may therefore look very different if the energy embodied in international trade is taken into account. However, while there are many historical studies that investigate the energy that is consumed within the borders of a nation (Csereklyei et al. 2016; Gales et al. 2007; Henriques and Borowiecki 2017; Kander et al. 2013; Krausmann et al. 2008; Rubio et al. 2010), only some of them focus explicitly on physical trade flows (e.g. Gingrich 2011; Schandl and Schulz 2002) and even fewer (Kander 2002; Kander and Lindmark 2006) attempt to calculate historical energy or CO_2 emissions flows incorporated in trade. Without such calculations, the relationship between energy use, economic development and patterns of consumption is obscured.

This paper contributes to the debate on the environmental consequences of international specialization. To understand the role of trade on the environment, this paper investigates the amounts of energy and hidden energy in the bilateral trade between Denmark, an agricultural country, and the UK, an industrial country, from 1870 to 1913. This is made possible by the construction of novel historical embodied energy intensities, expressed in gigajoules per ton, on the flows of energy which were required to produce the most important products traded between the two countries.

There has been much research on the economic impacts of the globalization of c. 1870–1913 on the European periphery. It is generally agreed that the Nordic countries benefited from their trade-oriented policies, rapidly converging to the income levels of the core countries, while Iberia fell behind, arguably, at least in part, for the opposite reason (O'Rourke and Williamson 1997). Research on the ecological consequences of this globalizing trade is usually limited to the impact of the New World in the industrialization of Europe, more specifically Britain (Pomeranz 2000; Hornborg 2006), or demand for some particular products (e.g. Tully 2009). Pomeranz (2000) is perhaps the most cited example of this ecological approach. He argues that what made Britain different from China was not only the access to abundant domestic coal but also access to cheap land-intensive goods from the New World. By his calculations, in 1830, it would have required 25–30 million acres, or almost half the total land area of Britain, to produce substitutes for three of the country's most important imported products—sugar, cotton and timber. A similar approach has also been followed by others, who stress that in terms of physical quantities (tonnes), the South has been a recent net exporter of goods to the North, with a constant deterioration of the terms of trade (Pérez-Rincón 2006; Muradian and Martinez-Alier 2001; Muñoz et al. 2011; for broader surveys, Brolin 2006; Barbier 2005).

While many have focused their work on the emergence of relations of dependency between the global South and North, others have stressed the ecological impact of the Industrial Revolution. The explosive increase in coal and iron production and consumption can be expressed in terms of the hectares of forestland needed to support this transition (Kjærgaard 1994; Kander et al. 2013; Madureira 2012; Sieferle 2001; Wrigley 1988, 2010) leading to the obvious but powerful conclusion that Modern Economic Growth would not have come about without an energy transition from wood to coal. Just as the coal-using industrial leaders increasingly imported biomass that incorporated hidden energy, it was also the case that exports from coal-fired furnaces and factories would have contained substantial amounts of embodied energy conveyed to consumers abroad. This flow has never been seriously investigated. Kander et al. (2013) provisionally estimated that deducting the coal embodied in UK exports of cotton, wool and iron, would lead to a revision downwards of its coal use by around 12% in 1850. In conclusion, the review of the literature demonstrates that while some studies have touched on the ecological flows embodied in trade, the empirical data remains very limited and research has focused on only a narrow (though important) set of perspectives, such as relations between the North and South.

Denmark provides an interesting contrast with the UK because it is a country with virtually no fossil fuel reserves that developed through agriculture and rapidly reached high-income levels. Furthermore, it was an extremely open economy where trade was of the utmost importance. Danish exports were largely composed of agricultural goods, mostly butter and pork, which were sent to the industrial cities of the UK. In turn, Denmark imported most of its raw materials, including energy, iron and minerals, from Britain and Germany. In addition to these major imports of fossil fuels, one might plausibly expect that the energy hidden in energy-intensive imports from these countries also greatly outweighed any energy hidden in its agricultural exports. Such a conclusion would probably have the support of authors such as Kjærgaard (1994) who ignored these agricultural exports, considering only the coal embodied in iron imports and thus reaching the conclusion that Denmark's development was only possible due to the transition from wood to coal and iron. Specialization in this view would be a case of a coal-rich, energy-intensive country driving a developmental path towards low-energy-use agriculture, with massive net outflows of energy from Britain towards Denmark.

However, ignoring agricultural exports can be misleading. By drawing inspiration from the methods of social ecology (Haberl 2001), Henriques and Sharp (2016) have previously shown that Danish agriculture actually became highly energy-intensive during the period, needing vast amounts of feed for cows, as well as coal for its dairy sector. This work deepens this perception, by drawing on the combination of insights of social ecology and process analysis to develop a novel methodology which more fully accounts for the total amounts of feed and coal hidden in Danish agricultural exports. As it will be discussed in this paper, the relatively high-energy intensity of Danish agriculture, once all the inputs are properly accounted for, means the idea that coal-poor and agricultural countries are necessarily net hidden energy importers from the industrial core must be rejected.

We begin our study by introducing the different patterns of socio-economic and environmental transition in the UK and Denmark and the main trade flows taking place between the two economies. Next, in 'Methods and data', we explain the methods used to calculate energy flows embodied in the Anglo-Danish trade. The 'Results' section summarizes the results and shows that by 1913 Denmark had become a significant net exporter of hidden energy to the UK. The last section provides a discussion and conclusions.

