Henriques, Sofia Teives; Sharp, Paul; Tsoukli, Xanthi; Vedel, Christian

Adaptability, diversification, and energy shocks : A firm level productivity analysis

Primary publication

Henriques, Sofia Teives; Sharp, Paul; Tsoukli, Xanthi; u. a. (2024): Adaptability, diversification, and energy shocks: A firm level productivity analysis, in: Energy Economics, Amsterdam [u.a.]: Elsevier Science, vol. 139, no. 107887, pp. 1–22, doi: 10.1016/j.eneco.2024.107887

Energy Economics 139 (2024) 107887

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Adaptability, diversification, and energy shocks: A firm level productivity analysis

Sofia Teives Henriques [a,b], Paul Sharp [c,d,e,*], Xanthi Tsoukli [f], Christian Vedel [c]

[a] University of Porto, School of Economics and Management, CefUP, Portugal
[b] Department of Economic History, Lund University, Sweden
[c] University of Southern Denmark, Denmark
[d] CAGE, UK
[e] CEPR, UK
[f] University of Bamberg, Germany

ARTICLE INFO

JEL:
N54
O13
Q40

Keywords:
Coal
Dairying
Denmark
Energy
Geography
Peat
Productivity

ABSTRACT

Energy economists have long argued that energy systems need to be adaptable in the face of shocks. In the early twentieth century, Denmark embodied the opposite, with its industry almost entirely dependent on imports of coal from the UK. Towards the end of the First World War, however, and well into the 1920s, coal imports became expensive and more difficult to obtain. Local diversification was possible, however, through peat. We exploit detailed microlevel data from butter factories, covering the period 1900–28. Employing an event study approach, we find significant productivity advantages for firms closer to available peat fields in the wake of the coal shortage, and that these gains persisted even when peat was no longer used. Our results thus suggest that public policy might aim to support adaptability for firms less able to transition to more sustainable energy if that is the price of longer-term efficiency and survival.

1. Introduction

> "On no one quality, on no one process, on no one route and on no one field must we be dependent. Safety and certainty in oil lie in variety and variety alone."
> - Sir Winston Churchill in 1913 (quoted by Yergin, 1991, p.160)

What is the role of energy, energy diversification, and energy security for growth, both at the firm- and the macroeconomic levels? This question is more pressing than ever. Since the fall of 2021, consumers and businesses in Europe have been threatened by gas shortages due to supply stoppages, with associated shocks to the prices of natural gas and electricity. The crisis is not limited to Europe, with the International Energy Agency describing the situation in 2022 as the "first global energy crisis" and a "reminder of the fragility and unsustainability of our current energy system." (IEA, 2022) It is of course easy to motivate the study of history through the lessons it might have for today, but such episodes are rare, and those with the appropriate setting and data to examine the aforementioned questions even rarer. In fact, the world of the 1920s is eerily similar to that of the 2020s: one of pandemic, war, and industrial action, combined with an energy crisis involving price shocks of similar magnitudes to recent years. The former is the setting for the present work, and we appeal specifically to the Danish case to illustrate the impact at the firm level of energy shortages, and how these can be offset, in the short run at least, through the opportunity to diversify – even to inferior energy carriers.

Europe has a pressing need to ensure a short-run supply of affordable energy sources to avoid hits to economic growth and the bankruptcy of businesses. Despite the European Union's ambitious goals to decarbonize its energy system by 2050, short term expediency has meant that inferior energy sources have increasingly been called upon, with Germany and other European countries returning to coal.[1] In this

* Corresponding author at: Department of Economics, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark.
E-mail address: pauls@sam.sdu.dk (P. Sharp).

[1] "Germany is firing up old coal plants, sparking fears climate goals will go up in smoke", *Washington Post*, August 1, 2022.

https://doi.org/10.1016/j.eneco.2024.107887
Received 1 May 2024; Received in revised form 18 August 2024; Accepted 31 August 2024
Available online 3 September 2024

environment, today's Denmark is seen as something of a paragon, as made clear by the President of the European Commission, Dr. Ursula von der Leyen, in her annual State of the European Union address on September 14, 2022.[2] Thus, in the 2021 World Energy Trilemma Index published by the World Energy Council (WEC), Denmark was given an AAAa grade and ranks third in the world (after Sweden and Switzerland), based on measures of energy equity, environmental sustainability, and energy security. The latter includes an assessment of the ability to withstand and respond to system shocks. It was Churchill who first introduced the concept of energy diversification to ensure energy security. He did so on the eve of the First World War, in order to justify powering the Royal Navy by imported oil rather than inferior domestic coal as a preventive measure to avoid a German invasion. This was prescient, since some years later, in the midst of the war, and faced with rising coal prices, coal-importing countries and firms around Europe had few options available as British or German coal became increasingly inaccessible. Some countries responded, like the Denmark of the 1970s, by leapfrogging to clean energy sources of superior quality, such as hydropower (Henriques and Sharp, 2021). Despite remaining neutral, Denmark, however, found itself in an unenviable position as the war progressed.

The Danish case is uniquely positioned for testing the importance of energy diversification for industry for three reasons. First, Denmark was unusual at the time for having become almost exclusively dependent on imports of coal from the UK during its rapid industrialization in the last decades of the nineteenth century. Moreover, before it began exploiting North Sea oil in the 1970s, Denmark had practically no domestic energy resources, beyond local supplies of lignite and peat – it had for example neither the fast-running water nor the abundant forests of its Nordic neighbors. British coal went to fuel both Danish private and industrial uses, with a large share going to the hundreds of butter factories, or creameries, that had established themselves in every corner of the little kingdom from the 1880s, making it the largest butter exporter in the world. Ships brought in coal from the UK, and returned to Britain laden with Danish food products. When coal supply constraints started making themselves felt towards the end of the First World War, and well into the 1920s, Danish industry, including the butter factories, began to suffer. The forests had mostly been felled for shipbuilding over centuries of war with Sweden, and despite modest attempts to revive them in the nineteenth century (Kjærgaard, 1994) fuelwood remained a minor component of Danish energy consumption.[3] The main domestic alternative, peat, a traditional carrier of inferior potential,[4] was available in only limited amounts, and very locally.

The second unique characteristic of this case is that the vast majority of the butter factories were cooperatively owned by the farmers who supplied the milk. This meant that the ability to diversify energy supplies depended on whether or not peat could be sourced locally from the fields of the farmers. Finally, we have available, and have collected, uniquely detailed firm-level data for 590 creameries from 1900 to 1928, covering the period before the energy crisis and some years after, but stopping before the onset of the Great Depression. We thus have an opportunity to study the importance of energy diversification on the firm level, and within a single institutional framework.

Although they were locked into coal-dependent production technologies, we demonstrate that the creameries were able to adapt quickly to the new conditions, in part through the exploitation of local supplies of peat. Factories located closer to it were especially favored during a period which nevertheless was extremely difficult for the industry and saw massive falls in production. We employ an event study strategy, finding that creameries closer to freshwater deposits – a soil type associated with peat formation formed during the Holocene – were more productive in the wake of coal shortages (although of course less productive than they had been prior to the crisis). Using this measure, we avoid potentially endogenous reasons for why some creameries might switch to peat, for example better management, and thus exploit random variation in peat as a natural experiment for the benefits of being able to adapt. To measure efficiency, we use a contemporary measure, the milk/butter ratio, or the amount of milk it took to produce a unit of butter (the lower, the "better"). Interestingly, this advantage was maintained even after coal supplies resumed, and we provide estimates of the substantial economic significance of this in terms of the value of the butter produced. Finally, we present evidence consistent with this being due to some firms exiting the market (those further from peat are more likely to stop reporting data), with the creameries closer to peat receiving milk from greater numbers of suppliers / shareholders. It seems that they were then able to invest more than their rivals which had less easy access to peat (or were at least better positioned to replace depreciating capital), which we capture through the number of machines they operated for separating cream from milk, an important component of butter production.

We thus contribute to contemporary debates by demonstrating how a leading industry, composed of many small firms which were highly dependent on an imported fossil fuel, and how a small country, also highly dependent on coal, from practically only one foreign source, and with only "inferior" alternative fuel sources, coped in the face of an exogenous price shock and energy restrictions. We show that while the switch to peat did not avoid an energy and economic crisis for the industry, it allowed businesses that were able to switch to peat to avoid going bust. This also serves to emphasize that, since the availability of alternatives matters, it might pay to have a larger stock of reserves in place. Our finding that businesses closer to peat sources saw longer term advantages is also interesting, given that peat was only a short-run solution, and the industry returned to (cheaper and higher-quality) coal as soon as the restrictions ended. Thus, short-term diversification in times of crisis can lead to relatively favorable outcomes later.

We can hypothesize that the reason for the long-term advantage was that relatively higher profitability and relatively less uncertainty regarding energy prices meant that "peat users" invested more in their capital stock. This would be consistent with the work of Yoon and Ratti (2011) who find that uncertainty regarding energy prices reduced the response of firms to investment resulting from growth in sales. We know from historical accounts that the machinery used by the factories, the automatic cream separator (a centrifuge) depended at the time on a certain minimum efficient scale of production. This became more of an issue for creameries further from peat, which were more likely to exit the market, releasing their owners, the farmers, to deliver to creameries closer to peat. They thus retained production capacity, avoided breaks in production, maintained productivity, and were able to invest more – we find that they were more likely to operate more than one centrifuge – guaranteeing their superiority beyond the energy crisis. This suggests that today's firms, when presented with rising energy bills, should consider alternative energy sources for their operation to improve their chances of long-term economic survival, even if this means only a short-run solution to reduce energy costs. In fact, this has indeed already

[2] *"Half a century ago, in the 1970s, the world faced another fossil fuel crisis. … Only a few visionaries understood that the real problem was fossil fuels themselves, not just their price. Among them were our Danish friends. When the oil crisis hit, Denmark started to invest heavily into harnessing the power of the wind. They laid the foundations for its global leadership in the sector and created tens of thousands of new jobs. This is the way to go! Not just a quick fix, but a change of paradigm, a leap into the future."* https://ec.europa.eu/commission/presscorner/detail/ov/SPEECH_22_5493 [retrieved 2022-09-19]. See Johansen (2021) for more on the history of wind power in Denmark.

[3] By the early twentieth century, the area covered by forests had recovered to about 6 to 7 % of Denmark's total land area, up from a low of approximately 4 % during the first half of the nineteenth century (Thaarup, 1819; Bergsøe, 1847; Warming, 1913). Before the First World War, fuelwood and muscle work combined accounted for about 7 to 8 % of primary energy use (Henriques and Sharp, 2016).

[4] I.e. less dense, and also more polluting, although the latter was not understood properly or indeed of concern for contemporaries.

happened in the Danish dairy industry a century later. Peder Tuborgh, CEO of Arla, the giant Danish-Swedish cooperative which succeeded the hundreds of creameries we study here, admitted that they were switching back to oil for some milk processing operations "as a short-term measure" in response to "the threat of gas supplies being unavailable to us at some stages during the coming winter months".[5]

The remainder of this paper is as follows. The following section presents a review of the relevant literature. Section 3 provides the historical background, Section 4 presents our data, and Section 5 our empirical strategy. Section 6 gives our results, and finally, Section 7 concludes.

2. Literature review

In an influential article, Walker et al. (2004) argued that three related attributes of social-ecological systems are important for how they develop: resilience, adaptability, and transformability. Blum and Legey (2012) took this to the concept of energy security, noting the importance of energy as a key-resource to economic development, and that it must be "sufficient, affordable and environmentally sustainable." Energy economists have noted the importance of diversification in energy baskets (Stirling, 2010), and that this can be associated with economic growth by promoting technological change and reducing susceptibility to uncertainty shocks (Gozgor and Paramati, 2022). However, it has also been noted that large energy producers such as Germany and the UK tended to have higher levels of concentration in their energy mixes, and while small energy producers (often coal-poor countries) had lower levels, by the turn of the twentieth century, most had transitioned to coal (see e.g. Rubio Varas and Muñoz Delgado, 2019). Such dependence on one energy source, typically coal at early stages of industrialization, meant that they became locked into coal-dependent means of production with obvious implications for energy security. This led to severe shortfalls when supplies were limited, such as during the First World War and the 1920s. At this point swift diversification to alternative sources became necessary, and countries, such as Switzerland, which rapidly diversified to hydropower, saw both short- and long-run gains (Brey, 2021). Nevertheless, from the perspective of economic history, it has long been argued that the availability of coal was crucial for the process of industrialization in the nineteenth century (see for example Cipolla, 1962; Wrigley, 1988, 2010; Pomeranz, 2000; Allen, 2009; Fernihough and O'Rourke, 2020), and cheap coal is considered to have played a role for the timing of industrialization with coal-rich countries and regions industrializing earlier than others (Kander et al., 2017).

Blum and Legey (2012) note that energy security "represents the guarantee that individuals and firms in an economy are able to benefit from the welfare that energy can create" (see also Bohi and Toman, 1996; IEA, 2007; Ang et al., 2015; Gasser, 2020). While the classic definition from the IEA was "uninterrupted availability of energy sources at an affordable price" in the aftermath of the 1970s oil crises, more recent definitions reflect more general concerns. For example, the European Union's definition is "uninterrupted physical availability of energy products on the market at a price that is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development (European Commission, 2000). Thus, the concept can mean different things depending on the priorities of policymakers (Yergin, 2006; Tol, 2023).

Following Walker et al. (2004), Blum and Legey (2012) explain that guaranteeing energy security requires the economy to demonstrate: resilience, so that temporary and permanent energy related effects can be handled; adaptability, i.e. preparedness to respond to sudden energy related changes, and transformability, so that it can evolve towards a more secure energy configuration.[6] Much work on modern times highlights the role of the government for ensuring this, see for example Lo (2011) on Indonesia, Japan, Korea and Taiwan during recent decades of rapid economic growth, and Vögele et al. (2018) on the phasing out of coal-fired power plants in Germany. The present work contributes through the historical example of a country and industry which was heavily dependent on imported energy, but needed to adapt quickly in the face of unprecedented challenges to supply. As we will discuss below, the government played a role, but individual firms also demonstrated adaptability.

Although there are many papers investigating the impact of price shocks and energy security on macroeconomic aggregates of countries (see e.g. (Le and Nguyen, 2019), there is little empirical evidence at the firm level. The present work thus makes an important contribution by estimating the effect of price shocks and unavailability of energy to businesses on the one hand, and the impact of diversifying to alternative energy sources during an exogenous shock on the other. The work of Yoon and Ratti (2011) is closest to ours. They investigate the effect of price shocks on investment in 2600 US manufacturing firms over the period 1971 to 2006, finding that energy price uncertainty reduces the investment of firms in response to sales growth. Rentschler et al. (2019), study the impact of electricity outages on costs using microlevel data for 143,000 firms, finding that firms in developing countries lose $82 billion per year and firms incur significant costs in secondary equipment ($64 billion). Similarly, Fisher-Vanden et al. (2015) consider the impact of power shortages for 23,000 energy intensive Chinese firms between 1999 and 2004. They find that Chinese firms re-optimized among inputs to production by substituting materials for energy (both electric and non-electric sources)—a shift from "make" to "buy" of intermediate inputs to production. While such outsourcing was costly, these firms were able to avoid substantial productivity losses by doing so. The impact of energy shortages in India was considered by Allcott et al. (2016) and Pakistan by Xu et al. (2022). Finally, Stucki (2019), analyses the relationship between firm energy costs and the productivity effects of investment in green technologies with firm level data from Austria, Germany, and the US. These are found to be significantly positive for companies with higher energy costs.

