The preference for sea-coales in London: the Great Fire as a technology shock*

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1 Introduction

When and how coal became a major energy source in England remains something of an open question. Studies of the history of the coal industry suggest that coal was not in widespread use as of 1550, but dominated the London fuel supply by 1700. Identification of the rate of technological change and fuel substitution during that period remains difficult to adjudicate. This paper tests the pace of fuel switching in the mid-17th century. It exploits the Great Fire of London in 1666 as a shock to the London housing supply, whose effect on fuel demand should provide information on the relative demand for coal at mid-century. Using this shock, I am unable to find any significant discontinuity in London coal consumption. This may indicate that coal adoption was already well-advanced in London by 1666, or that the technology adoption rate among replacement housing approximated the prevailing rate of adoption among the destroyed housing. I discuss the implications of either finding in the conclusion.

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2 Historical background

Studies of comparative rates of industrialization have credited England's abundant coal reserves with its status as early industrializer.(Nef, 1932; Flinn, 1984) However, the process by which England switched from a wood-fueled economy to a coal-fueled economy remains somewhat opaque. Nef (1932) argues that high firewood prices by the late 16th century drove Londoners to adopt Newcastle "sea-coales" as a cheaper fuel, despite their reputation for noxious fumes. Price series for wood and coal shown in figure 1 clearly show coal's relative price advantage during this period. During the period 1600-1700, coal prices in London were around 35% lower on average than the equivalent amount of wood heat.[1] However, Te Brake (1975) documents that coal had price advantages over wood in the 14th century as well, but that energy switching did not persist; population stagnation reduced the pressure on firewood supplies and thus reduced prices. Coal prices appear to have surpassed firewood prices in the late 18th century, yet clearly England did not revert to a wool economy. This raises the question of why the 16th-17th century substitution of wood with coal proved permanent.

Allen (2009) argues that 16th century Englishmen enjoyed higher wages which, coupled with relatively cheap coal energy prices, led to the permanent substitution of coal and machinery for labor. However, industrial uses for coal were slow to emerge. Coal was adopted as a direct substitute for wood in thermal applications like lime-burning and salt-boiling. A royal edict required its use in glass making after 1615.(Hartshorne, 1897) But it was not used in iron smelting until the Darby's invention of a coal-fired blast furnace around 1710, or in the steam engine until Newcomen's innovations around the same time period. The development of coking methods, which reduced the presence of noxious

[1] Note that Clark (2004) finds that wood and coal prices in England were about equal until 1700. However, his calculations cover all of England, whereas these calculations are for London only. He admits that relative wood prices might have been higher in London, given the local nature of firewood markets.

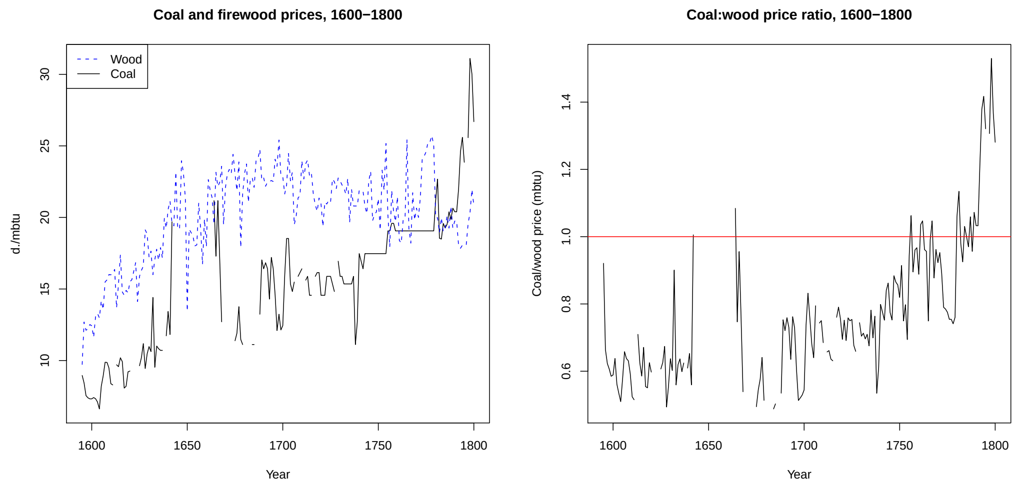

Figure 1: Coal and firewood prices in London in the 17th century. Coal data for Westminster Abbey from Beveridge (1939). Firewood data from Clark (2004).