Socio-economic and environmental transitions in the UK and Denmark: 1800–1913

Both the UK and Denmark were by 1913 economically successful countries, enjoying high levels of income, nutrition and human development, as seen in Table 1. Nevertheless, their processes of development and the associated environmental transitions differed.

The environmental transition associated with British economic development has been extensively discussed (Allen 2009; Schandl and Krausmann 2007; Schandl and Schulz 2002; Kander et al. 2013; Wrigley 1988, 2010, 2016). Improvements in agricultural productivity and a cheap domestic source of energy—coal—resulted in a pioneering process of rapid population

Table 1 The socio-economic and environmental transition in the UK and Denmark, some indicators (1800–1913)

	UK			Denmark		
	1800	1870	1913	1800	1870	1913
GDP p.c., constant $1990	2097	3190	4921	1274[b]	2003	3912
Share of agriculture in GDP (%)				55%[b]	49%	30%
Population (millions)	10.8	31.4	45	0.9	1.9	3
% of workers in agriculture	35	22	12	55[b]	48	42
% of workers in industry		42	44		22	24
Urbanization (%)	19	56 [a]	69	16	23 [a]	36
Coal production (Mt)	13	115	292	0	0	0
Output of pig iron (Mt)	0.6	6.1	10.4	0	0	0
Output of crude steel (Mt)	0	0.3	7.8	0	0	0
Coal consumption, GJ p.c.	34	86	124	1	11	31
Domestic energy consumption, GJ p.c.	68	122	148		44[d]	70
Food consumption, Kcal, p.c.	2614	2649	3099	3173[c]		3145
Meat consumption and dairy (%)	26%		35%	36%[c]		28%
Life expectancy		41	54		46	58
Human Development Index (UK 1913 = 100)		78	100		80	103

Sources: GDP and population: Maddison (2010); workers in agriculture and industry, 1870 and 1913: Broadberry et al. (2010); DK, 1820: Hansen (1984); UK, 1811: Mitchell (1988); coal, pig iron and crude steel output: Mitchell (1988, 2007); urbanization: Bairoch and Goertz (1986); domestic energy consumption, UK: Schandl and Krausmann (2007) and Krausmann et al. (2008); DK: Henriques and Sharp (2016) for food, fossil fuels, draught animals, wind and water. We added feed consumption for non-working animals (cattle, pigs, sheep and poultry) net of their food output to avoid double counting. Food consumption, % meat consumption and dairy: UK, 1800: Harris et al. (2015); UK, 1909–1913: US Department of Labor (1917); DK, 1800: Thestrup (1971); DK, 1914: SD (1949). Life expectancy and HDI from Leonard and Ljungberg (2010)

[a] 1880

[b] 1820

[c] Copenhagen

[d] 1876

growth, urbanization and a restructuring towards energy-intensive industrialization. By 1870, Britain produced about one quarter of world industrial output and accounted for around 40% of world manufactured exports (Magee 2004).

Until the mid-nineteenth century, English agriculture was largely able to meet the nutritional needs of its rapidly growing population, but from that date, the linkage between domestic land use and food provision broke down (Schandl and Krausmann 2007). This had already occurred in the provision of some raw materials, most famously in the cases of cotton and timber and other wood products; later in the century, wool would also be largely sourced from overseas. Continuous industrialization led to a rise in income levels and to a shift in the composition of the diet, from cheap and monotonous starchy foods to more expensive animal protein and fats—a process usually referred to as the nutrition transition (Grigg 1995; Otter 2012; Smil 2013). Falling costs of long-distance transportation facilitated by steamers and railways, the abolition of trade barriers (such as the repeal of the corn laws in 1846) and the possibility of mechanical refrigeration (from late 1870s) meant that food could be produced cheaply elsewhere and shipped to Britain. By 1913, almost 60% of the calorific needs of the British were provided by far-away lands such as New Zealand, Argentina and the USA but also by neighbouring agricultural economies such as Denmark and the Netherlands (Turner 2004).

Danish economic development is indissociably linked to this process of nutrition transition occurring in Britain and north-west Europe. Without iron ore, coal, forests or water power, Denmark's spectacular growth in the 1870–1913 period was based on specialization in a form of high-value added but also environmentally expensive animal-based export agriculture (Henriques and Sharp 2016). Table 2 briefly characterizes some major features of this transition in terms of land, energy use and food output. In the mid-1870s, Denmark had already a developed mixed agriculture, practicing a system of eight-field crop rotation, including grass crops—meadows and permanent pastures had become relatively unimportant. Although a significant share of the crop output (73%) was given to non-working animals (cattle, sheep, pigs and poultry), most of the farmer's profits were coming from the sale of cereals (Jensen 1937). In these 40 years, Denmark tripled the production of animal-based foods, responding to the changes in European diets. By 1913, Denmark had achieved a notably higher share of its value added in agriculture coming from livestock than any of its European neighbours (Federico 2005). Although already high by European standards in 1870, the country achieved very high rates of growth in both land and labour productivity up until the 1910s (van Zanden 1991; Federico 2005). By the latter date, the agricultural land/worker ratio was not far behind that found in both the industrialized UK and a distant settler society like New Zealand (Federico 2005).