3. Historical background

Denmark spent centuries looking for coal, but to no avail (Ranestad and Sharp, 2021). British coal (traded for agricultural produce) nevertheless played an important role for Denmark's agricultural transformation and development through the dairy industry from the late nineteenth century (Henriques and Sharp, 2016), where the largely cooperatively owned creameries spread rapidly around the country from 1882 using the steam-powered automatic cream separator, a centrifuge, which by more efficiently extracting cream from milk (an important and previously time and labor-intensive step in butter production) greatly increased the scale and quality of production (see e.g. Lampe and Sharp, 2018). Although Denmark had effectively no domestic coal deposits, cheap imports were available across the whole country due to her particular geography, with nowhere far from one of the 135 ports (one third of the European total) involved in the coal trade, with the creameries accounting for around 10 % of Denmark's total industrial consumption of energy for steam power (Henriques and Sharp, 2016). With the onset of war in 1914, however, Denmark's favorable access to British coal was threatened, and ultimately creameries were forced to exploit other sources of fuel. This is illustrated in Fig. 1, which demonstrates both the heavy reliance of the Danish economy on coal before the Second World War, and its use of domestic peat supplies during the period of coal shortages, although coal was the major energy source

[5] "Arla Foods to unveil new 'green' milk-pricing system", *Agriland*, August 31, 2022.

[6] See also Bhattacharya et al. (2016) for a survey of the mixed results regarding the relationship between renewable energy use and growth.

throughout. For the sake of comparison, energy consumption is converted into petajoules (PJ), a measure of energy.

Never had the energy system in Europe been more secure than on the eve of the Great War, following a century of productivity gains in steam technology. And yet, the new geography of energy resources, where 81 % of world coal production (1321 million tons, including lignite) and 94 % of world coal exports (155 million, including bunker but excluding secondary coal products) was concentrated in just three countries, the US, the UK and Germany, meant that for most countries in the world access to cheap energy came with the trade-off of increasing external dependence.[7] Table 1 gives an overview of the extent of coal dependence for nine coal-importing countries in Europe, where we list first the neutral countries during the First World War, and then the allies. Coal consumption varied from 50 to 60 % of total primary energy consumption in Sweden, Spain and Italy, to 70–80 % in Norway and Switzerland, and to about 90 % in Denmark, France and the Netherlands. It was the second energy carrier after fuelwood only in slowly industrializing Portugal.

The second important point to take from Table 1 is that importing countries had different levels of external dependence. France was one of the most coal-based economies, but also the least dependent on foreign energy sources since domestic mines were able to provide for about two thirds of its coal consumption. The reliance on foreign sources of energy was the greatest in Denmark, representing 92 % of all energy and 100 % of coal, followed by the Netherlands (with 79 % of all energy and 82 % of coal), where domestic coal extraction had recently started to develop on a larger scale (Hölgens, 2019). Third, countries differed in where they sourced their coal from. The supplier concentration index in Table 1, based on the Herfindahl-Hirschman index, measures how diversified coal imports were in terms of supply sources, a key factor of energy security today. Denmark's level of concentration was high, although lower than that for Portugal or Norway, since most of its coal imports came from Britain. Some other countries like France, the Netherlands or Switzerland had a more diversified structure of coal suppliers, relying on both German, UK and Belgian coal (Fremdling, 1995).

In short, the challenges facing coal production and trade during the First World War meant that shipping became dangerous and expensive, and countries jealously safeguarded access to a resource which was crucial for the war effort. But this did not end with the Armistice in 1918 for three principal reasons. First, the outbreak of the so-called Spanish flu in 1918 had some direct impact on production of coal, as well as other less direct effects as we discuss briefly below. Second, difficult labor relations followed the war, and miners' strikes had a large impact

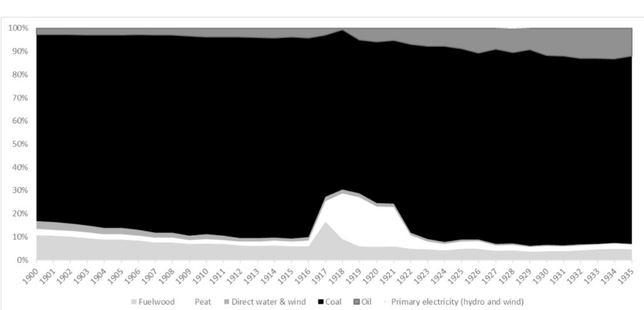

Fig. 1. Primary Energy Consumption in Denmark, 1900–1935 (% of total petajoules).
(Source: Normann (1959))

Table 1
Coal dependence in selected European countries in 1913.

	Energy[a] consumption pc.	Coal share in energy consumption	Coal imports in total coal consumption	Coal supplier concentration Index HHI
	GJ	%	%	(0 < HHI ≤ 1)
Denmark	36	88	100	0.87
Netherlands	55	94	82	0.62
Norway	49	70	100	0.96
Spain	22	53	50	0.81
Sweden	56	52	94	0.93
Switzerland	28	78	100	0.66
France	52	91	32	0.44
Italy	15	64	98	0.76
Portugal	17	37	99	0.98

Source: Energy consumption: DK: Henriques and Sharp (2016) NO: Statistisk Sentralbyrå (1955), p.24. Portugal:(Henriques, 2011), ES: Rubio (2005) and Iriarte-Goñi and Infante-Amate (2019). CH: (Historische Statistik der Schweiz, 2012). All others, see Kander et al. (2013). Share of coal imports in total coal consumption: own construction from above sources and Imperial Mineral Resources Bureau (1921, 1922), ES: Coll and Sudrià (1987), FR: Barjot (1991), Central Bureau of Statistics Netherlands (2022). Coal supplier concentration index: own construction, using a Herfindhal-Hirschman index, which is equal to the sum of the squares of each country of origin share in imports, $\sum si^2$: DK: (Statistics Denmark, 1959); PT: Miranda (1987), NO: Norges officielle Statistik (1914), Imperial Mineral Resources Bureau (1921, 1922).
Note: (a) Includes coal and brown coal, peat, oil, fuelwood, and primary electricity.

on supply (Podobnik, 2006). Finally, trade policy became more restrictive in the 1920s. Fig. 2 illustrates the impact on coal imports and prices from the Danish perspective, although this does not tell the whole story. Both imports and prices were regulated at times, and there was considerable uncertainty of supply over and beyond the observable fluctuations, making alternative sources such as peat attractive.

As we discuss more in Appendix A, the declines in production illustrated in Fig. 3 owed much to the events of the First World War and the 1920s, and, as we demonstrate below, to a consequential decline in the productivity of Danish creameries, in part due to shortages of coal.

4. Data

To understand the impact of coal shortages and uncertainty on the Danish creameries, as well as the importance of peat as an available fuel source, we take data from the aforementioned MDS, for which we refer to Sharp et al. (2023) for a full discussion of all the variables in the database, which we hand-collected from the original sources. For the present purposes, we use the milk/butter ratio, i.e. the kilograms of milk required for 1 kg of butter, which was a standard measure of efficiency at the time (the lower the better). It is important to note that the butterfat content of milk is not determined by the feed given to the cow, and by this time Danish farmers were almost exclusively using the Danish Red breed (Lampe and Sharp, 2015, 2018), so any differences in productivity cannot be attributed to differences in feeding and/or nutrition. Previous studies (Henriksen et al., 2011) have demonstrated that efficiency was mostly determined by the technology employed and to a lesser extent the way in which production was organized, although all creameries in our sample were cooperatives with similar cream separators. But what is important for the present work, is that the centrifuge required a certain minimum level of input to function effectively (see also Henriksen et al., 2011), so any stoppages in production, for example due to fuel shortages, would have a negative impact.

We also take from MDS whether the creamery used peat, coal or other sources of fuel, principally firewood, as the reference category. Another important characteristic of the creamery is the number of shareholders (the farmers who both owned and supplied the cooperative), which indicates the size of the creamery and might also be

[7] Imperial Mineral Resources Bureau (1921), *The Mineral Industry of The British Empire and Foreign Countries. War Period: Coal, Coke and Biproducts (1913–1919)*, part 1.

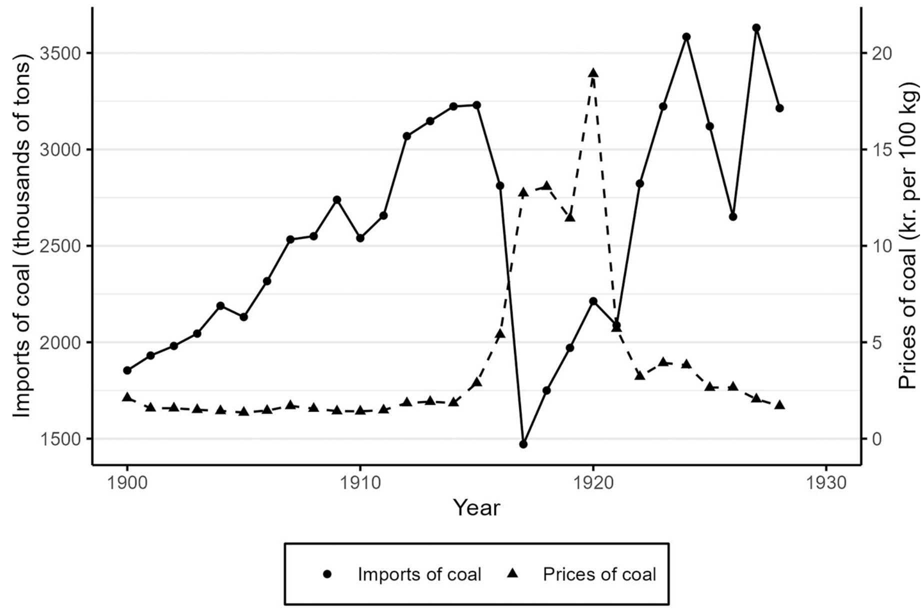

Fig. 2. Coal Imports and Prices in Denmark, 1900–1928.
Note: The axis for imports starts at 1500 kt in order to make the two series more comparable.
(Source: (Normann, 1959))

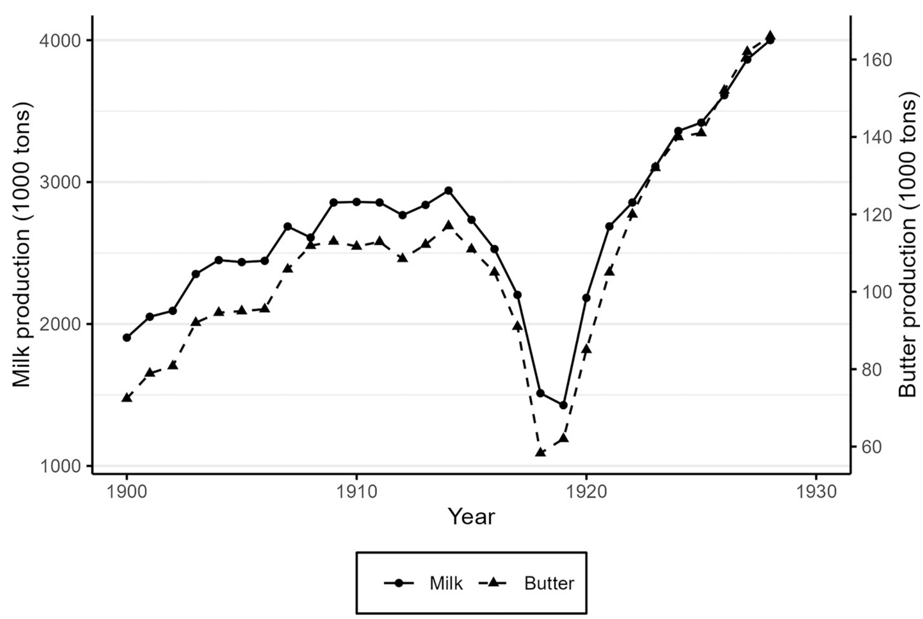

Fig. 3. Danish Milk and Butter Production, 1900–1928.
Note: The axis for milk production starts at 1000 kt and for butter at 60 kt in order to make the two series more easily comparable and the fluctuations more visible.
(Source of data: Johansen (1985))

important for productivity if for example there are economies of scale at the level of the creamery. We take the location of the creameries from Ellbrecht (1915–18), who provides the postal address of all creameries for the years 1915–18. We have converted this to geographical co-ordinates manually. The main explanatory variable is based on the distance to potential peat deposits. Using the map of freshwater deposits provided by Pedersen et al. (2011), we construct the distance between the freshwater soil type. Since this soil type formed at the beginning of the Holocene, around 12,000 years ago, it is clearly exogenous to the other variables we consider. Then, to proxy for the ease of access to coal, we use distance to the coast (in km). Summary statistics are provided in Table 2, where we also compare observables prior to the First World War, finding little obvious difference prior to the onset of the conflict.

Fig. 4 provides a map of Denmark (in its pre-1920 borders), where we have illustrated both the location of peat and the creameries in our sample. Note that this illustrates where it was possible to extract peat, and not whether this actually took place, for which data is lacking. It is clear that there is variation in the distance of creameries to the nearest land with soil type that is suitable for peat, which motivates our empirical strategy. Fig. 5 demonstrates the share of creameries reporting use of peat (often together with other fuels), consistent with the historical narrative. We take within 500 m as “close to” peat. Although this might sound like a small distance, peat needed to be on the land of the farmers, who in turn could then supply peat as well as milk to the

Table 2
Summary and balancing statistics.

	Group	n	mean	sd	min	max
Distance peat	All data	13,395	0.68	0.78	0.00	7.62
Within500m		13,395	0.52	0.50	0.00	1.00
Year		13,395	1914.98	7.92	1900.00	1928.00
MB ratio		13,395	25.10	0.87	20.40	28.50
Butter		13,395	97,271.87	44,920.90	4433.50	362,467.00
Milk		13,395	2,484,519.18	1,124,074.68	282,236.00	9,215,963.00
Shareholders now		13,012	157.92	70.64	15.00	560.00
Centrifuges		7577	1.68	0.63	1.00	4.00
Distance coast		13,395	9611.98	9511.68	34.36	46,890.62
Distance peat	Beyond 500 m	2757	1.19	0.86	0.50	7.62
Year	before 1914	2757	1907.25	3.84	1900.00	1913.00
MB ratio		2757	25.59	0.65	22.30	28.50
Butter		2757	94,243.98	39,628.55	4433.50	273,926.50
Milk		2757	2,423,693.51	1,006,646.67	403,943.00	7,049,160.50
Shareholders now		2725	162.12	75.01	15.00	560.00
Centrifuges		236	1.82	0.65	1.00	4.00
Distance coast		2757	8920.72	9619.10	34.36	46,890.62
Distance_peat	Within 500 m	3073	0.21	0.14	0.00	0.50
Year	before 1914	3073	1907.26	3.82	1900.00	1913.00
MB ratio		3073	25.62	0.65	20.40	28.00
Butter		3073	95,303.90	40,134.18	13,434.50	254,892.00
Milk		3073	2,462,995.75	1,030,497.51	376,901.50	6,422,574.50
Shareholders now		3042	162.09	72.51	15.00	425.00
Centrifuges		256	1.86	0.67	1.00	4.00
Distance coast		3073	9925.05	9043.36	47.09	44,279.46

Creameries missing 4 or more annual observations before and after 1913 were excluded.