vapors in the coal that tended to foul industrial products, progressed slowly. Price and consumption series for Westminster Abbey, Winchester College, Eton College, and King's College, Cambridge, all show the continued purchase of wood or charcoal alongside coal throughout the 17th and 18th centuries.(Beveridge, 1939; Nef, 1932) Several authors have suggested that England retained a diverse fuel system, using wood and water as well as coal, well into the 19th century, particularly outside London.(Hammersley, 1957)

Residential use of coal may have progressed faster. Allen (2009) has argued that the widespread adoption of coal for home heating in London in the 17th century may have provided the stimulus necessary to stabilize coal demand and encourage intensive production. Anecdotal accounts from London in the late 16th century find upper-class ladies complaining of the foul stench given off by coal burned in their hearths, but mourning the shortage of the same coals in the 1630s.(Nef, 1932) However, full information on the pace of coal adoption remains unclear.

Nevertheless, the data present an empirical puzzle. In 1600, London appears to have imported around 200,000 tons of of coal per annum for a population of approximately 100,000 people. In 1700, it imported around 500,000 tons for 500,000 people.[2] In *per capita* terms, then, coal consumption appears to have fallen. Part of the decline is no doubt due to the migration of industry out of London. The departure of the glass works from London after the 1615 royal decree banning the use of firewood in glassmaking provides one such example. Absent more detailed indices of industrial production in London, estimating this effect in more detail becomes difficult. Amidst these competing sets of changes, estimates of just how fast Londoners adopted coal remain uncertain.

3 How much coal and how fast? Housing as a natural experiment

Housing provides a potential way into this problem. In the 17th century, domestic demands for home heating and cooking fuel are plausibly static on a *per capita* basis. Allen (2001) suggests that an annual *per capita* energy budget of approximately five million btu obtained in England through the 17th and early 18th centuries. Clark (2004) suggests the equivalent of 0.5 tons of coal per year, closer to ten million btu. It was only with the increased living standards that came with the industrial revolution that this energy budget grew. Furthermore, the *per capita* demand for housing was relatively constant, again until rising living standards permitted both larger homes and smaller households.

Satisfying this energy budget for a mid-century London population of around 400,000 people would have required between 80,000-200,000 tons of coal or 116,000-232,000 tons of wood per year. On coal terms, if London had burned only coal for residential heating, this would have constituted around 30-50% of the total estimated coal import (~350,000 tons) in that period. On the assumption that London had not switched entirely, the residential demand for fuel was thus probably somewhat less. Clark (2004) cites sources suggesting

[2] Population statistics from (Harding, 1990).

that Londoners burned perhaps 0.3 tons of coal annually on average, leaving 0.2 tons to be made up by other sources. Nevertheless, precise data on the fuel mix is lacking given the lack of data on firewood supply statistics.

The relationship between housing and fuel choice depended on one particular technological innovation, which was known but not universally adopted as of 1600. Conversion of residential heating to coal would have required the adoption of new hearth and chimney technology. Hearths designed for firewood lack the concentrated airflow and confined combustion chamber required to make most efficient use of hard coals. Food cannot be cooked directly over coal, because the noxious fumes poison the food and the cook alike. Thus households wishing to convert to coal would have needed to make a series of investments in new hearths, chimneys, and stoves. Anecdotal evidence suggests that the technology must have been well-known by the 1640s, when higher-class households in London came to rely on coal rather than wood. But widespread demand for coal would only have come with widespread adoption of coal hearths among the larger classes.