Table 2 Modernization in Danish agriculture 1876–1913

	1876	1913
Livestock units (LU), 1000 units[a]	2003	3607
Horses, working animals (%)	16	14
Cattle (%)	57	52
Pigs (%)	9	23
Poultry (%)	4	9
Others (%)	14	2
Fertilizers (1000 t)	0.2	259
Fossil fuels (PJ)	–	4
Land use		
Agricultural area (million hectares)	2.7	2.8
Cereals (%)	41	41
Rootcrops (%)	2	13
Grass and hay crops, in rotation (%)	33	30
Fallow (%)	9	6
Meadows and permanent pastures (%)	14	11
Production and productivity measures		
Cereal yield (kg/ha)	1525	2006
Butter per cow (kg/cow)	49	117
Crop output (PJ)	45	93
Feed for non-working animals[b] (PJ)	33	80
Dairy, eggs and meat output[c] (PJ)	4	11
Efficiency conversion plant to animal food (%)	12	14

Sources: own construction from Jensen (1937), Lindhard (1926) and SD (1968, 1969)

[a] LU is based in feed requirements of a given animal in relation to a milch cow = 1 LU

[b] Excludes skim milk for pigs and calves which was 1.2 PJ in 1876 and 6 PJ in 1913

[c] Dairy includes only food due to human nutrition (butter, cheese, milk and skim milk to humans). If skim milk to feed was included in both numerator and denominator, efficiency raises from 15% in 1876 to 20% in 1913

The story of this transition is well documented (Henriksen 1993, 2009; Henriksen et al. 2011; Lampe and Sharp 2015). The first phase, until circa 1890, was characterized by the expansion of butter production. The quick diffusion of the steam cream separator, selective breeding, the stabling of cows in the winter, improvements in livestock nutrition and a new institution—the cooperative dairy—increased the supply and quality of butter per cow. In the 1890s, following a German ban of imports of live pigs, and making use of the relatively large quantities of skimmed milk obtained as a by-product of butter production to feed pigs, Denmark would also specialize in the production of a mild-cured type of bacon specifically destined for the British market. Finally, by the beginning of the 1900s, eggs began to be produced in large quantities for the external market. Denmark managed this transition without changing substantially the area under cultivation. The major difference in land use in 1913 relative to 1876 was the expansion of root crops for winter fodder at

Table 3 The Anglo-Danish trade 1870–1913, thousand pounds and percentages

	Danish exports to the UK			UK exports to Denmark			
		1870	1913			1870	1913
Total	1000 £	3053	23,831	Total	1000 £	1992	5792
Crops, grain (%)	%	47	1	Food	%	19	7
Live animals	%	5	0	Coal	%	15	38
Bacon, meat	%	12	39	Iron and machinery	%	15	12
Butter and fats	%	25	45	Textiles	%	34	18
Eggs	%	0	9	Non-metallic minerals	%	2	1
All other products	%	10	5	All other articles	%	16	25

Source: HMSO (1871a, 1914)

the expense of meadows, grass crops and fallow and the intensification of feeding animals with grain. The trebling of animal food output required two and a half times more feed than in 1876. This increased demand was mostly covered by changes in the productivity of crops, which doubled, following the more intensive application of fertilizers, manure and machinery. Still, Danish land was not sufficient. Nutrition for livestock for dairy and meat production now took about 86% of the crop output of the country, and the remaining 14% was not enough to feed both draught animals and the Danish population. Thus, the shift to an animal-based agriculture required imports of concentrates and grain from abroad. From 1876 to 1913, Denmark energy consumption (including feed for non-working animals) rose from 44 to 70 GJ per capita. Agriculture accounted for around 50% of these figures, and with a share of 30% of Danish GDP, this made it the most energy-intensive sector of Danish economy (calculated from data in Tables 1 and 2).

As is shown in Table 3, the structure of the Anglo-Danish trade is intrinsically connected with the story of the development of the two countries.

In 1870, Denmark had a large trade surplus with Britain, with its exports consisting mostly of agricultural products, of which around 50% was grain. However, significant changes would occur in the composition of exports during the following years, reflecting a high-technology agricultural specialization towards animal products. The Full English Breakfast originated in the 1840s and became popular in the following decades (O'Connor 2013). By the 1890s, bacon, butter and eggs were consumed at any time of day (Burnett 1966). Denmark captured the market for the growing share of this type of breakfast foods, supplying the UK with 45% of its butter, 39% of the bacon and 9% of the eggs by 1913 (Nüchel and Thomas 1966). At that time, Danish exports were four times larger in terms of value than its imports from the UK.

The importance of this trade was thus paramount for Denmark, since the UK was the final destination of about two-thirds of Denmark's agricultural exports in the period immediately before WWI. By contrast, the UK accounted for a smaller share of Danish imports, around 27% in 1870 and 18% in 1913, coming in second place after Germany as a trading partner (Henriksen and Ølgaard 1960). Trade with Britain was of critical importance however, as it was the source of all the coal and a major proportion of the iron and steel consumed in Denmark. The structure of UK exports to Denmark was dominated by coal, iron and steel products, machinery and textiles. Coal would become increasingly dominant up until 1913, reflecting Denmark's development in export sectors such as cement, dairying and shipping.