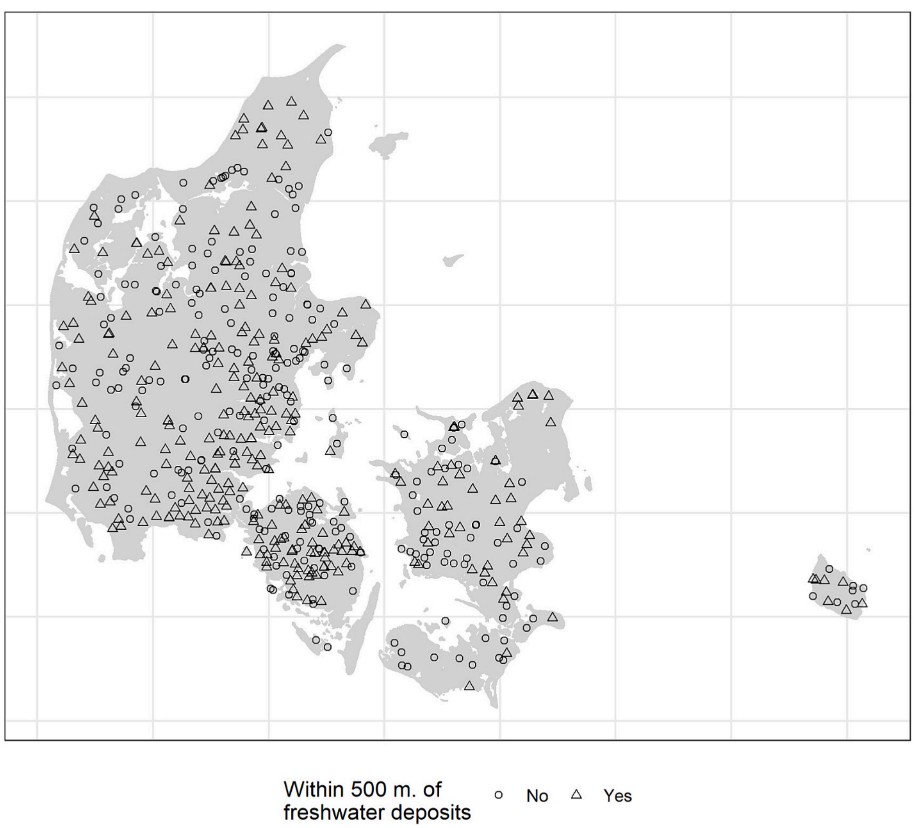

Fig. 4. Location of Creameries in our Sample Relative to Freshwater deposits.
(Source: Geographical Survey of Denmark and Greenland (GEUS); Ellbrecht (1915–18))

creameries. Thus, location was extremely important for the ability to exploit peat. Nevertheless, we also employ other measures below.

We have excluded creameries not found in Ellbrecht (1915–18) (and where we therefore do not know where they were located), or if we do not observe the MB ratio. Also, we have only included creameries which reported at least 4 years between 1900 and 13 *and* 1914–28. This left us with a total of 590 creameries and 13,395 observations. Apart from ensuring variation before and after the outbreak of the First World War, this also means that those which were located in the part of southern Jutland which became German after the Second Schleswig War of 1864,

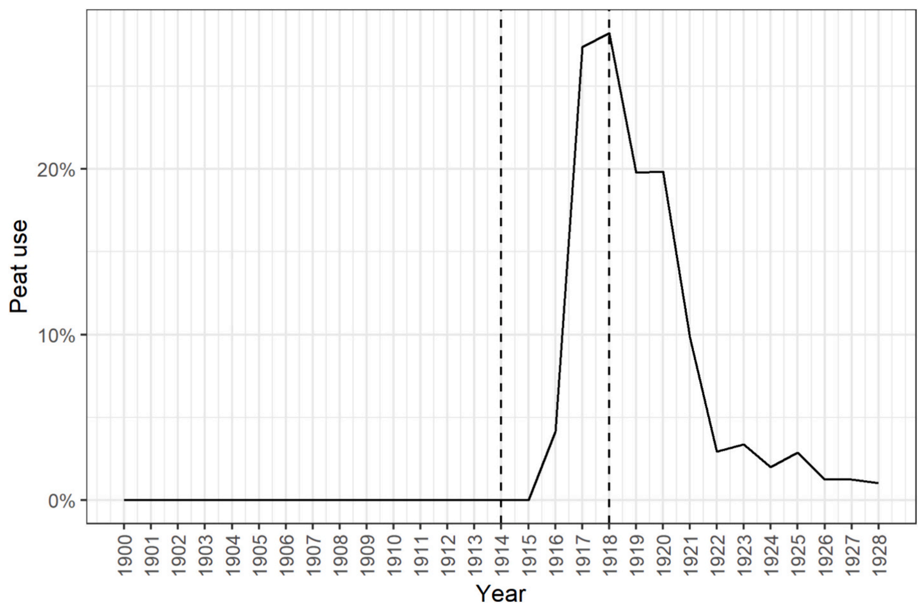

Fig. 5. Percentage of creameries reporting use of peat as part of their fuel consumption.
Note: Prior to 1915 no creameries reported the use of peat.
(Source: MDS.)

but voted to become part of Denmark from 1920, are not included. Apart from the obvious issue that none of them reported prior to 1920, they were also rather different from the other creameries in our sample, having experienced multiple difficulties following "reunification". Rasmusssen (1982) explains how they had to transition rapidly after having suffered from years of under-investment, and whole creameries had to be replaced. The region was also characterized by a larger proportion of private creameries which had a reputation for poorer quality. In fact, recognizing a threat to the reputation of Danish produce, measures were taken to discriminate against the newly Danish creameries, and they were given easily identifiable numbers under the *lurmærke* system, which guaranteed Danish standards of production through an official brand. Although they improved somewhat through the 1920s, in the 1930s they still used more milk per butter than rest of Denmark, and had lower quality. It was only in 1950 that these differences disappeared.

5. Empirical strategy

What we set out to test is whether adaptability and the availability of alternative energy supplies is beneficial during an energy crisis – specifically that which Denmark experienced during and shortly after the First World War. For this we use an exogenous measure based on the local availability of a soil type which is associated with peat formation. Although MDS contains a variable for whether any specific creamery used peat for any specific year, it does not contain information about the amounts used. Moreover, whether or not a creamery transitioned to peat is subject to a number of confounding factors, for example the ability of creamery management, human capital and whether there was excess labor available for peat digging. None of these confounders can however influence the formation of soil types, which for the case of Denmark, was largely determined during the last ice age. Thus, from data on soil types from Pedersen et al. (2011) we extract the location of "freshwater deposits" – a soil type associated with peat formation. From this we construct an exogenous proxy for adaptability as an indicator for whether creameries were close to this soil type. This has the advantage of being the simplest possible way of measuring this, while being a reflection of the actual process of peat collection and use. The farmers (who of course owned the cooperative creameries) would collect peat from their fields to use at the creameries where their milk was processed into butter. It is thus a very local supply. Our measure roughly divides creameries into one half which is close to the alternative fuel and the other which was not. Fig. 6 shows how productivity developed in the creameries within and beyond 500 m of freshwater deposits. Since the measure is relative to the annual mean, and the two groups are of roughly equal size, the deviations from the mean in each year are roughly equal in size and of opposite sign. Of course, one can imagine many other ways of measuring the potential for peat formation. In Appendix B1, we consider two alternative measures.

Our main regression is as follows:

$$MB\ ratio_{it} = Peat_{it} \times Year_t \beta_t + \mathbf{z}'_{it}\boldsymbol{\gamma} + \varepsilon_{it} \tag{1}$$

where $\mathbf{z}'_{it}\boldsymbol{\gamma}$ is a vector of controls and fixed effects and their corresponding parameters, and $Peat_{it}$ is our indicator of proximity to freshwater deposits. This is interacted with $Year_t$, which in turn causes β_t to be our parameter of interest - the effect of peat availability each year. ε_{it} is the error term. The set of controls include creamery and year fixed effects as well as region by year fixed effects and controls for time varying effects of distance to the coast with decile dummies. The dummies are constructed by slicing the distances to the sea into deciles and constructing a dummy for each decile. This yields a simple non-parametric estimate for the effect of distance to the coast in order to limit potential concerns over functional form. According to conventional definitions, all of Denmark is coastal, with nowhere further than 50 km from the coast, and inland waterways thus play a limited role. Rail was important for reaching more inland areas, but distances were not great, with the average distance to a station of just 4.1 km, and no significant difference by proximity to peat. However, we fear that our measure of exogenous peat availability might mechanically be correlated with the distance to the sea, and since we have no priors about the functional form of this relationship, we prefer to model this in a non-parametric way. We also include a specification where we exclude all creameries within 10 km of a harbor.

6. Results

6.1. Event study

The year-specific results specified in the above equation are illus-

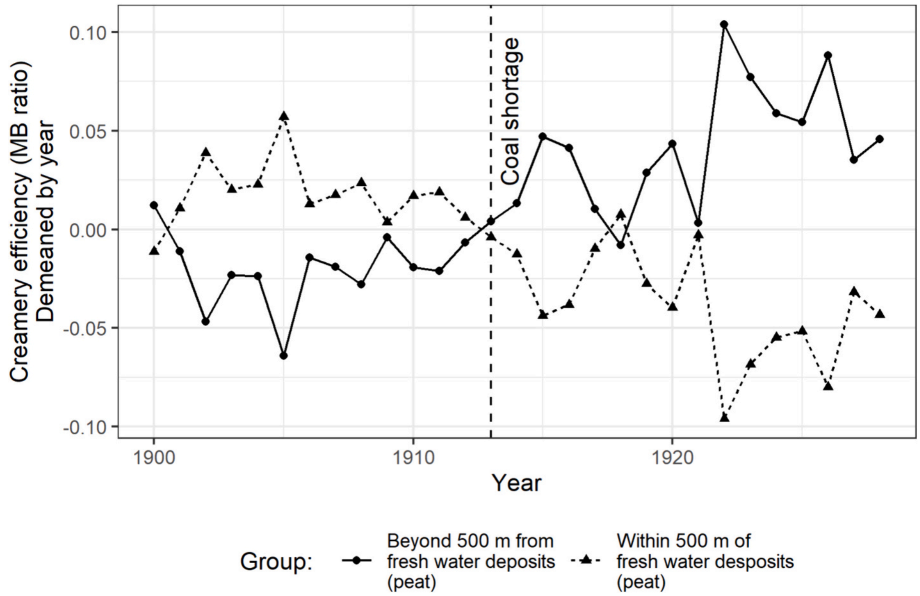

Fig. 6. Efficiency of creameries.

trated in Fig. 7 with $Peat_{it}$ defined as a dummy for creameries located within 500 m of freshwater deposits.

Apart from the first couple of years, the coefficients of the effect on the pre-war years are close to zero and not statistically significant, suggesting that there are no pre-war trends in milk/butter ratios that are driving the results. The effects in the years during and in particular following the war are negative, and thus associated with increased productivity, and often statistically significant, as is to be expected given the historical narrative presented above since coal only became scarce towards the end of the war, but various regulatory measures aimed to offset this – although as is clear from the results it ultimately could not fully compensate for the disruption. Note moreover the persistence of the effect into the 1920s, which we seek to explain below – geographical advantage during coal shortages had medium-run effects. The average productivity advantage stabilizes around −0.126 less milk required for every unit output of butter after the war. Table 3 reports the year-specific estimates in detail. Alternative specifications (a continuous measure of distance to freshwater deposits, a measure of density) are given in Appendix B1, but make little or no qualitative difference to our findings. Appendix B2 excludes observations closer than 10 km to a harbor, in case there is some sort of connection between freshwater deposits and ports not accounted for by distance to the coast. This removes a lot of observations and thus power, but our results are otherwise unaffected. Finally, Appendix B3 gives the results of a simple difference-in-differences estimation, as well as including the number of shareholders and cows as an indicator of scale. This removes some of the effect, since scale of production is a mediator of the effect of the coal shortage.

A remaining question is whether the effect is economically significant. To answer this, we make a back of the envelope counterfactual estimate, which answers how much value the parameter estimate implies in terms of 2010 USD. A change in MB ratio relates to an implied change in Butter output (keeping milk constant) in the following manner:

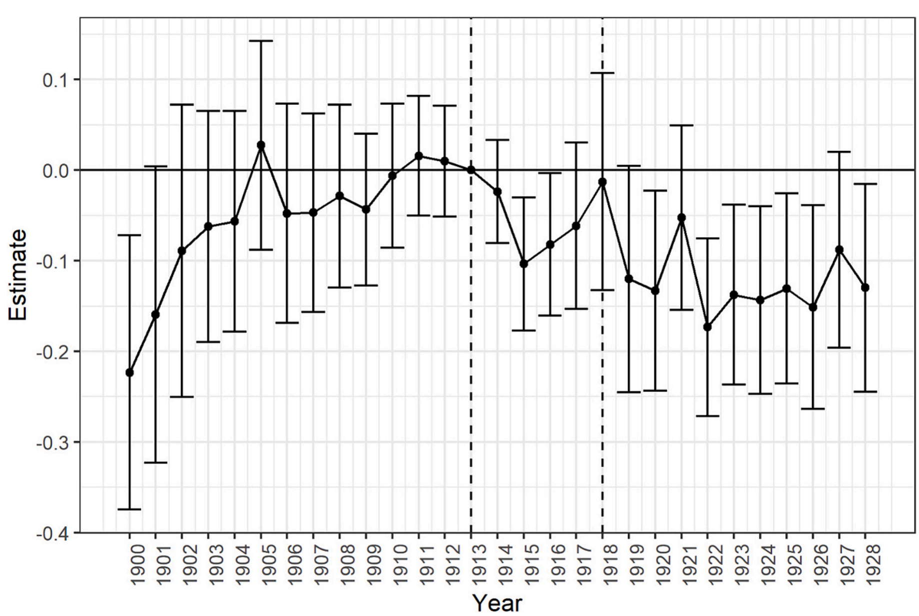

Fig. 7. Impact on MB ratio of being within 500 m of freshwater deposits.

Table 3
All parameter estimates from Fig. 7:.