How much would such modifications have cost? Absent detailed construction bills for the period, the cost of raw materials and labor can provide an estimate. Beveridge (1939) provides the prices for timber, bricks, and mortar at Westminster Abbey in London at the middle of the 17th century. One thousand bricks (13 s.), a load of mortar (4 s.), and one hundred board feet of timber (6.25 s.) might have sufficed for a new chimney. The craftsman who built the chimney, in perhaps 3 days' labor, earned around £35 (700 s.) annually.(van Zandan, 2010) This would have totaled 30 s., or 4% of a craftsman's annual income. At a median coal-firewood price differential of 6.3 d. (0.53 s.) per million btu in London during this period, and an annual energy budget of 5 million btu, this investment would have repaid itself in around 11.4 years without accounting for discounting.[3] Thus

[3]See appendix A for more detail on the relative price data and conversion factors.

the price signals were not very strong given the relatively low cost of energy at the time.

A simple model will serve to demonstrate the relationship of the London housing stock to coal demand. I assume a housing stock at 1600, H_0, that consumes only wood. In each period t, a portion of that original housing stock δ wastes and is fully replaced. Population growth p creates a need for additional housing, which is fully satisfied. Thus the *per capita* housing stock remains constant. Both δ and p are constant for all periods t. Therefore, the housing stock at time t is given by 1.

$$H_t = H_0(1 - t\delta) + pH_0t + H_0t\delta \tag{1}$$

$$= H_0 + pH_0t^2 \tag{2}$$

When new housing is built, it adopts coal-burning technology at a rate θ_t. That is, for any amount of housing built at time t, θ_t is coal-burning and $1 - \theta_t$ is wood-burning.

Thus the number of homes built at time t that burn coal, $dH_{c,t}$ is given by equation 3.

$$dH_{c,t} = pH_0\theta_t + \delta H_0\theta_t \tag{3}$$

$$= H_0(p + \delta)\theta_t \tag{4}$$

$H_{c,t}$, the total number of coal-burning homes at t, is then given by equation 5. Equations 7-9 give the equivalents for the wood-burning housing stock. Note that this assumes that all new housing lasts indefinitely.

$$H_{c,t} = \int_t H_0(p + \delta)\theta_t \tag{5}$$

$$= H_0(p + \delta)\int_t \theta_t \tag{6}$$

$$dH_{w,t} = -\delta H_0 + \delta H_0(1 - \theta_t) \tag{7}$$
$$= H_0\delta(-\theta_t) \tag{8}$$

$$H_{w,t} = H_o\delta \int_t (-\theta_t) \tag{9}$$

Given this, the proportion of coal-fired homes in London at time is provided by equation 10.

$$\frac{H_{c,t}}{H_t} = \frac{H_0(p+\delta)\int_t \theta_t}{H_0 + H_0 pt} \tag{10}$$
$$= \frac{(p+\delta)\int_t \theta_t}{1 + pt} \tag{11}$$

This exposes a few different ways in which shocks can manifest themselves. If the rate of housing decay, δ, suddenly changes, then the share of the housing stock burning coal will change rapidly from time t to time $t+1$. Alternatively, positive or negative shocks to population may have the same effect. Finally, some change in the technology adoption rate (a function of the price / quality /availability of the technology) θ_t could also create rapid fluctuations in the demand for coal versus wood.

3.1 Identification strategy

This paper exploits an exogenous shock to the London housing supply to estimate how fast that change occurred. In 1666, the Great Fire of London began in a bakery and quickly spread to the adjoining homes. It proceeded to burn for three days. The Lord Mayor of London, judging that the fire so small that "a woman could piss it out", and reluctant to order the destruction of buildings to create firebreaks, delayed the firefighting effort until the conflagration had grown out of control. When the fire finally died out, it had destroyed the housing of about 90% of the residents of the City of London (the portion of London inside the old Roman Wall). That constituted about 13,000 homes for 70,000 residents.(Tinniswood, 2003) The concentration of fire damage in the poorer area of London inside the old Roman wall meant that the poor were particularly affected. In contrast, it did not reach the more aristocratic district of Westminster, nor the royal palaces at Whitehall.