Methods and data

In order to quantify the flows of energy and hidden energy embodied in the Anglo-Danish trade, we use trade data in physical volumes (tonnes). The total amount of energy embodied in the Anglo-Danish trade is then divided into two main components. The first component—that we simply call Energy—is obtained by multiplying the tonnage of traded energy goods—food and fuels—by the appropriate heat content, measured in gigajoules.[1] This gives us the energy consumed directly in the importing country.

The second component—that we call Hidden Energy—refers to the sum of the primary energy inputs, coal, oil, firewood, primary electricity and feed[2] (for both working animals and non-working animals), which was used in the process of producing the traded good. In accounting for hidden energy requirements, we include both direct energy requirements—fuel and feed directly used in the final production stage of that good—and indirect energy requirements, energy consumed during the extraction and production of the raw materials and intermediary inputs into the traded final good. Traded energy goods also have hidden energy. For primary energy carriers, such as coal, hidden energy includes the coal used

[1] For fuels, this is their lower heating value, while for food and animal feed, this is their metabolizable calorific value.

[2] Feed for draught animals is the feed necessary to keep them alive during the year, even during non-working periods.

to mine the coal. In the case of final energy goods (such as coke, electricity or livestock products), hidden energy requirements refer to the transformation losses that occur in the process of the conversion from primary energy of coal into coke or electricity or of feed into eggs, bacon or butter.[3] This is to avoid double counting with the energy content of the traded final energy carrier, which already accounts for the result of this conversion. The sum of the two components—energy and hidden energy—is defined as energy embodied in trade.

Our method of accounting hidden energy in trade is thus a kind of process analysis (Bullard et al. 1978) which sets relatively strict boundaries around the production process. We do not account for energy embodied in the machinery used in production of the traded good, or energy used in transporting the raw materials or final products, as it would be done in full life cycle analysis approaches.[4] Including physical capital and transport would create very great measurement and boundary problems given the data available (one would have to know rates of capital depreciation for particular manufacturing processes, for example). Of course, to some degree, transport of goods each way between Britain and Denmark will be cancelled out, although by no means entirely because of the complexity of shipping routes and the different characteristics of cargoes. Due to the proximity of the two countries, the overall impact of transport would also be small. Although we measure the energy content of traded food, we do not consider human labour as an energy input to the system. This is one of many possible approaches (Fluck 1992), chosen due to its simplicity and negligible impact on the results. We provide an expanded discussion on methodological issues in the Supplementary Material. Our main contribution is to apply process analysis to historical data and explicitly account for the role of feed as an input to livestock products.

To calculate the hidden energy in trade, we construct an intensity indicator which measures how much energy (in GJ) was required to produce a tonne of the final traded good. This is done for two benchmark dates, ca. 1870 and 1913. This requires establishing the main stages of production, the energy and non-energy inputs at each stage, and weighting those inputs according to simple input–output recipes. For example, if the production of 1 t of paper requires the input of 1.6 t of coal and 0.8 t of pulp, the hidden energy intensity of paper is equal to the sum of the embodied energy (energy + hidden energy) of 1 t coal multiplied by 1.6 and the hidden energy of 1 t of pulp multiplied by 0.8.

The values used to calculate hidden energy must be drawn from a multiplicity of sources. For the UK manufacturing, the most important sources are the Royal Commission on Coal of 1871 (HMSO 1871b) and Census of Production of 1907 (HMSO 1913). For Denmark, we use production, agricultural statistics and sectoral reports (SD 1916a, b, 1917, 1968, 1969), along with a few foreign sources for the most important inputs to Danish agriculture (i.e. US Bureau of Census 1917; OCE 1914). A full explanation of the method, sources and how values have been calculated for each significant product is provided in the Electronic supplementary material.

Figure 1 illustrates the system boundaries and steps in accounting for embodied energy in agricultural products. The first step to calculate the hidden energy in agricultural products is to collect information on energy used in the fields, i.e. feed for draught animals, fossil fuels or energy embodied in artificial fertilizers. It is not possible to trace exactly how these were allocated to individual crops (of which there would often be several within one farm), so the sum of agricultural energy inputs into cultivation was allocated to crop outputs according to the cropped area (excluding grass and hay, even if in crop rotation[5]). Data on the yield per hectare could then be used to attribute energy inputs per unit of each kind of product. This is of course a simplification which is done due to the lack of more detailed information on draught animal and fertilizer requirements per area of different crops.

The second step is to calculate energy inputs into livestock products. These can firstly draw on the energy inputs into crops and oil cakes in combination with national estimates of the crops used as feed (SD 1968, 1969; Lindhard 1926).[6] The feed is then allocated to different types of animals on the basis of Standardized Livestock Units (see Table 2), while the composition of their nutrition was derived from a literature review on actual feeding practices (Winkel 1881; Bøggild 1901). Taken together, this allowed us to calculate the feed input by type of livestock and the energy embodied in that feed. These values were then distributed to the individual livestock products (i.e. meat and milk for cows; poultry and eggs for chicken) using the proportion of gigajoules that each product took up in total food production. Energy embodied in butter was allocated on the basis of the milk input/butter output ratio, also deducing from these figures the energy content of the important by-product skim milk which was used for fattening pigs.[7] Finally, we included coal use in slaughterhouses and dairies.