Dependent Variable:	MB ratio
	(1)
Within500m × Year1900	−0.2233*** (0.0772)
Within500m × Year1901	−0.1592* (0.0834)
Within500m × Year1902	−0.0891 (0.0824)
Within500m × Year1903	−0.0621 (0.0651)
Within500m × Year1904	−0.0565 (0.0621)
Within500m × Year1905	0.0276 (0.0588)
Within500m × Year1906	−0.0476 (0.0616)
Within500m × Year1907	−0.0469 (0.0559)
Within500m × Year1908	−0.0285 (0.0515)
Within500m × Year1909	−0.0434 (0.0428)
Within500m × Year1910	−0.0063 (0.0405)
Within500m × Year1911	0.0159 (0.0338)
Within500m × Year1912	0.0098 (0.0312)
Within500m × Year1914	−0.0236 (0.0291)
Within500m × Year1915	−0.1036*** (0.0376)
Within500m × Year1916	−0.0820** (0.0401)
Within500m × Year1917	−0.0614 (0.0468)
Within500m × Year1918	−0.0129 (0.0611)
Within500m × Year1919	−0.1202* (0.0638)
Within500m × Year1920	−0.1332** (0.0563)
Within500m × Year1921	−0.0525 (0.0518)
Within500m × Year1922	−0.1733*** (0.0499)
Within500m × Year1923	−0.1376*** (0.0506)
Within500m × Year1924	−0.1435*** (0.0529)
Within500m × Year1925	−0.1305** (0.0536)
Within500m × Year1926	−0.1512*** (0.0574)
Within500m × Year1927	−0.0878 (0.0552)
Within500m × Year1928	−0.1298** (0.0586)
Fixed-effects	
Creamery_ID	Yes
Year	Yes
Year_region	Yes
Observations	13,395

Clustered (Creamery_ID) standard-errors in parentheses
Signif. Codes: ***: 0.01, **: 0.05, *: 0.1

$$\Delta Butter = Milk\ for\ butter \times \frac{-\Delta MB}{MB_1(MB_1 + \Delta MB)} \tag{2}$$

Here ΔMB is the change in the milk/butter ratio and MB_1 is a reference MB ratio. The implied change in butter output ($\Delta Butter$) can then be converted to Danish kroner (DKK) using the butter prices of MDS and these can in turn be converted to 2010 USD using historical price indices and the exchange rate between DKK and USD in 2010. The derivations of this are described in Appendix B4. Using the above formula for the median creamery, we can estimate that an improved MB ratio of 0.126 implies an additional 492 kg of butter output for the counterfactual (i.e. a creamery beyond 500 m of peat instead). This corresponds to 2236 nominal DKK per year in the period 1919–1928. Converting this to 2010 USD[8] this implies 10,786[9] additional USD in potential output every single year for median creameries without easy peat access.

6.2. Mechanisms

MDS provides a rich set of variables we can use to confirm the mechanisms underlying our findings. Our hypothesis is that creameries were less able to maintain minimum efficient scales of production and thus efficiency if they lacked alternative fuel sources. This would be visible initially in higher milk/butter ratios, but might ultimately lead to less ability to maintain and invest in capital equipment. This in turn would lead to greater inefficiency even beyond the period of the coal shortages, and might even threaten the survival of the creamery itself.

We consider evidence of this by first noting that if our story is to be confirmed, and in particular if we wish to understand the long-term productivity impact of proximity to peat, we might expect that creameries further from peat might simply have had to close. Thus, if it were the case that creameries with and without access to peat performed equally following the coal shortage, then we would expect creameries with different access to peat to keep reporting at the same rate to MDS. If, however, creameries performed worse, it might be the case that they performed so poorly that they had to close, in which case they would never report again. As we will demonstrate, this was the case, which points to the long-term financial impact of energy shortage, even after it has ended, as a major cause of the adverse effects we observe. It also means that our results above will be biased downwards, in the sense that the least efficient creameries would leave the sample.

Thus, for each creamery we check the year it was established. For some creameries we do not have this information and we instead use the first year they reported. Next, we ask when the creamery made its last report to MDS. We can reasonably suspect that many creameries that stopped reporting were shut down in the years following their last report. We use this information to construct a balanced panel of all creameries and whether or not they likely still exist as recorded from their reports to the MDS. We construct a variable, "observed", which encodes this. It is constructed as a dummy taking the value 1, if two conditions are met and 0 otherwise. The two conditions are:

1. The current year is after or equal to when the creamery was established or made its first report to the MDS.
2. The current year is before or equal to the year the creamery made its last report to the MDS.

We then only consider creameries observed in 1913, and plot in Fig. 8 what percentage in each group (closer or further away from freshwater deposits) did not make their final report – so called Pseudo-Kaplan-Meier curves. Clearly, those further away suffered more.

What happened to the farmers who supplied those creameries that closed? Some might have left the industry of course, but those dairy farmers who remained would have had to deliver to other creameries. Thus, more supporting evidence for our story would be a widening gap in the number of farmers (shareholders) between the two groups of creameries. Fig. 9 confirms that this is in fact the case.

This might of course be reflected by changes in the relative scale of production, but Fig. 10 reveals that this is not the case.

Thus, the productivity gap as measured by the MB ratio did not change because the creameries grew larger or smaller. We hypothesize instead that what survival and greater productivity, initially caused by maintaining the minimum efficient scale of production, allowed them to do was to increase investments, and that this caused the longer-term differences in productivity. Evidence for this is presented in Fig. 11, which illustrates the number of creameries in each group with more than one centrifuge. This declines everywhere due to the massive decline in production noted above. But it declined noticeably further away from freshwater deposits.

7. Conclusion

There is a broad consensus that energy resources are important for development, that coal was essential for early industrialization, and some suggestion that alternative energy sources might have been a barrier to modern economic development. Energy economists have, however, highlighted that energy systems need to be adaptable in the

[8] Converting 1920s butter prices to modern USD equivalents is not without controversy. But the point of this back-of-the-envelope exercise is not precision but accuracy. For the purpose of making these conversions (also in future projects) we have developed a small R function, available on request.

[9] A clustered bootstrap of the regression of this estimate (clustered on the creameries, 1000 repetitions) yields a 95 % "exact" confidence interval between 3379 USD and 17,850 USD. A histogram covering the implied change in value for all creameries is included in Appendix B4, Fig. B4.1.

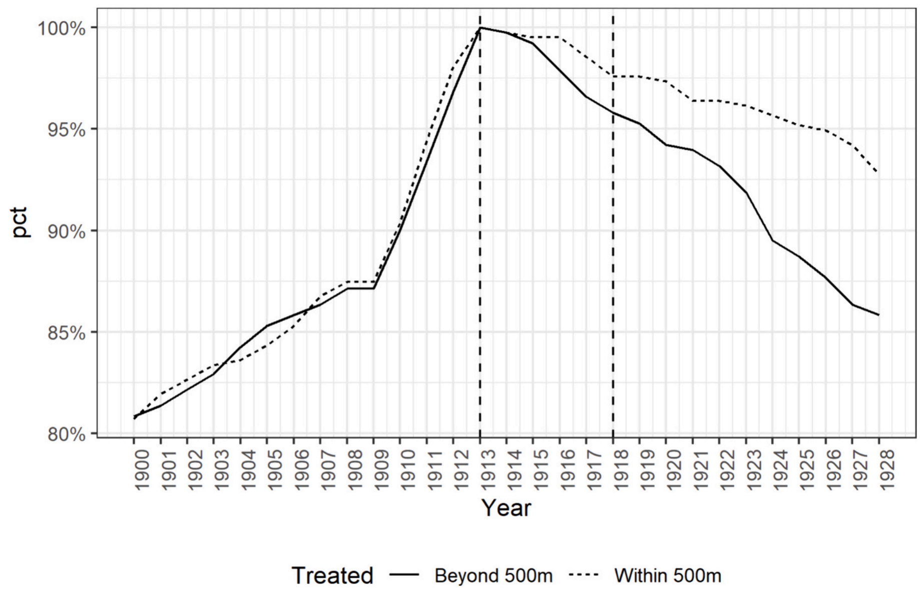

Fig. 8. Pseudo-Kaplan-Meier Curves for Creamery Survival.

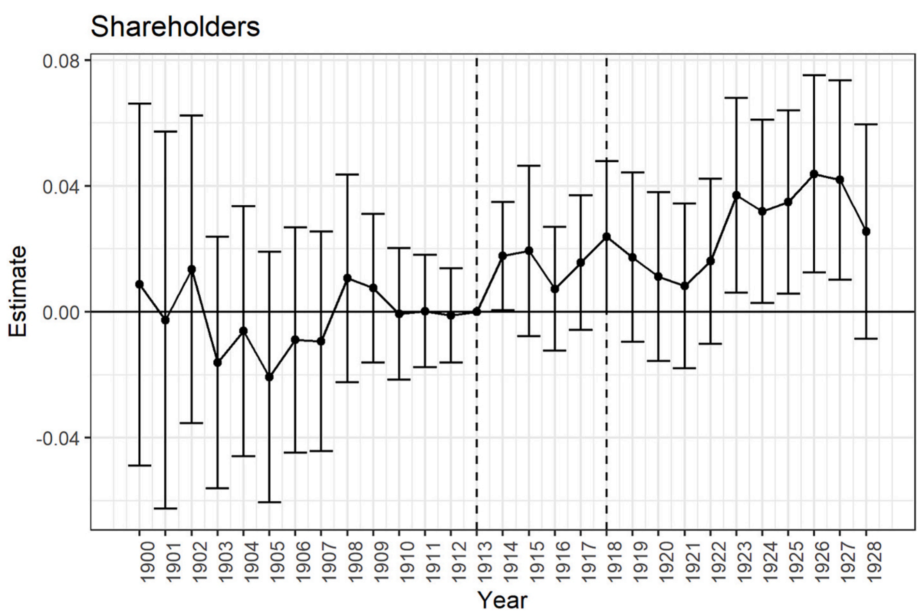

Fig. 9. Outcome log(Shareholders).

face of shocks. We explore this using the case of Denmark, a country dependent on imports of coal for industrialization, but which faced sudden coal constraints with the onset of the First World War. Using a novel dataset of firm-level data on Danish butter factories, we explore their productivity before and after the First World War, when imports of coal from the UK declined and became more uncertain. In an event study approach, we found that creameries closer to areas with soil type suitable for peat were more productive, i.e. they used less milk to produce one kilogram of butter. Thus, as contemporary reports noted, and our empirical results support, Danish creameries proved able to adapt to this difficult situation. However, geographical factors meant that this favored some creameries over others, introducing Denmark to the issues of local energy supply often considered to have been crucial for early industrialization, but which had not previously been an issue (Henriques and Sharp, 2016), due to the easy import of coal to any part of Denmark. Nevertheless, we find that those creameries that were able to adapt maintained a productivity lead until the late-1920s, when shortages of coal ceased to be a concern. Peat was certainly not sufficient to provide a long-term energy diversification strategy, but its availability, and the ability of the creameries to adapt, meant that some creameries were not as hard hit as others.

Of course, the Danish experience can only partially inform contemporary political discussions, as this was a case of a technical solution that was far from capital intensive. Peat could be used in the same steam engines as coal, and the majority of changes were relative to the intensity of labor used when handling the fuel, etc. Businesses today might need to invest considerably more to change their energy sources, with most presently depending on grid energy only. Also, this case does not consider the fact that short-run measures need to be as environmentally efficient as possible so as not to not hamper the long-term decarbonization targets. This is where policy can play a role, by facilitating the financing of renewable and more efficient technology for small businesses, such as solar collectors or heat pumps. On the other hand, at the grid level, regulators can protect small businesses from price spikes.

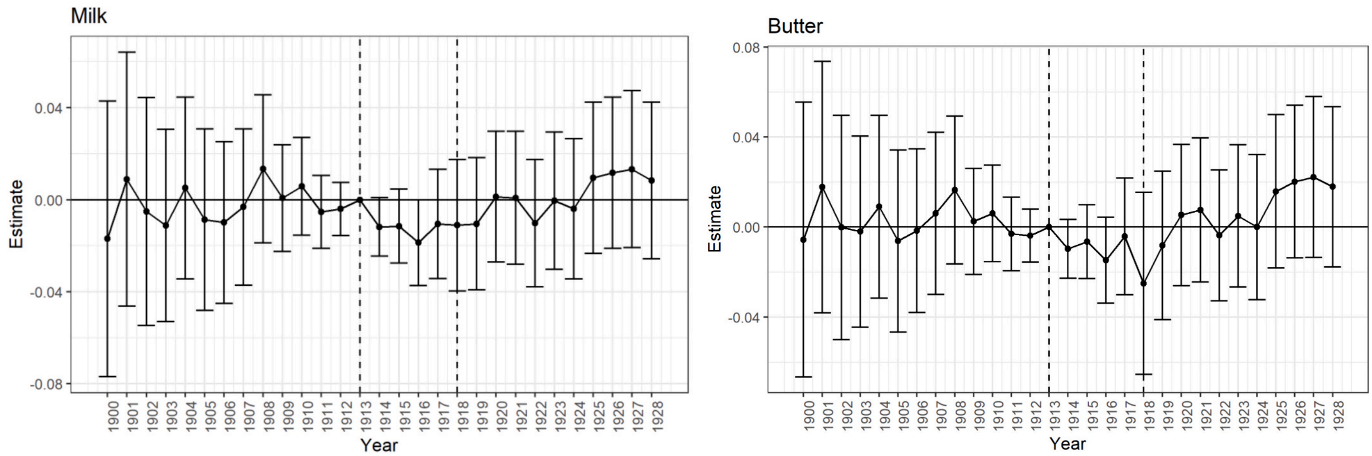

Fig. 10. log(Milk) and log(Butter).

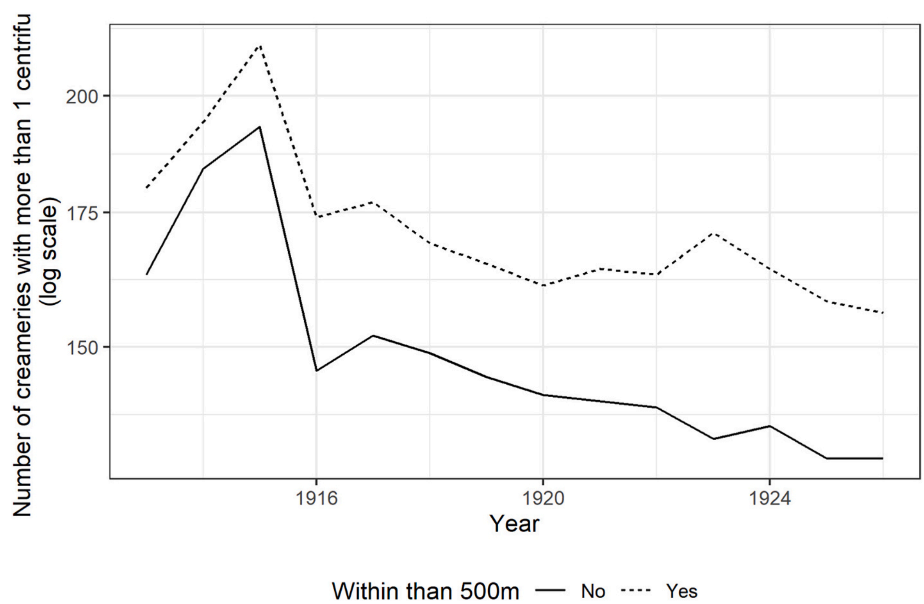

Fig. 11. Number of Creameries with More Than One Centrifuge.