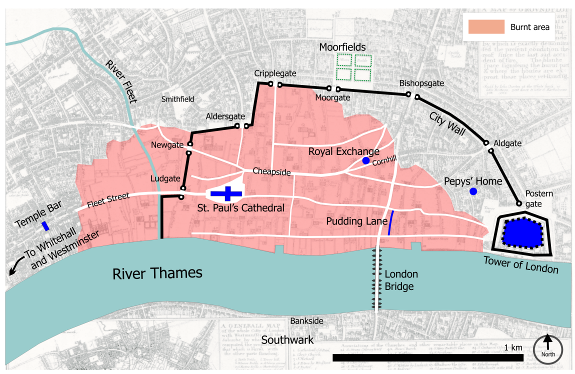

Figure 2: Map of the extent of the London fire

The Great Fire can be interpreted as a shock to δ in equation 10. The City of London suddenly had a much larger stock of housing to replace than it would have at any normal time t. For any $\theta_t > \frac{H_{c,t}}{H_t}$, the new housing would have burned coal at a higher rate than the housing it replaced. Thus the rate of coal use in London would be expected to grow very quickly in a short period around the fire. This therefore provides one measure of the rate of technology adoption. If no significant change in the rate of coal consumption is found, it suggests that coal adoption was far-advanced at the time of the fire. Conversely, if coal consumption is discontinuous around 1666, it suggests that at mid-century, the conversion of the London energy system to coal was still in progress.

Data on London coal consumption is available but limited. Flinn (1984) provides two potential measures, shown in figure 3. Most London coal supplies came from coastal shipments from the Tyne coalfields around Newcastle.[4] Thus data on the total coastal shipments of coal provide a proxy for London demand. After 1670, data on actual coal imports to London become more common. As the figure suggests, those data track reasonably well with coastal shipments after 1690, but poorly before that point. This paper assumes that shipment data is accurate for the period prior to 1700.

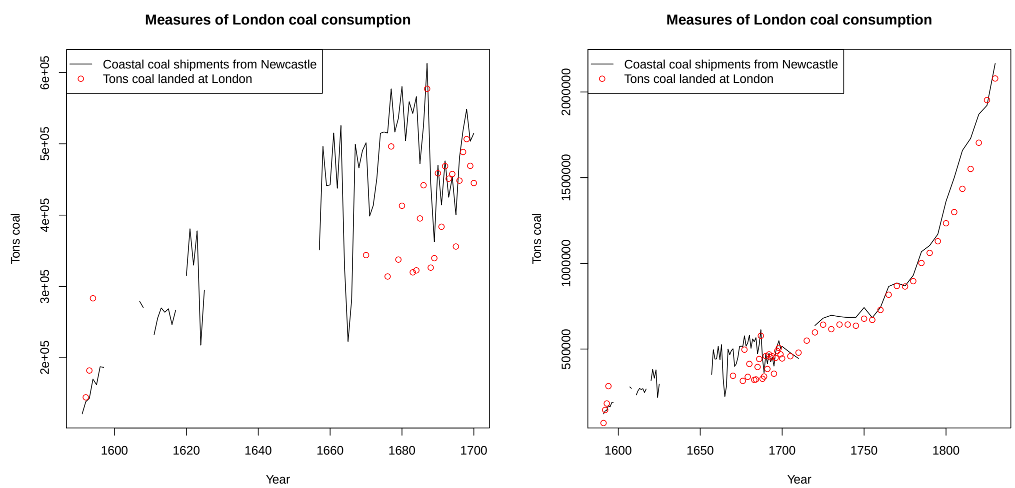

Figure 3: Measures of coal consumption in London in the 17th century

This data also presents three historical challenges. First, the 17th century saw numerous wars both within England and between England and the Continent. Both domestic and foreign wars disrupted coal supplies. Newcastle became a Royalist stronghold dur-

[4]Other coastal coalfields, such as those around Sunderland, also provided coal to London. But matching data series for Newcastle and Sunderland coal shipments aren't available. Overland shipments were prohibitively expensive until the construction of canal networks and then the railroad.

ing the English Civil War and lived under blockade until 1645. The First Dutch War (1664-1667) and the Wars of the League of Augsburg (1689-1700) both saw regular attacks on the east coast shipping routes that brought coal from Newcastle to London. Given the lack of economical overland transportation options, this would have severely depressed coal supplies and thus the rate of coal adoption.