[3] The term hidden energy requirement is slightly different from the term total energy requirements used in other studies (Aguilera et al. 2015) since the second includes for example all coal used in the production of electricity (both the energy to be transformed into the electricity and that which is lost generating it).

[4] See Aguilera et al. (2015) for a historical estimation of energy embodied in transport and machinery for agricultural inputs.

[5] Under the assumption that grass did not require a significant amount of animal labour and fertilization, even if grass in rotation benefited from the last.

[6] Feed crops were reported in million fodder units. One Scandinavian fodder unit (SFU) is a measure of metabolized energy which equals to approximately 12.5 MJ.

[7] In the process of separating cream from milk for 1 kg of butter, about 26 l of skim milk was produced. While an important share of the gigajoules of the output, skim milk had a negligible economic value. Due to this, the energy content of skim milk is allocated to pork nutrition, but the hidden energy of skim milk is allocated to the butter, the principal product.

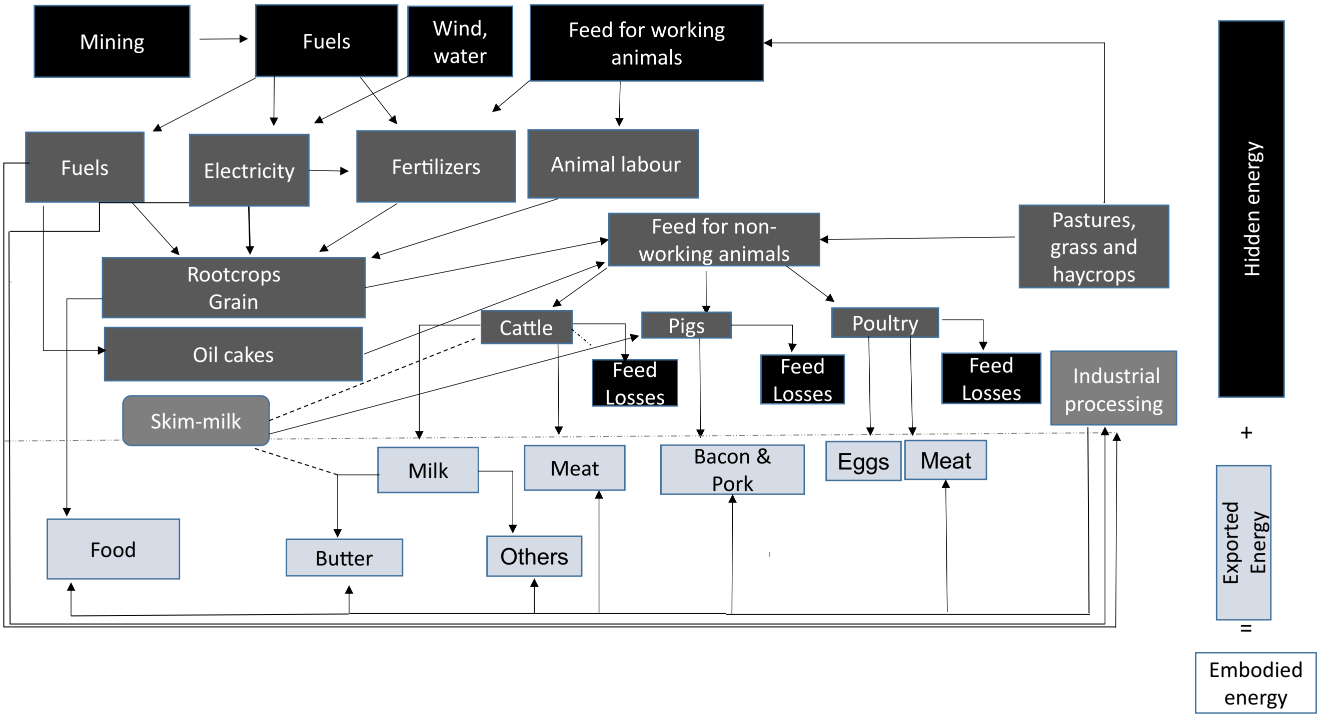

Fig. 1 System boundaries in accounting for embodied energy in Danish agriculture export products. Note: *black boxes* = hidden energy, *light-gray boxes* = exported energy. Feed losses (hidden energy) correspond to the transformation losses that occur in the process of the conversion from primary energy of feed into eggs, meat and dairy (exported energy)

Figure 2 shows some of the embodied energy intensities (energy + hidden energy) in gigajoules per ton for the different products traded between Denmark and the UK.

Among the most important export products from the UK, salt, sugar and coal are less energy-intensive products with coefficients varying between 15 and 30 GJ/t, while cotton and woollen are the most energy-intensive products (200–300 GJ/t). The energy intensities for the different types of iron and steel vary quite substantially, depending on the phase of production (66–177 GJ/t). We can see however that livestock products exported from Denmark are some of the most energy-intensive of our sample of products, with coefficients varying between 115 GJ/t for pork in 1870 to about 500 GJ/t for butter in 1870s. Finally, we show the importance of energy efficiency gains between 1870 and 1913 for many of the industrial products but also for butter production, the latter being associated with increasing milk yields per cow.