Measures such as the decoupling of non-gas (especially renewable) electricity producer prices from the price of gas would be essential so that the diversification of energy sources in grid electricity translates into lower prices for the consumer.[10]

While short-term fuel-switching measures to peat protected the creameries near peat reserves, the technological advantage of being an early adopter of the steam-powered cream separator was eroded by the end of the First World War. Diversity in the Danish case, was not, as Stirling (2010) explains, a free lunch, and the lack of significant technological change associated with it, had later productivity effects for Danish industry. By the early 1930s, the Danish energy system within dairying contrasted hugely with the electrification of the US and Swedish industries. This might suggest that there were some lock-in effects and/or that some technologies are better than others in times of crisis. On the other hand, the Danish strategy, and that of the creameries, for securing affordable and timely energy supplies had various elements, which did not consist merely of the diversification of fuel sources. Indeed, we see similar measures being taken today, with some countries reversing the phase-out of coal and switching back to a less efficient and more polluting fuel as a short-run measure to halt energy costs, or EU regulations setting increasing mandatory levels of gas storage to prepare for the winter 2022–23. According to the EU, one fourth of all energy consumption is in gas, and the majority of EU countries import all their supplies, and, like Denmark in the past, many of them are also reliant on a single source and single transport route, and there is understandably an increasingly lively debate about how to diversify,[11] and the EU has responded with the plan "Repower Europe".[12] The present work suggests that the EU and others might look to lessons from the 1920s as well as those from the 1970s.

CRediT authorship contribution statement

Sofia Teives Henriques: Writing-original draft, Formal analysis, and Visualization, Writing – review & editing, Methodology,

[10] https://www.ft.com/content/8a9662ef-1ff9-4edf-b0cf-1abb377d08a5; ec.europa.eu/commision/presscorner/detail/en/ip_23_324

[11] See for example Matsumoto et al. (2018), de Rosa et al (2022), Mišík (2022), and Osicka and Cernoch (2022).

[12] European Comission (2022)https://commission.europa.eu/publications/key-documents-repowereu_en

Investigation, Funding acquisition, Conceptualization. **Paul Sharp:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xanthi Tsoukli:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christian Vedel:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

none.

Acknowledgements

This project was made possible through generous funding by Independent Research Fund Denmark (DFF– 6109-00123) and FCT - Fundação para a Ciência e a Tecnologia, I.P. (UIDB/04105/2020). Moreover, the digitization required many research assistant hours. Two of the authors of this paper started as RAs, but we would also like to thank Peter Baunsgaard, Peter Gerner Ejersbo, Nick Ford, Jakob Baltzer Henriksen, Maja Uhre Pedersen, Andreas Slot Ravnholt, and Emil Nørmark Sørensen. Nina Boberg-Fazlic, Peter Sandholt Jensen, Astrid Kander, Markus Lampe, Eoin McLaughlin, Kevin H. O'Rourke and Johanna Rickne provided valuable feedback. Finally this project has been presented at the Cork FRESH Meeting, the 4th HEDG Mini-Workshop for Young Scholars, the 2nd SDU Workshop on Economic and Business History, the 3rd Annual Meeting of the Danish Society for Economic and Social History, the 4th Agricliometrics meeting in Madrid, the XIX World Economic History Congress in Paris, two DGPE workshops, and several times at the PhD seminar series of the Department of Economics at the University of Southern Denmark. We would like to thank every participant at these events for insightful questions and comments.

Appendix A

A.1. Historical background

As is well-known, the story of energy during early industrialization is very much tied up with that of coal. Steam power based on coal eventually spread into most economic sectors including transportation (Kander et al., 2013), and railroads and steamships meant that even countries with no coal, but with long coast-lines, such as Denmark, were able to industrialize (Henriques and Sharp, 2016), while those with large interior regions, such as Ireland and Portugal, saw industrialization mostly confined to coastal areas (Bielenberg, 2009; Henriques and Sharp, 2021). In general, the availability of cheap energy sources, combined with market access, has been shown to have determined the scale of industrial production to a greater or lesser degree (Crafts and Wolf, 2014; Nielsen, 2021).[13]

The combination of a high share of coal in the energy system, extreme dependence on external markets, and reliance on a sole supplier made Denmark particularly vulnerable and ill-prepared to face energy supply shocks, something that could be only partially counterbalanced by its strategic position as a neutral country and Britain's food supplier and by its profitable shipping sector. Thus, by 1916 exports from Britain and Germany had already collapsed to about one half of their 1913 levels. Independently of each country's energy resources and policies, the First World War was a huge shock to the energy system of all coal-poor countries. Within Europe, the allied forces were the first to experience significant disruptions, despite the UK prioritizing coal deliveries to support war aims. By 1916, France lost much of its mining potential after invasion (Notz, 1918); Italy and Portugal would join the allies later, and in 1915 and 1916 had reduced their coal consumption by around one fourth. Neutral Portugal experienced increasing problems guaranteeing coal for businesses, also due to the lack of a suitable fleet, as British ships were directed to war efforts and goods had to be transported in the ships of neutral countries (Miranda, 1991).

Beyond the obvious effects of the war itself, there is increasing evidence to suggest that the influenza pandemic might also have played a role for the economic difficulties which were to follow. Boberg-Fazlic et al. (2021) demonstrate that the flu had a significant impact, independent of that of the war, on subsequent trade policy, corresponding to an increase of one third of a standard deviation in tariffs for the countries in their sample. More directly, the Spanish flu caused serious disruptions in coal supplies around the world (Kelley and Osterholm, 2008). An article in the New York Times of August 5, 1918, for example, reported that coal had not been delivered from Germany to Switzerland for the last four days after many miners stopped working due to the illness. Similar issues occurred in North America, with one report noting in October 1918 that "coal became difficult to obtain and fuel supplies for the sick and for industry diminished" (MacDougall, 2007). The pandemic resulted in declines in shipments, and numerous collieries were reportedly closed and that those that were open were struggling to produce with "depleted forces" as quoted by Kelley and Osterholm (2008). As Joseph B. Dickson, an anthracite coal distributor, testified on December 2, 1918 to the US Senate "My own feeling is that the gradual shutting down of war industries and the return to natural conditions will relieve the pressure in a very, very short time. I believe it would have been relieved by this time if we had not had this epidemic, which very materially interfered with the production of anthracite coal" (Dickson, 1918). In support of this, Velde (2020) found a relationship between mortality by state in the US and the labor supply shock, although for Denmark itself, Dahl et al. (2020) find that the epidemic, and non-pharmacological interventions, led to short-run declines in income in those municipalities which were hardest hit, although the recession was V-shaped, with full recovery after 2–3 years, as captured by income and unemployment data. The impact on agriculture was quite severe, however.

At the outset of the war, among the neutral countries, the Netherlands, a country with an agricultural specialization pattern very similar to

[13] By contrast, although non-coal energy resources such as peat might be able to sustain economic growth in preindustrial times, as in the case of the Netherlands (de Zeeuw, 1978), Landes (1969) has pointed out that early industrializers succeeded by copying the British model, and reliance on waterpower or charcoal, due to relative prices, was often an obstacle to successful technology adoption. In a similar vein, Allen (2009) explains that cheap peat in the Low Countries meant that, despite high rates of urbanization, abundant coal stretching from northeastern France through Belgium and into Germany were largely unexploited, and the industrial revolution failed to be a Dutch-German achievement. There was simply no economic incentive to open coal mines, and by the nineteenth century cheap supplies from Newcastle meant that German coal remained unexploited until relatively late. Mokyr (2009), on the other hand, has argued that the industrial revolution did not need steam, and that neither did steam necessarily require coal. In fact, counterexamples for the importance of coal abound, for example the United States (Melosi, 1982; Schurr and Netschert, 1960) and Sweden (Kander, 2002; Kander et al., 2017; Lindmark and Olsson-Spjut, 2018), where wood and charcoal were important energy carriers in early stages of industrialization. Sweden is in fact an interesting case in point, where it proved possible to adapt to the lack of coal and establish a sizeable iron industry in the nineteenth century (Rydén, 2005; Ducoing and Olsson-Spjut, 2021).

Denmark, dependent on imported fertilizers and feedstocks, seemed to be the country hit hardest by the supply shock, with coal at 80 % of 1913 levels in 1916. The country was caught in a difficult diplomatic situation between the UK and Germany, which involved accepting an allied blockade of Germany, but at the same time exchanging its food surplus for coal from them (de Jong, 2005). In contrast, Denmark and Sweden were able to somewhat maintain their coal supplies in the first years, albeit at an increasing cost, and Switzerland and Norway even managed to expand them, the latter due to increased volumes of shipping trade given its neutral status (Imperial Mineral Resources Bureau, 1921, 1922). Then, during the second half of the war, coal imports dropped massively in all European countries leading to state rationing of coal to key industrial sectors and major restrictions in public lighting and transportation services. Prices of coal imports were high in all countries except Spain, which almost did not import coal: from 332 % above pre-war levels in France to 884 % in Norway. Coal-poor countries had to turn to alternative power sources. Some accelerated their transition to a high-quality secondary energy carrier, electricity, with all the productivity benefits this entailed. In Norway, Sweden, Switzerland, and Italy, where there were plenty of waterfalls, hydropower was the solution. Already a promising source of power by 1900 and a major factor for their catch up with the industrial leaders before the war, the drop in the relative price of electricity to coal due to the war provided further incentives for expansion. After the war, hydropower would continue to give an important contribution to productivity and growth in those countries.

For others, war meant sudden profitability of local mines and increased state support and subsidies for domestic coal. This was the case in Spain, where an agreement to increase mine working hours allowed for an intensification of production during the war[14]. Subsidies were given depending on the class of consumer, followed by sectoral quotas which increased participation of domestic coal in most sectors (Coll and Sudrià, 1987). The Netherlands would also rely increasingly on its own coal, with domestic extraction up by a factor of five since 1913 and providing three quarters of all coal consumed in 1918. Others, such as Sweden and Portugal, turned to less energy dense, traditional sources of energy such as fuelwood as an immediate response to prevent households from freezing, industry from closing and railroads from coming to a halt. Without waterfalls, domestic coal, or forests to turn to, Danish businesses faced a particularly delicate situation: their alternative was peat.

To assess the impact of the coal shortages on Denmark, we draw on three main sources. Rasmusssen (1982) provides an excellent general overview of the state of the Danish dairy sector during the First World War and into the 1920s, but only mentions the issues with supplies of coal in passing. We thus supplement this with detailed information provided in a report presented to the Ministry of the Interior in 1921, following the abolition of limits on the consumption of foreign fuel on January 10 of that year (Cock-Clausen, 1921). In addition, we have information from Dansk Mejeri-Drifts-Statistik (MDS, 'Operational Statistics for Danish Creameries'), which provides the source of much of our data, and where almost every volume begins with a discussion of the state of the industry in the year for which the data is presented (usually the previous year).

From 1899 a Committee for Creamery Statistics was responsible for compiling extremely detailed statistics annually for a large sample of creameries in Denmark, published as MDS (for more information, see Sharp et al. (2023)). Information on the fuel used by the individual creamery is registered for the years 1900–1928, presumably reflecting the years over which this was considered to be of importance. The vast majority of creameries exclusively used coal until the First World War, but in the final years of the war and subsequently other fuels are reported, reflecting the desperation of the owners, including brushwood, peat, briquettes, firewood, coke, heather, sawdust, lignite, straw, coal scraps, and of course a mixture of these (although no information on the proportions used). Electricity was first reported for powering the machinery in 1915 and only for one creamery. This contrasts with the rapid expansion of electricity in other sectors at the time, but as van der Vleuten (1998) explains, the Danish dairy industry was slow to express interest in electricity beyond its use for lighting, for which it was usually generated by the creamery's boiler. Some of this might have been due to lock-in to steam-power, but he argues that this was largely a rational decision: steam engines were not only reliable, but also produced the large amount of steam needed for pasteurization. Thus, by 1900 power was simply seen as a "by-product" of heat production, and it was only from the 1930s that butter factories began to shift from steam to purchasing electricity with changes in pasteurization techniques.

The choice of fuel is not discussed in great detail in MDS before the war. The earliest discussion is in the report for 1901, where large differences in the cost of fuel is reported, and creameries are encouraged to look to peat for a cheaper alternative, although the writer states that it would not be possible to use peat alone. The reports for 1912–1915 discuss expensive coal and transportation, and by the report for 1916 (published in 1917) it is described how peat was the cheapest fuel, followed by wood, and then coal. One of the most interesting discussions is given in the report for 1917. The author discussed the declining milk production and the very high price of coal and other necessities, as well as discontent among employees, despite the fact that high demand and prices gave a high net income per pound of milk. He praises the adaptability of the creameries, noting that few used coal alone and importantly that local conditions regarding access to fuel were important, such as access to peat. By the report for 1918 only ten creameries were exclusively using coal, and peat is specifically mentioned as an important fuel source in the report for 1919. Unfortunately, the reports for 1920–25 provide no analysis, but the one for 1926 explains how the early part of the year had witnessed high coal prices due to coal strikes in the UK, but that the creameries had learned to adapt due to the war, although again access to alternative sources of fuel was important. It is these reports which led us to investigate the importance of peat in the following. While coal had previously been more-or-less equally accessible to creameries in all parts of the country, it seems that the compilers of MDS observed that local geography began to play a much larger role towards the end of the First World War, and well into the 1920s.

With regards to the situation of Danish agriculture more generally in this period, Rasmusssen (1982) explains that neutrality during the First World War had been an economic and political priority. 60 % of Danish exports went to the UK before the war, and 28 % went to Germany. Denmark was, however, never again to experience as free and open markets for export of its agricultural produce as it had before the war. With the declaration of war on August 4, 1914, it was suddenly impossible to export butter. Danish sailors refused to sail unless they received considerably higher payments and insurance, fearing a largely maritime war.

Eventually an agreement was reached, and the first ships set sail on August 9, 1914. But this episode had cost the creameries dearly, and few buyers were to be found during one of the summer's warmest and most milk-abundant periods. The situation was worst for those without refrigerators, but was also bad for the rest, since it was rare to have capacity for more than 8–10 days of production. For some creameries an additional issue was that 53,000 men were called up to the "Sikringsstyrken" (Security Force) in connection with the government's acceptance of German demands to mine the Great Belt between the islands of Funen and Zealand.

Denmark had a strong negotiating position for maintaining neutrality due to its importance for both British and German supplies of food, and was able to continue trading with both belligerent parties. A law was passed on August 6, 1914 allowing the Minister of Justice to issue export bans, so that trading patterns from before the war could be maintained and in order to secure a supply of important foodstuffs for Denmark. Then, on August 9, 1914 an Extraordinary Commission (overordentlig kommission), under the Minister of the Interior, was constituted which could pass measures to

[14] The *Economist*, June 9, 1917.

secure the supply of necessary goods, organize distribution, and regulate prices. These two laws formed the basis of the Danish regulation of business during the war.

Some of the first regulations passed regarded agriculture. Thus, on August 28, 1914 the Extraordinary Commission took control of grain storage around Copenhagen, and gradually exerted more control over grains through 1914. On December 11, 1914 an export ban on vegetable oils for margarine production was introduced, since this was considered to be preferable to banning exports of butter, and in general dairying was not much impacted at this stage, reflecting its prioritization as a major source of Danish export revenue. There was an idea that it was better to rely on the UK market despite high prices in Germany, since it was felt that any gains from German exports would be short-lived, although by 1915 the German market became more and more attractive due to increasing prices. Exports became regulated from October 11, 1915, and could henceforth only take place through export channels approved by the Ministry of Agriculture. Fifty-seven exporting firms approved this on the condition that they followed a distribution plan. This made it possible to behold previous trading connections, and to divide profit on different markets between the creameries, but of course cost agriculture a significant amount of money.

There was not a large impact on production until 1916, when milk production fell under the level from before the war, and by the end of the conflict these falls were dramatic. The onset of U-boat warfare from January 31, 1917 meant that any ship, hostile or neutral, would be a target, and trade between Denmark and the UK practically ceased until June 1917 when the convoy system was introduced. The Danish government wanted to avoid trade going to Germany, and began stockpiling goods destined for the UK, but this failed to have much effect, and besides, the UK placed restrictions on trade with neutral countries, making it difficult to get hold of UK goods, including coal. The situation became worse and worse, and from the beginning of July 1917 UK exports of feed to Denmark almost stopped, at the same time as the US, which was Denmark's biggest supplier of grain and feed, introduced export bans. From October 4, 1917 all exports to Denmark, except coal (on which more below), were halted, and Denmark could only trade with the central powers, Sweden, and Norway. The resultant fall in grain and feed imports led to a large decline in milk production. With the accompanying loss of raw materials for margarine production, Denmark had to eat its own butter. By the summer and fall of 1917 the government attempted to keep prices down through subsidies, but from January 1, 1918 rationing was introduced. Only in September 1918 was it possible to make a trade agreement with the US, and necessary raw materials arrived again, but this came at a cost. Denmark was obliged to supply shipping to the US on top of that already supplied to the UK (as discussed below), and could only import goods from the US which were strictly necessary for the domestic market, and exports of agricultural goods to Germany were limited, although, since production had fallen so much, this never reached the maximum level permitted.

With the armistice of November 11, 1918 there was no quick return to normality. The milch cow herd had been reduced by 13 %, and a lack of feed continued to limit milk production. In January 1919 Denmark began negotiating an easing of restrictions on trade, and the following month agreement was reached guaranteeing the supply of feed, seed, artificial fertilizer, corn and copra, marking the beginning of a normalization of trade between the UK and Denmark. The export ban on butter was abolished on December 6, 1920. With continental Europe in chaos, the UK was the only real buyer of large quantities of Danish agricultural produce the first year after the war, but prices were low since the British government monopolized the purchase and distribution of bacon and butter. At the same time, feed prices only fell slowly. Only on April 1, 1921 were UK restrictions removed, free trade was reestablished, and Danish milk production almost reached the level of 1915. The UK took most of Danish exports, with Germany taking much of the rest. Nevertheless, prices fell since Danish milk production increased more than demand, made worse by a fluctuating world market price and an increasing krone exchange rate, especially when Denmark rejoined the gold standard in 1924–5, although this had the advantage that imports of feed became cheaper.

As regards the coal trade, Cock-Clausen (1921) explains that with the outbreak of war Denmark was already poorly positioned in terms of energy supplies. Strikes in the UK had meant that the transportation of coal from the UK to Denmark was extremely limited from July 1914 to the middle of August. Thus, when the UK entered the war on August 4 and regular shipments stopped, Denmark was extremely ill prepared in terms of coal reserves, since nearly all had been used during the strike. On August 18, 1914 the Extraordinary Commission reached an agreement so that coal importers lowered the price of coal and coke and calmer conditions were maintained through the remainder of 1914, although towards the end of the year prices again began to increase due to lower production in the UK (in part due to miners being called into service) and increasing demand from the UK itself as well as France, Italy, Russia and the rest of Scandinavia. In February 1915 the British government established a committee to investigate the reasons for the increasing price of coal. This suggested that exports to neutral countries should be limited, and from May 13, 1915 coal and coke could only be exported to neutral countries with special permission, and should not be reexported to the countries which were at war with the entente. Eventually Denmark reached agreement with the UK authorities that they would not limit coal exports to Denmark below the quantity which was usually used.

In the first half of 1916 Denmark was witnessing smaller imports of coal from the UK at higher prices and began looking for alternative sources. By October 1916 regular imports were arriving from Germany, and on October 24, 1916 the Ministry of the Interior established the "Continental Coal Committee" (Fastlandskuludvalget), which was to administer a reserve of ca. 90,000 tons of German fuel. Already at the end of January 1917 there was a shortage of fuel, but the Continental Coal Committee initially refused to release its reserves since it did not want to create competition for private importers. Then, the blockade of the North Sea from February 1, 1917 meant severe coal shortages, and the Ministry of the Interior introduced price regulation of foreign fuel and regulated the trade of coal, coke, cinders, and briquettes. The Committee began selling reserves, which kept many businesses, including creameries, afloat, despite few imports. The reserves were depleted by September 1917, and the Committee was wound up. Fortunately, imports from the UK had resumed in April 1917, but on April 10 the UK decided that all ships coming from the west could only take goods for the countries for which they flew the flag, and that ships could not load bunker coal in British ports without first taking on duties to help the UK. For Denmark, this meant that on June 20, 1917 agreement was reached with the UK to supply 200,000 tons deadweight for British use, and thereby acquired the right and the duty to import 100,000 tons of coal from the UK. Towards the end of the war, even the UK was experiencing coal shortages, and exports were banned to most neutral countries until mid-January 1919. Denmark had however imported a large amount of German fuel in the first ten months of 1918, and had some reserves.

The end of the war brought little respite. In January 1919 British miners called for higher wages, shorter working days, and the nationalization of coal mines. In response, the British government set up the "Sankey commission", named after the judge who chaired it, and a temporary agreement was reached in the Spring, and imports returned to similar levels to before the war. Nevertheless, the question of rapid nationalization continued to fuel conflicts, and the British government started to stockpile coal in preparation for a strike, with miners in Yorkshire striking in the fall.

The UK response was to require that Danish shipping brought timber from the Baltic in return for coal from August. While the Danish government attempted to negotiate, Danish shipping became trapped in British ports due to a rail strike which in turn led to a ban on the export of fuel until October. Denmark was forced to charter Swedish and Norwegian shipping, which was extremely expensive, and looked for alternative suppliers to the UK and Germany, although options were limited. Belgium met some of the demand, but ran into problems when they banned exports, so by May 1919

Denmark was forced to turn to US coal. Only small amounts arrived, however, due to an increased dollar exchange rate, a miners' strike from November 1919 to March 1920, and a strike among rail officials in April and May 1920. It was only from the fall of 1920 that exports increased.

Thus, the first half of 1920 witnessed very limited coal imports and massive increases in prices, with the US and Germany continuing to be of minor importance, and UK imports uncertain. Denmark was again forced to agree to export timber. Miners stopped working during Christmas and well into January, particularly due to Scottish workers' demand for a long Christmas and New Year vacation. Danish shipping again became trapped in UK ports as coal from neutral ships was requisitioned for reserves, and when supplies increased again at the end of January, British, French and Italian vessels were prioritized. The Danish krone's declining value from the end of 1919 meant that the government set up the Common Currency Council (Valutafællesraadet), which from January 1920 determined that currency would not be allowed to be used for imports of coal and coke except in authorized vessels. However, imports were mostly limited due to the situation in the UK. Although the UK decided that Denmark could be guaranteed at least 60,000 tons per month, and in fact supplies were never as low as that, it was anyway far from enough to cover what the country needed, estimated to have been around 200,000 to 250,000 tons per month. Danish reserves fell to less than during the U-boat blockade.

Responding to the crisis, in 1920 the Extraordinary Commission and other bodies encouraged the greatest possible care in the use of fuel. Measures were enacted to enforce this for the use of gas, electricity, and fuel for heating. Bans on the import of coal to Jutland were considered, since they had local reserves of peat and lignite, but this proved impossible. A port strike from March 31 to June 15, 1920 frustrated efforts, but imports were coordinated through Copenhagen. In the second half of 1920 prices increased very rapidly, and although large imports from the UK and the US alleviated this, it was decided to continue with a cautious approach, since it was believed that the situation could change rapidly: although Denmark had large reserves, there was still the threat of a coal miners' strike in the UK. The UK removed all domestic restrictions on July 1, but regulated exports, but then a strike began on October 16 and the exports were halted again. Although the strike ended on November 5, higher wages had been offered, so it was impossible to import as cheaply as before. Nevertheless, the last two months of 1920 saw very rapid falls in prices and on January 10, 1921 the Ministry of the Interior removed all regulations of prices, distribution, etc. It was not until the end of the 1920s that coal prices and imports stabilized.

Appendix B

B.1. Alternative measures of peat

We mainly rely on the binary measure presented in Section 5, which has the advantage of simplicity and relies on the fewest parameters and/or functional form assumptions. Moreover, as will be shown, it also provides a nicely exogenous measure of peat availability.

Our preferred measure, 'Within 500 m', is a dummy for whether the creamery was within 500 m of freshwater deposits. The main advantage is that this measure is incredibly simple, and for the econometrics which follows it also limits worries over functional form. Our second measure, 'log (Distance^{-1})', is a generalization of this. Instead of the dummy we use the distance to freshwater deposits directly. We take the inverse for ease of interpretation since this then reflects the proximity. This has the added advantage of still being a continuous measure, which reflects the degree to which peat was available. Our third measure 'log(Density)' is a further generalization aimed at capturing the local supply of peat more directly. We draw a dot for every 100 m all over Denmark, and for each creamery we count the number of dots within 5 km that contain 'freshwater deposits.' We divide this by the total number of dots within 5 km to get a measure of the local density of peat.

In order to test whether our measures might capture not just potential but actual use of peat, we then estimate a linear probability model for whether a creamery reported the use of peat (as noted in the text, only the use of peat was reported, not the quantity used). We allow this to be dependent on various measures of treatment, based on one of our three measures, as follows:

$$Peat_{it} = Treatment_{it} \times Year_t \beta_t + \mathbf{z}_{it}^{'} \boldsymbol{\gamma} + \varepsilon_{it}$$

Here *Peat* is an indicator of whether a creamery, *i*, had peat in their fuel mix at time *t*. *Treatment* is either one of our three measures. β_t is the average (marginal) effect of treatment at time *t*. *Year* = 1913 is excluded as the reference year, since it was the year before the outbreak of the First World War and the resultant coal shortage. An issue with the density measure is that it mechanically captures the distance to the coast. The closer the creamery is to the coast, the more dots in a 5 km circle will be in the sea, where 'freshwater deposits' by definition cannot be located. This forces the density down, and for this reason we need to control for the distance to the coast to obtain a clean measure of peat availability.

Fig. B1.1 illustrates the results of the linear probability model. Clearly, all three measures plausibly explain peat use. Fig. B1.2 illustrates that our event study (Eq. (1)) is insensitive to the choice of measure. Finally, Fig. B1.3 provides an alternative distance specification using a dummy for creameries within 200 m of freshwater deposits.

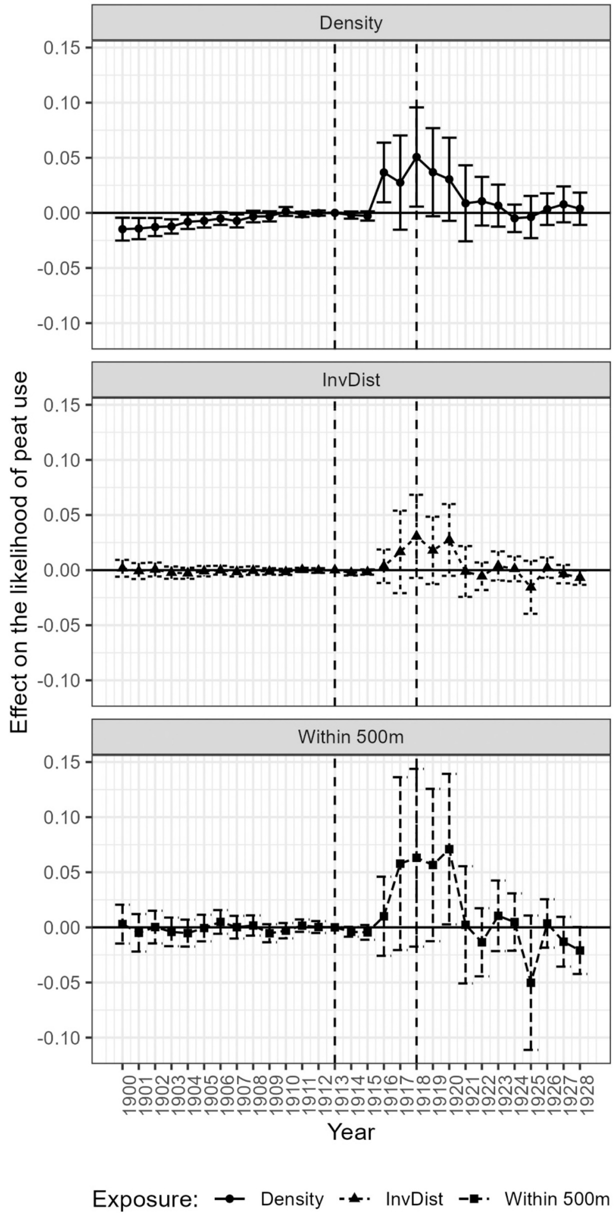

Fig. B1.1. Probability of peat use given three alternative measures of peat availability.

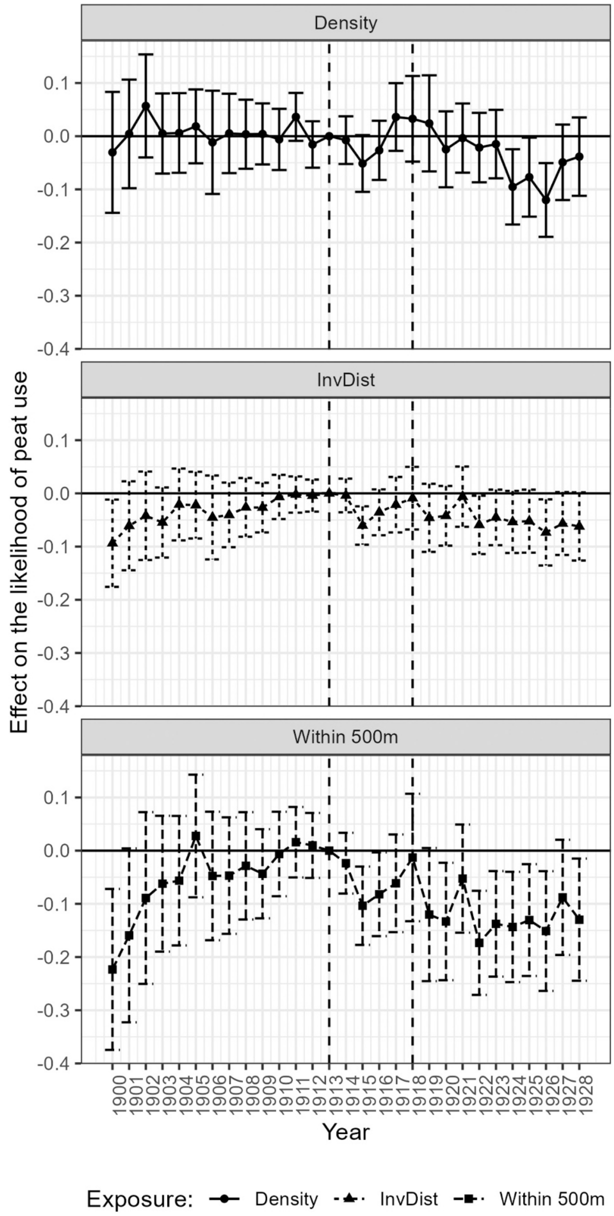

Fig. B1.2. Impact on MB ratio of all three measures of local peat availability.