Results

Table 4 reports the energy embodied in the trade of the two countries in 1870. At this date, the balance of energy and hidden energy in Anglo-Danish trade exhibits the

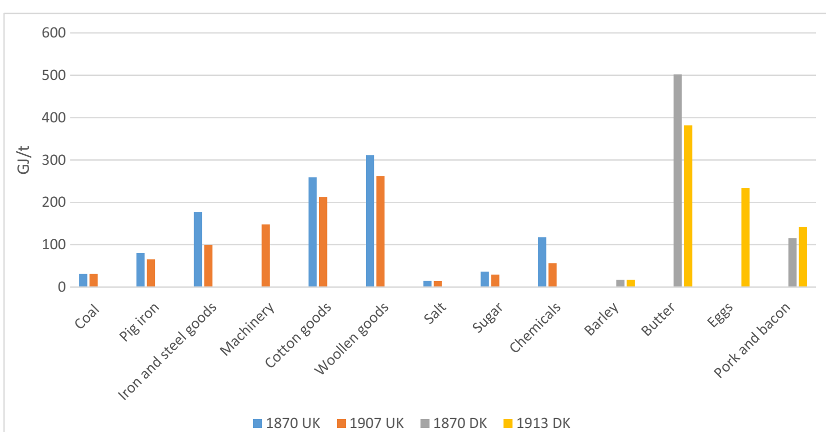

Fig. 2 Embodied energy intensities of the most important traded products (GJ/t). Source: own construction from sources listed in 'Methods and data' section and Electronic Supplementary Material

Table 4 Energy Flows embodied in the Anglo-Danish trade, 1870, petajoules (PJ)

	Quantities	Energy (1)	Hidden energy			Total hidden (2)	Total (1 + 2)
			Feed to food	Feed to draught	Coal		
	t	PJ	PJ	PJ	PJ	PJ	
UK exports to Denmark							
Coal	715,810	21			1.3	1.3	22
Iron and steel	39,848				7.1	7.1	7.1
Chemicals	4799				0.7	0.7	0.7
Cottons	1678			0.1	0.3	0.4	0.4
Others					0.6	0.6	0.6
Total		21		0.1	10	10	31
Denmark exports to UK							
Butter	6453	0.2	2.5	0.5		3	3.2
Cereals and flours	162,399	1.9	0	0.8		0.8	2.7
Bacon and pork	4781	0.1	0.3	0.1		0.5	0.6
Others	1597	0	0.1	0		0.1	0.1
Total		2.2	2.9	1.5	0	4.4	6.7
Net imports Denmark		19	−2.9	−1.4	10	6	24

expected pattern. The industrialized country, the UK, exported significant amounts of coal (31 PJ). One third of this coal was embodied in industrial products (10 PJ), especially iron and steel (7 PJ). Denmark had a clearly negative trade balance in both energy and hidden energy, with net imports of total primary energy exceeding 24 PJ. Denmark exported only land-based energy to the UK, either in its revealed or in its hidden form (6.7 PJ). Kjærgaard's (1994) argument that Denmark managed to grow on the basis of imported coal and iron seems correct.

By 1913, we see however significant changes in the pattern of energy flows incorporated in trade, shown in Table 5. Firstly, the flows of embodied energy were much larger. In the case of exports from the UK to Denmark, this is primarily because of the increased flow of coal, but with Danish exports to the UK, the expansion came

Table 5 Energy flows embodied in the Anglo-Danish trade, 1913, petajoules (PJ)

	Quantities	Energy (1)	Hidden energy			Total hidden (2)	Total (1 + 2)
			Feed to food	Feed to draught	Coal[a]		
	t	PJ	PJ	PJ	PJ	PJ	PJ
UK exports to Denmark							
Coal	3,316,000	97			6.5	6.5	104
Iron and steel	75,045				7.6	7.6	7.6
Textiles	3394			0.1	0.7	0.8	0.8
Food	77,167	0.5		0.1	0.5	0.7	1.2
Others					1	1	1
Total		98		0.2	16	17	114
Denmark exports to UK							
Butter	86,707	2.9	22	2	6	30	33
Bacon and pork	129,327	2.2	11	4.1	1.5	16	18
Eggs	26,022	0.2	3.8	1.8	0.3	5.9	6.1
Others		0.6	0.4	0.2	1.2	1.7	2.3
Total		5.8	37	8.1	9	54	60
Net imports DK		92	-37	−8	8	-37	54

[a] Includes other fuels in small proportion

largely from a 12-fold increase in the hidden energy contained in agricultural exports. The energy intensity of exports increased in both cases, as Danish exports rose in value by a factor of 7.8 between 1870 and 1913, as opposed to a factor of 9 in embodied energy, while UK exports rose by a factor of 2.9 in value but 3 in embodied energy.

Secondly, in terms of total embodied energy flows, Denmark continued to present a negative trade balance, with net imports increasing from 24 PJ in 1870 to 54 PJ in 1913. This is to be expected, since as a coal-poor country Denmark imported 93% of its coal consumption from the UK.

The most interesting result is the hidden energy component of the total energy in trade. By 1913, the hidden energy in Danish exports (54 PJ) had become three times larger than that in UK exports (17 PJ). Denmark also moved from a situation in 1870 where hidden energy made up around two-thirds of embodied energy exports to one in 1913 where it accounted for 90% of a much larger total. UK exports moved in the opposite direction, with the hidden share becoming smaller, falling to 15%, from 32%. British exports to Denmark were increasingly dominated by coal, but we can also note that while iron and steel exports almost doubled in weight terms, in absolute terms, the hidden energy in them did not change—an indication that in this sector, the figures were affected by very significant improvements in efficiency. Although Denmark was an exporter of hidden energy, it remained a net importer of hidden coal (8 PJ) from the UK.