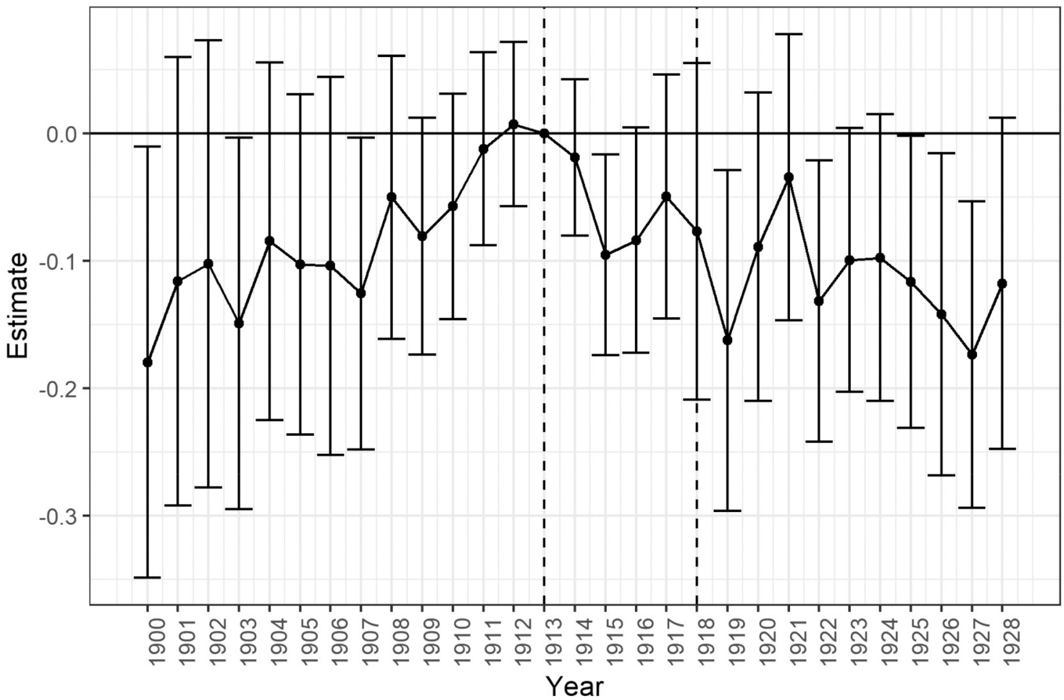

Fig. B1.3. Impact on MB ratio of being within 200 m of freshwater deposits.

B.2. Excluding creameries close to ports

In order to ensure the robustness of our findings, we conducted an additional analysis by excluding creameries located within 10 km of a port. The rationale behind this exclusion is to eliminate any potential bias introduced by creameries that may have benefited from proximity to ports, which could facilitate access to imported coal and other resources, potentially affecting their operations differently from more inland creameries.

We utilized the dataset of ports from the Sound Toll Registers (https://www.soundtoll.nl/), focusing on Danish ports. The 299 creameries located within 10 km of a port were identified and subsequently excluded from the dataset. The leaves 291 creameries for the analysis.

Following this exclusion, we re-estimated our main regression to assess whether the exclusion of these creameries altered our primary results. The results, presented in Fig. B2.1, indicate no qualitative differences compared to our main findings. In fact, the effect sizes are slightly larger in the restricted sample, which is consistent with the hypothesis that being further away from ports, and thus from coal imports, might have amplified the impact of the shocks under study.

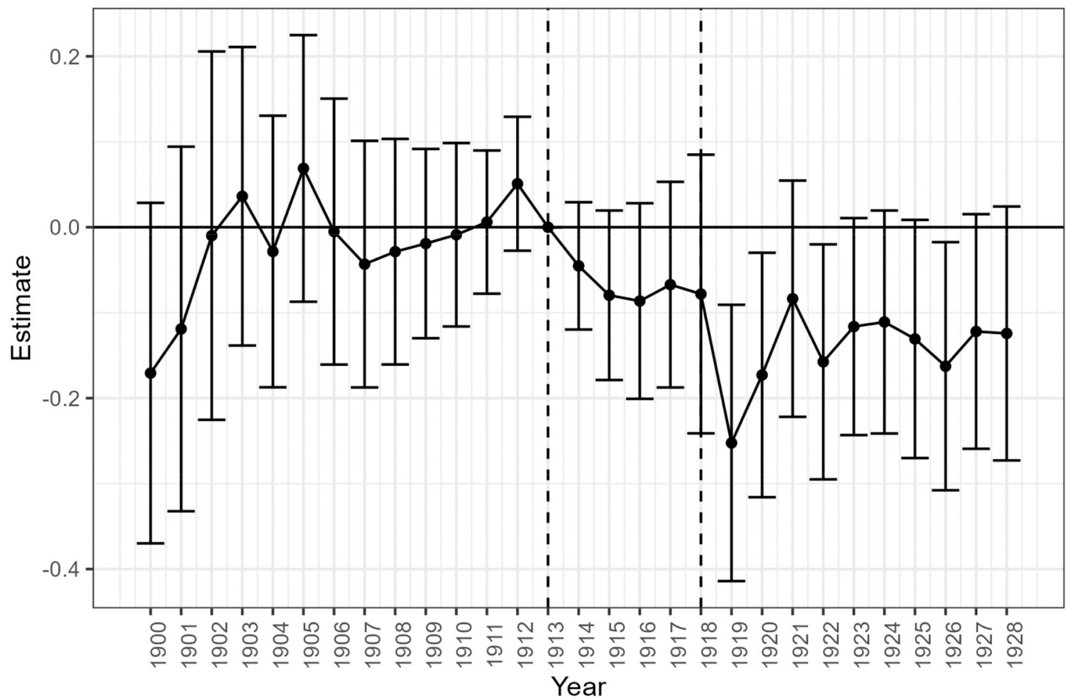

Fig. B2.1. Effect on MB ratio for creameries further than 10 km from a port.

Notes: This figure shows the same estimates as in Fig. 7 but where creameries closer than 10 km from a port has been excluded.
Source: MDS.

B.3. *Simple difference-in-differences estimates*

Table B3.1 presents the results of a simple difference-in-differences estimation using 1913 as the cutoff. Column (1) includes no controls, column (2) adds Year x Region FE + controls for distance to coast, and column (3) adds controls for the size of the creamery, log(*Cows*) and log(*Shareholders*). Note that the effect is small and generally insignificant, which is consistent with the event study, which demonstrated (consistent with the historical evidence), that the larger effects occur later. In columns 4–6 we thus also test this using 1921 as the cutoff. The post-1913 indicator remains negative but loses significance, which the post-1921 indicator is statistically significant. After this year the coal shortage had mostly ended, but the creameries with better access to peat are much more productive. The controls are introduced in the same way as in columns 1–3.

Table B3.1
Simple difference in difference table.

Dependent Variable:	MB ratio					
	(1)	(2)	(3)	(4)	(5)	(6)
Within 500 m x Post 1913	−0.0935**	−0.0552	−0.0579	−0.0479	−0.0252	−0.0264
	(0.0432)	(0.0387)	(0.0408)	(0.0415)	(0.0381)	(0.0401)
Within 500 m x Post 1921				−0.1068***	−0.0702**	−0.0765**
				(0.0336)	(0.0348)	(0.0380)
log(Shareholders now)			0.0677			0.0708
			(0.0732)			(0.0731)
log(Cows now)			−0.0865*			−0.0861*
			(0.0473)			(0.0472)
Creamery FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Year × Region FE	–	Yes	Yes	–	Yes	Yes
Year × Distance to coast	–	Yes	Yes	–	Yes	Yes
Observations	13,395	13,395	11,719	13,395	13,395	11,719
Creameries	590	590	590	590	590	590

Clustered (Creamery ID) standard-errors in parentheses.
Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

B.4. *Converting parameter estimates to economic significance*

In Section 6.1 we present a method for converting the parameter estimates of milk/butter ratios into more intuitively meaningful units. We thus

[15] www.nationalbanken.statbank.dk, DNVALA

converted the changes in the MB ratio into changes in **butter** output and we converted butter into its **nominal value** using butter prices. We convert these into **real values** using the historical price index from Statistics Denmark (data series PRIS8), which is then converted to USD. Some definitions follow.

MB is the milk to butter ratio in milk production:

$$MB = \frac{Milk\ for\ butter}{Butter} \tag{1}$$

ΔMB is the change in milk butter ratio (e.g. a parameter estimate) which we want to convert to a measure of value. MB_2, MB_1 is the milk to butter ratio after and before the change.

$$\Delta MB = MB_2 - MB_1 \tag{2}$$

$\Delta Butter$ is the change in butter induced by a change in MB ratio $\Delta MB \rightarrow \Delta Butter$:

$$\Delta Butter = Butter_2 - Butter_1 \tag{3}$$

From this we can derive how to make the conversion.

(1) implies that

$$Butter = \frac{Milk\ for\ butter}{MB} \tag{4}$$

(3) and (4) implies (with productivity calculated for a given level of input)

$$\Delta Butter = Butter_2 - Butter_1$$

$$\Delta Butter = \frac{Milk\ for\ butter}{MB_2} - \frac{Milk\ for\ butter}{MB_1}$$

$$\Delta Butter = Milk\ for\ butter \times \frac{MB_1 - MB_2}{MB_1 \times MB_2}. \tag{5}$$

From (2) it then follows that

$$\Delta Butter = Milk\ for\ butter \times \frac{-\Delta MB}{MB_1(MB_1 + \Delta MB)}. \tag{6}$$

This is then converted into real values using the following formula:

$$\Delta Nom.value = \Delta Butter \times Price\ butter$$

$$\Delta Real\ value = \frac{\Delta Nom.value}{Price\ index} \tag{7}$$

The price index we employ is the PRIS8 series from statistics Denmark but where the base year is changed to 2010, such that we get the value in 2010 prices, which can be converted to 2010 USD. This is performed using the average exchange rate from 2010 of 5.625670 DKK/USD obtained from the Danish central bank's website.[15] Of course, one might still speculate about the validity of the long-run price indices, but we believe this gives a reasonable reflection of the magnitude of the impact.

Fig. B4.1 uses this method to provide estimates of the implied changes in the value of output for all creameries in our sample in 1918, following the parameter estimates.

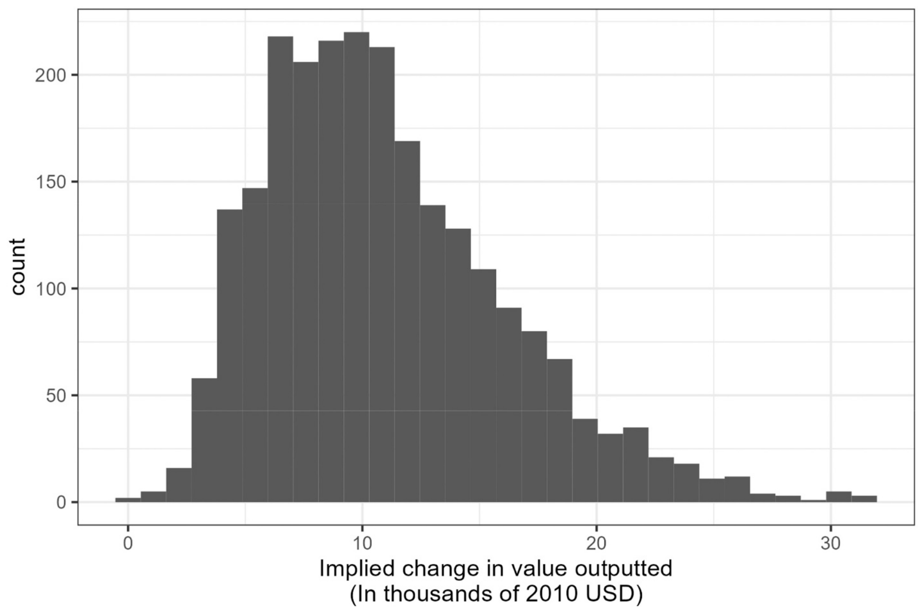

Fig. B4.1. Change in Output value implied by parameter estimate.
Notes: This figure uses the average parameter estimate after 1918 (−0.126) and converts it into the implied change in output at value for each butter factory in the sample.
Source: MDS.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107887.

References

Allcott, H., Collard-Wexler, A., O'Connell, S.D., 2016. How do electricity shortages affect industry? Evidence from India. Am. Econ. Rev. 106 (3), 587–624. https://doi.org/10.1257/aer.20140389.

Allen, R., 2009. The British Industrial Revolution in Global Perspective. Cambridge University Press.

Ang, B.W., Choong, W.L., Ng, T.S., 2015. Energy security: definitions, dimensions and indexes. Renew. Sust. Energ. Rev. 42, 1077–1093. https://doi.org/10.1016/j.rser.2014.10.064.

Barjot, D., 1991. Annuaire Statistique de L'Économie Française aux XIX et XXe siécles, L'énergie aux XIX et XXe siécles, vol. II. Presses de L'École Normale Supérieure, Paris.

Bergsøe, A.F., 1847. Den danske stats statistik, vol. II. Forfatterens forlag, Copenhagen.

Bhattacharya, M., Paramati, S.R., Ozturk, I., Bhattacharya, S., 2016. The effect of renewable energy consumption on economic growth: evidence from top 38 countries. Appl. Energy 162, 733–741. https://doi.org/10.1016/j.apenergy.2015.10.104.

Bielenberg, A., 2009. Ireland and the Industrial Revolution: The Impact of the Industrial Revolution on Irish Industry, 1801–1922. Routledge.

Blum, H., Legey, L.F., 2012. The challenging economics of energy security: ensuring energy benefits in support to sustainable development. Energy Econ. 34 (6), 1982–1989. https://doi.org/10.1016/j.eneco.2012.08.013.

Boberg-Fazlic, N., Lampe, M., Pedersen, M.U., Sharp, P., 2021. Pandemics and protectionism: evidence from the "Spanish" flu. Human. Social Sci. Commun. 8 (1), 1–9. https://doi.org/10.1057/s41599-021-00833-7.

Bohi, D.R., Toman, M.A., 1996. The Economics of Energy Security. Kluwer Academic Publishers, Boston/Dordrecht/London.

Brey, B., 2021. The Long-Run Gains from the Early Adoption of Electricity. Working Papers ECARES 2021–23. ULB – Universite Libre de Bruxelles.

Central Bureau of Statistics Netherlands, 2022. Coal and Coal Products, Mining, Import and Export accessed August 2022.

Cipolla, C.M., 1962. The Economic History of World Population. Pelican Books, London.

Cock-Clausen, H., 1921. Kulforholdene i Danmark 1914–1920. Statens Kulfordelingsudvalg, Copenhagen.

Coll, S., Sudrià, C., 1987. El carbon en España, 1770–1961, una história económica. Turner, Madrid.

Crafts, N., Wolf, N., 2014. The location of the UK cotton textiles industry in 1838: a quantitative analysis. J. Econ. Hist. 74, 1103–1139. https://doi.org/10.1017/S0022050714000874.

Dahl, C.M., Hansen, C.W., Jensen, P.S., 2020. The 1918 epidemic and a v-shaped recession: evidence from municipal income data. Covid Econ. 6. https://doi.org/10.1111/sjoe.12456.

de Jong, H., 2005. Between the devil and the deep blue sea: the Dutch economy during World War I. In: Broadberry, S., Harrison, M. (Eds.), The Economics of World War I. Cambridge University Press.

De Rosa, M., Gainsford, K., Pallonetto, F., Finn, D.P., 2022. Diversification, concentration and renewability of the energy supply in the European Union. Energy 253, 124097. https://doi.org/10.1016/j.energy.2022.124097.

de Zeeuw, J.W., 1978. Peat and the Dutch Golden age. The historical meaning of energy-attainability. AAG Bijdragen 21, 3–31.

Dickson, J., 1918. Shortage of coal and sugar. In: Statement to Senate Committee on Manufacturing. Government Printing Office, Washington, DC.

Ducoing, C., Olsson-Spjut, F., 2021. The energy transition in the Swedish iron and steel sector, 1800–1939. J. Energy Hist./Revue d'histoire de l'énergie (JEHRHE) 4 energyhistory.eu/en/ node/237.

Ellbrecht, G., 1915–18. Danske Mejerier. Illustreret haandbog for mejeribruget i Danmark. Selskabet til Udgivelse af Nationale Haandbøger, Copenhagen.

European Comission, 2000. Green Paper: Towards a European Strategy for the Security of Energy Supply. Office for the Official Publications of the European Commission. https://op.europa.eu/en/publication-detail/-/publication/0ef8d03f-7c54-41b6-ab89-6b93e61fd37c/language-en.

European Comission, 2022. Communication from the Comission to the European Parliament, The European Council, the European Economic and Social Committee and the Committee of the Regions RePower EU Plan, COM/2022/230 final. https://commission.europa.eu/publications/key-documents-repowereu_en.

Fernihough, A., O'Rourke, K.H., 2020. Coal and the European industrial revolution. Econ. J. 131 (635), 1135–1149. https://doi.org/10.1093/ej/ueaa117.

Fisher-Vanden, K., Mansur, E.T., Wang, Q.J., 2015. Electricity shortages and firm productivity: evidence from China's industrial firms. J. Dev. Econ. 114, 172–188. https://doi.org/10.1016/j.jdeveco.2015.01.002.

Fremdling, R., 1995. Anglo-German rivalry in coal Markets in France, the Netherlands and Germany 1850-1913. J. Eur. Econ. Hist. 25, 599–646.

Gasser, P., 2020. A review on energy security indices to compare country performances. Energy Policy 139 (August 2019), 111339. https://doi.org/10.1016/j.enpol.2020.111339.

Gozgor, G., Paramati, S.R., 2022. Does energy diversification cause an economic slowdown? Evidence from a newly constructed energy diversification index. Energy Econ. 109 (March), 105970. https://doi.org/10.1016/j.eneco.2022.105970.

Henriksen, I., Lampe, M., Sharp, P., 2011. The role of technology and institutions for growth: Danish creameries in the late nineteenth century. Eur. Rev. Econ. Hist. 15 (3), 475–493. https://doi.org/10.1017/S1361491611000128.

Henriques, S.T., 2011. Energy Transitions, Economic Growth and Structural Change: Portugal in a Long-Run Comparative Perspective (Doctoral Dissertation). Lund University, Lund.

Henriques, S.T., Sharp, P., 2016. The Danish agricultural revolution in an energy perspective: a case of development with few domestic energy sources. Econ. Hist. Rev. 69 (3), 844–869. https://doi.org/10.1111/ehr.12236.
Henriques, S.T., Sharp, P., 2021. Without coal in the age of steam and dams in the age of electricity: an explanation for the failure of Portugal to industrialize before the second world war. Eur. Rev. Econ. Hist. 25 (1), 85–105. https://doi.org/10.1093/ereh/heaa003.
Historische Statistik der Schweiz, 2012. HSSO, J.1. hsso.ch/2012/j/1.
Hölgens, R., 2019. Resource dependence and energy risks in the Netherlands since the mid-nineteenth century. Energy Policy 125 (February), 45–54. https://doi.org/10.1016/j.enpol.2018.10.020.
IEA, 2007. Energy Security and Climate Policy — Assessing Interactions. International Energy Agency, Paris, France.
IEA, 2022. World Energy Outlook 2022. International Energy Agency, Paris, France.
Imperial Mineral Resources Bureau, 1921. The mineral industry of the British empire and foreign countries. In: War Period. Coal, Coke and by-Products (1913–1919). London, Part I, HMSO.
Imperial Mineral Resources Bureau, 1922. The mineral industry of the British Empire and Foreign Countries. War Period. Coal, Coke and By-Products (1913-1919), Part III. HMSO, London.
Iriarte-Goñi, I., Infante-Amate, J., 2019. Continuity, change, and geographical differences in Spain's firewood consumption: a new estimation (1860-2010). Hist.. Agraria: Rev. Agricult. historia rural 77, 33–57. https://doi.org/10.26882/histagrar.077e01i.
Johansen, H., 1985. Danmarks Historie, Bind 9. Danish Hist. Statist. 1814–1980.
Johansen, K., 2021. Blowing in the wind: a brief history of wind energy and wind power technologies in Denmark. Energy Policy 152, 112139. https://doi.org/10.1016/j.enpol.2021.112139.
Kander, A., 2002. Economic Growth, Energy Consumption and CO2 Emissions in Sweden 1800–2000. Lund.
Kander, A., Malanima, P., Warde, P., 2013. Power to the People: Energy in Europe over the Last Five Centuries. Princeton University Press, Princeton.
Kander, A., Warde, P., Henriques, S., Nielsen, H., Kulionis, V., Hagen, S., 2017. International trade and energy intensity during European industrialization, 1870–1935. Ecol. Econ. 139, 33–44. https://doi.org/10.1016/j.ecolecon.2017.03.042.
Kelley, N., Osterholm, M., 2008. Pandemic Influenza, Electricity, and the Coal Supply Chain: Addressing Crucial Preparedness Gaps in the United States. Technical report, The Center for Infectious Disease Research and Policy (CIDRAP).
Kjærgaard, T., 1994. The Danish Revolution, 1500–1800: An Ecohistorical Interpretation. Cambridge Univ. Press.
Lampe, M., Sharp, P., 2015. Just add milk: a productivity analysis of the revolutionary changes in nineteenth-century Danish dairying. Econ. Hist. Rev. 68 (4), 1132–1153.
Lampe, M., Sharp, P., 2018. A Land of Milk and Butter: How Elites Created the Modern Danish Dairy Industry. University of Chicago Press.
Landes, D.S., 1969. The Unbound Prometheus: Technological Change and Development in Western Europe from 1750 to the Present. Cambridge University Press.
Le, T.H., Nguyen, C.P., 2019. Is energy security a driver for economic growth? Evidence from a global sample. Energy Policy 129 (August 2018), 436–451. https://doi.org/10.1016/j.enpol.2019.02.038.
Lindmark, M., Olsson-Spjut, F., 2018. From organic to fossil and in-between: new estimates of energy consumption in the Swedish manufacturing industry during 1800–1913. Scand. Econ. Hist. Rev. 66 (1), 18–33. https://doi.org/10.1080/03585522.2017.1401554.
Lo, L.H., 2011. Diversity; security; and adaptability in energy systems: A comparative analysis of four countries in Asia. In: World Renewable Energy Congress-Sweden; 8–13 May; 2011; Linköping; Sweden. Linköping University Electronic Press, pp. 2401–2408. No. 057.
MacDougall, H., 2007. Toronto's health department in action: influenza in 1918 and SARS in 2003. J. Hist. Med. Allied Sci. 62, 56–89. https://doi.org/10.1093/jhmas/jrl042.
Matsumoto, K., Doumpos, M., Andriosopoulos, K., 2018. Historical energy security performance in EU countries. Renew. Sust. Energ. Rev. 82 (June 2017), 1737–1748. https://doi.org/10.1016/j.rser.2017.06.058.
Melosi, M.V., 1982. Energy transitions in the nineteenth century economy. In: Daniels, H., Rose, H. (Eds.), Energy and Transport: Historical Perspectives and Policy Issues. Sage.
Miranda, S., 1987. O declínio da supremacia Britânica em Portugal (1890–1939), PhD dissertation, Universidade de Lisboa, unpublished version.
Miranda, S., 1991. Portugal: o círculo vicioso da dependência (1890–1939). Teorema, Lisbon.
Mišík, M., 2022. The EU needs to improve its external energy security. Energy Policy 165 (April). https://doi.org/10.1016/j.enpol.2022.112930.
Mokyr, J., 2009. The Enlightened Economy: An Economic History of Britain, 1700–1850. Yale University Press, New Haven, CT.
Nielsen, H., 2021. Coal and sugar: the black and white gold of Czech industrialization (1841-1863). In: Lund Papers in Economic history, No. 2021, p. 229.
Norges officielle Statistik, 1914. Norges Handel 1913, Kristiania.
Normann, H., 1959. Danmarks Energiforsyning 1900–1958 / Energy Supply of Denmark. In: Statistiske Undersogelser No. 2. The Statistical Department, Copenhagen.
Notz, W., 1918. The World's coal situation during the war: I. J. Polit. Econ. 26 (6), 567–611.
Osicka, J., Cernoch, F., 2022. European energy politics after Ukraine : the road ahead. Energy Res. Soc. Sci. 91 (March). https://doi.org/10.1016/j.erss.2022.102757.
Pedersen, S.A.S., Hermansen, B., Nathan, C., Tougaard, L., 2011. Digitalt kort over danmarks jordarter. 1:200.000. De Nationale Geologiske Undersøgelser for Danmark og Grønland, Klima- og Energiministeriet, Denmark, 2nd edition.
Podobnik, B., 2006. Global Energy Shifts: Fostering Sustainability in a Turbulent Age. Temple University Press, Philadelphia.
Pomeranz, K., 2000. The Great Divergence: China, Europe and the Making of the Modern World Economy. Princeton University Press, Princeton.
Ranestad, K., Sharp, P.R., 2021. Success through failure? Four centuries of searching for Danish coal. Bus. Hist. https://doi.org/10.1080/00076791.2021.1879053 (forthcoming).
Rasmusssen, J., 1982. Dansk mejeribrug 1914-55. In: Bjørn, C. (Ed.), Dansk mejeribrug 1882–2000. De danske Mejeriers Fællesorganisation, Odense, Denmark, pp. 189–308.
Rentschler, J., Kornejew, M., Hallegatte, S., Braese, J., Obolensky, M., 2019. Underutilized Potential: The Business Costs of Unreliable Infrastructure in Developing Countries., Policy Research Working Paper; No. 8899. World Bank, Washington, DC June. http://hdl.handle.net/10986/31919.
Rubio, M.D.M., 2005. Economia, energia y CO2, España 1850-2000, Cuad. Económicos de ICE. 70 (2), 55–71.
Rubio Varas, M.D.M., Muñoz Delgado, B., 2019. Long-term diversification paths and energy transitions in Europe. Ecol. Econ. 163, 158–168. https://doi.org/10.1016/j.ecolecon.2019.04.025.
Rydén, G., 2005. Responses to coal technology without coal. Swedish iron making in the nineteenth century. In: Evans, C., Rydén, G. (Eds.), The industrial revolution in iron: the impact of British coal technology in nineteenthcentury. Europe. Ashgate, Aldershot, pp. 111–128.
Schurr, S.H., Netschert, C., 1960. Energy in the American Economy 1850–1975: An Economic Study of its History and Prospects. The Johns Hopkins Press.
Sharp, P., Henriques, S.T., McLaughlin, E., Tsoukli, X., Vedel, C., 2023. A microlevel analysis of Danish dairy cooperatives: opportunities for large data in business history. Enterp. Soc. 1–29. https://doi.org/10.1017/eso.2023.5 forthcoming.
Statistics Denmark, 1959. Danmarks Energiforsyning 1900-1958. Statistiske Undersogelser 2. Statistics Denmark, Copenhagen.
Statistisk Sentralbyrå, 1955. Økonomisk Utsyn 1900–1950, SamfunnsØkonomiske Studier, 3, Oslo.
Stirling, A., 2010. Multicriteria diversity analysis. A novel heuristic framework for appraising energy portfolios. Energy Policy 38 (4), 1622–1634. https://doi.org/10.1016/j.enpol.2009.02.023.
Stucki, T., 2019. Which firms benefit from investments in green energy technologies? – the effect of energy costs. Res. Policy 48 (3), 546–555. https://doi.org/10.1016/j.respol.2018.09.010.
Thaarup, F., 1819. Vejledning til det Danske Monarkies Statistik, Vol. 1–6. Christopher Græbe, Copenhagen.
Tol, R.S., 2023. Navigating the energy trilemma during geopolitical and environmental crises. arXiv preprint. arXiv:2301.07671.
van der Vleuten, E., 1998. Electrifying Denmark: A symmetrical history of central and decentral electricity supply until 1970. Unpublished PhD thesis. University of Aarhus, History of Science Department.
Velde, F.R., 2020. What Happened to the US Economy during the 1918 Influenza Pandemic? A View through High-Frequency Data. Working Papers 2020-11,. Federal Reserve Bank of Chicago WP.
Vögele, S., Kunz, P., Rübbelke, D., Stahlke, T., 2018. Transformation pathways of phasing out coal-fired power plants in Germany. Energy Sustain. Soc. 8 (1), 1–18. https://doi.org/10.1186/s13705-018-0166-z.
Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A., 2004. Resilience, adaptability and transformability in social–ecological systems. Ecol. Soc. 9 (2), 5.
Warming, J.W.J., 1913. Haandbog i Danmarks Statistik. G.E.C. Gads Forlag, Copenhagen.
Wrigley, E., 1988. Continuity, Chance and Change. Cambridge University Press, Cambridge, UK.
Wrigley, E., 2010. Energy and the English Industrial Revolution. Cambridge University Press, Cambridge, UK.
Xu, J., Akhtar, M., Haris, M., Muhammad, S., Abban, O.J., Taghizadeh-Hesary, F., 2022. Energy crisis, firm profitability, and productivity: an emerging economy perspective. Energ. Strat. Rev. 41 (April), 100849. https://doi.org/10.1016/j.esr.2022.100849.
Yergin, D., 1991. The Prize: The Epic Quest for Oil, Money and Power. Simon and Schuster, New York.
Yergin, D., 2006. Ensuring energy security. Foreign Aff. 85 (2), 69. https://doi.org/10.2307/20031912.
Yoon, K.H., Ratti, R.A., 2011. Energy price uncertainty, energy intensity and firm investment. Energy Econ. 33 (1), 67–78. https://doi.org/10.1016/j.eneco.2010.04.011.