The major change in the net balance of hidden energy was a result of Danish exports of processed food. In 1913, Denmark exported about 290,000 t of food products to the UK, 83% of which was butter, bacon and pork or eggs, representing more than 95% of its exports in value. A conventional energy analysis which did not take the hidden flows of energy into account would only register the final energy content of the food exports as an output in the Danish energy balance and as input in the UK's energy balance. This value of 5.8 PJ represents a mere 2–3% of total food consumption in the UK but about 40% of Danish food production, showing that a large share of the Danish food surplus was directed to the English market. But what this simple analysis misses is the very large amount of hidden energy that went into these exports. Besides the 5.8 PJ of food already accounted for, the Danes used an additional 53 PJ of hidden energy resources: 70% as feed for livestock raising (cows, chickens and pigs), 15% as feed for draught animal labour and 15% as coal. This means that 85% (51 PJ) of the energy that was incorporated in Danish exports to the UK was biomass, a land-based energy form. In 1913, the energy content of agricultural production was 93 PJ (as in Table 2), which means that if all resources had been Danish, 55% of Danish crop output (including pastures) would have been used to feed the UK. In contrast with feed, the amount of coal re-exported to the UK is modest (9 PJ) by comparison with the total coal consumption of the country (94 PJ, as in Henriques and Sharp 2016)[8] but a significant proportion of its industrial and agricultural coal consumption (40 PJ, as in Statens Kulfordelingsudval 1921). Finally, in a similar way, we can also compare the energy hidden in Denmark exports with total Danish energy consumption (circa 210 PJ, as derived from Table 1). This represents about 26% of domestic energy consumption, if feed for non-working animals is included in the calculations—a significant amount. If energy was defined more narrowly (excluding feed for non-working animals), then the energy embodied in trade would represent only 12% of Danish primary energy consumption. Historical energy balances that exclude the biological conversion from feed to food (Kander et al. 2013; Henriques and Borowiecki 2017) would be unable to capture the importance of the energy resources associated with the Danish trade to the UK.

How did Denmark manage to have such a huge proportion of its energy consumption locked in the English Trade? The above analysis ignores one important aspect of Danish transformation to an export-orientated and animal-based agriculture. A significant part of the energy embodied in Danish exports to the UK came from elsewhere, showing a globalization of the intermediate inputs necessary to its food exports.

To overcome the limitation of a bilateral analysis, Table 6 shows a decomposition of the energy embodied in the three main products exported to the UK in 1913—butter, bacon and eggs—into the different domestic and foreign raw materials required for its production, indicating main places of origin and place of use. To provide the British with the English breakfast, Denmark imported coal from the UK, grain and oil cakes to feed the animals from Germany, Russia and the USA and fertilizers from Chile and Norway, among others. Of the 58 PJ of energy embodied in these three products, only two-thirds (mostly feed) had an origin in Denmark. In addition, a small percentage of the embodied energy (10%) had not even crossed the borders into the country but was already hidden energy in imports to Denmark. This relates to the energy which was necessary to produce the foreign fertilizers, as well as the animal labour and fossil fuels needed to grow the foreign feed. It was the beginning of a

[8] Coal imports from the UK are 97 PJ (Table 5), more than 94 PJ of Danish coal consumption. The reason for this is that a proportion of the coal imports are re-exported afterwards as bunkers to ships engaged in foreign trade.

Table 6 Decomposition of energy embodied in Danish Exports to UK of butter, pork and bacon and eggs, 1913, petajoules (PJ)

	Origin	Place of use	Butter PJ	Pork and bacon PJ	Eggs PJ	Total PJ
1. Coal to industrial processing						
Mining the coal	UK	UK	0.2	0.0	0.0	0.2
Cream separation	UK	DK	2.6	0.0	0.0	2.6
Slaughterhouses	UK	DK	0.0	0.8	0.0	0.8
2. Domestic feed						
2.1. Feed (metabolizable)	DK	DK	20.0	10.1	2.7	32.8
2.2. Hidden energy in feed						
Animal labour	DK	DK	1.8	2.8	1.2	5.9
Fossil fuels (field, oil cakes)	Uk	DK	0.3	0.1	0.0	0.5
Mining the coal	UK	UK	0.0	0.0	0.0	0.0
Domestic fertilizers						
a. Coal to fertilizers	UK	DK	0.1	0.1	0.0	0.2
b. Mining the coal	UK	UK	0.0	0.0	0.0	0.0
Foreign fertilizers	NO, CL					
a. Coal, hydro-power	CL, UK, NO		0.2	0.3	0.1	0.6
3. Foreign feed						
3.1. Feed (metabolizable)	USA, RU, DE	DK	5.0	2.7	1.3	9.0
3.2. Hidden energy in feed						
Animal labour	USA, RU, DE	USA, RU, DE	0.2	1.2	0.6	2.0
Fossil fuels	unknown	USA, RU, DE	2.7	0.2	0.0	2.8
Energy to fertilizers	unknown	USA, RU, DE	0.0	0.1	0.1	0.2
Total			**33.1**	**18.4**	**6.1**	**57.6**
By origin						
Denmark			21.9	12.9	3.9	38.7
UK			3.2	1.0	0.1	4.3
Others			8.1	4.4	2.1	14.6
% embodied energy from Denmark			66%	70%	64%	67%
% embodied energy used in Denmark			90%	91%	87%	90%

Sources: own construction from sources listed in text. Trade partners taken from SD (1968); 1969)

DK Denmark, *RU* Russia, *DE* Germany, *NO* Norway, *CL* Chile

process of de-linking agriculture from domestic land that would only be intensified in the following decades (Schroll 1994; Kristensen et al. 2015).

Discussion and conclusions

In this paper, we analysed the impact of international specialization on resource use by quantifying the energy flows hidden in the Anglo-Danish trade through the construction of time-specific embodied energy intensities for the main traded products. Our main conclusion was that from 1870 to 1913, the process of nutritional transition occurring in Britain impacted energy use in a significant way in Denmark, such that the energy hidden on Danish agricultural exports to Britain came to outweigh the energy hidden in British coal-intensive manufacture exports to Denmark.

Many have argued that specialization could lead to a displacement of the environmental load of supplying raw materials and food towards peripheries and locking them into sectors with relatively low long-term potential for gains in productivity (Pérez-Rincón 2006; Muradian and Martinez-Alier 2001). Denmark was able to achieve high rates of productivity growth by adopting an energy-intensive agriculture founded on specialization for the British market. Yet the process of 'fuelling the English breakfast' in Britain required increasing quantities of domestic land devoted to feed crops. This may make Denmark seem something of a paradox, specializing in agriculture, yet simultaneously escaping the land constraints of the 'organic economy' that Wrigley (1988) argued was a primary characteristic of the Industrial Revolution. Denmark's growth remained heavily dependent on the land yet was able to maintain one of Europe's highest land/man ratio at around 3 ha per agricultural worker. Indeed, its relative factor endowment was almost entirely unchanged over this period (van Zanden 1991).

In his influential essay on the 'First Green Revolution', van Zanden (1991) identified two types of technologies used by north-western European countries to increase agriculture productivity. Labour-saving technologies, used when labour was scarce, included agriculture machinery and steam technology. Henriques and Sharp (2016) found much evidence for this development in Denmark, by showing that a combination of high wages and cheap coal (due to a favourable geography) induced the adoption of coal-based labour-saving technology, such as cream separators and threshers. Land-saving technologies, used when land was scarce, included purchase of fertilizers and the use of concentrate feeds. Van Zanden (1991) asserted that the importance of these land-saving innovations explained most of the gains in land productivity in Belgium, Denmark, Germany and the Netherlands. However, he could not fully explain Denmark's leading productivity performance when its increasing use of artificial fertilizers was in fact comparatively modest (van Zanden 1991).

This work allowed for a comparison of the demand for land and labour-saving technologies in an embodied energy perspective. The energy inputs to labour-saving (coal for cream separation and slaughterhouses, fuels used in field) were relatively small compared to the energy inputs into land-saving (imported feed, fertilizers). Support for van Zanden (1991) assertion can be found in tracing the Denmark's energy system and accounting for imports of feed and inputs into the feed for non-working animals. Denmark's position in an international trading network counteracted the fact that despite the enormous productivity changes, by 1913, the demand for animal feed already exhausted the capacity of domestic agriculture. Success rested upon a growing quantity of fertilizers, grain and oil cakes which had to be imported from abroad, globalizing the impact of this transition and meaning that agricultural success (and concomitantly, environmental impact) cannot be seen in purely national terms. In addition, specialization in livestock products and imports of feed also increased the quantities of manure available for soil fertilization. These developments overcame the problem of land scarcity in an agricultural economy and permitted a continued low price of land relative to labour. Denmark's position as having a high ratio of land to labour in 1870 (van Zanden 1991) was not eroded despite intensification.

Denmark is the pioneering example of intensive animal husbandry, preceding by decades the land use change and energy transition that would occur in other western agricultures, a phenomenon that is only beginning in China and India. Of course, Denmark is by no means representative of agricultural economies exporting to industrial nations, with its relative proximity and traditions allowing an early specialization in high-value dairy products and meat. However, rather than an outlier, it must be seen as part of a broad spectrum of importers to Britain encompassing nations as diverse as Barbados, Canada, New Zealand or Uruguay, each deserving of further empirical research. We see how the relations between a protein (and especially meat-rich) diet of high-income industrialized countries and large-scale environmental impact were established even before the tractorization and intensive use of chemicals that developed from the interwar years and especially in the second half of the twentieth century. And even in the period of globalization from 1870, the role of trade and energy in development cannot be understood only in terms of bilateral links but in the context of multilateral interactions that developed a new and complex geography of trade. The industrialization of Danish agriculture was a very energy-intensive process that was dependent on the use of vast amounts of land for feed—both in Denmark and elsewhere.

The results in this paper by no means diminish the role of coal as an explanation for agricultural growth—they complement it instead. By freeing domestic land that would have otherwise been retained to grow firewood for the heating needs of a growing population, coal imports from the UK were an additional way of providing relief to the problem of land scarcity in an agricultural economy. The powerful argument that the transition to coal is a necessary condition to modern economic growth (Wrigley 1988) remains as strong as ever.

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