Demand shocks were also common. London suffered two major plagues in the 17th century, in 1603 and 1666. The latter was particularly bad, killing 20% of the London population. Both population shocks would have depressed the residential demand for coal; the shock to the London coal supply is clearly visible in the years 1664-66 in figure 3. Given that London's population grew at a compounded rate of about 1% per annum over the period 1550-1700 (Harding, 1990), a population shock of 25% would have taken around 15-20 years to recover from, during which time long-term energy demand growth would have been depressed. Because these two years clearly deviate from trend substantially, I employ two methods to account for this. One method employs a set of dummy variables coding for plague years; the other imputes the 1664-1666 data on the basis of the prior linear time trend.

Third, any estimate of residential energy demand after the Great Fire must account for the lag that occurred in rebuilding the city. We shouldn't expect to find an abrupt discontinuity at 1666. Rather, the discontinuity should be estimated across some period after 1666. We can determine the duration of that period from two different historical records. First, the ambiguity of property rights required the Crown to establish the Fire Court in 1667 to adjudicate competing claims to land prior to rebuilding. Reddaway (1951) suggests that this court would have touched approximately 10% of the property in London. The Court sat from 1667 to 1672, and appears to have heard approximately 50% of its cases by 1670.(Jones, 1966) Separately, the terms of the Rebuilding Acts, passed in January 1667, required that every plot be re-surveyed prior to commencing reconstruction. Guildhall records provide the time and location of each surveying job.(Reddaway, 1951, chapter 9) Survey records cover approximately 9,000 plots, 90% of which had been surveyed by 1670. Thus it appears that the majority of the City of London housing stock would have been rebuilt by 1671-72.

Estimation of the discontinuity proceeds via OLS. Consistent with Perron (1989), the regression includes the time variable, dummies indicating the location and duration of the shock, and additional controls. Equation 12 provides the specification, where D is 0 before 1666 and 1 after, and T is 0 before 1666 and t after. Covariates, represented by X_i, control for winter temperature variation and the years in which plagues or wars occurred.[5] This estimate uses the data up to 1700. After 1700, the onset of the industrial revolution leads to clearly non-linear growth in coal demand that would distort the estimate of time trends around the neighborhood of 1666.

$$P = \alpha + \beta_1 t + \beta_2 D + \beta_3 T + \phi_i X_i \tag{12}$$

For each estimate, the discontinuity was measured between 1666 and 1672 on the basis of the model output using data with no plagues, wars, or temperature anomalies. 95% confidence intervals for each estimate were calculated using a parametric bootstrap. The fully-specified model was also run on a 5-year moving average measure of coal consumption. Confidence intervals for this version of the model were bootstrapped by first resampling the 5-year averages and then running the regression against the resampled averages. Raw regression results are presented in table 2. Estimates of the magnitude of

[5] Temperature data comes from the long-term European paleoclimate data estimated by Luterbacher et al. (2004). Temperature anomalies prior to 1658 use the winter temperature measurement. Data after 1658 use the January temperature measurement. All data are measured relative to the 1961-1990 mean temperature. Plague years are 1603 and 1665. War years are 1630, 1640-1660, 1665-1667, 1672-1674, and 1689-1700.

the shock and 95% confidence intervals are presented in figure 1. Projected data for each model are shown against the actual data in figure 5. The smoothed data are shown in figure 4, and the estimated effects from the smoothed data in table 3.

Estimates of the degree of discontinuity range from several thousand tons of coal to approximately one hundred thousand tons. If we assume a 5 million btu *per capita* energy budget per person *per annum*, then the 1670 City of London population of around 80,000 would have consumed around 400 billion btu per annum, equivalent to around 16,000 metric tons of coal. Thus if 50% of the housing stock had burned wood ahead of the Fire, and all converted to coal thereafter, that would have led to am 8,000-ton permanent increase in the demand for coal in London. This is most consistent with the estimate based on the imputed data, though this estimate is statistically indistinguishable from zero.

4 Discussion and Conclusions

With the exception of the implausible estimator containing no controls or imputation, all of the estimates of the London coal consumption discontinuity around 1666 failed to reject the null hypothesis of zero effect. Given the data available, there are two possible explanations, which the methods used here cannot distinguish. Either coal adoption had already reached 100% of the City of London housing stock as of the 1660s; or the rebuilt housing burned coal at more or less the same rate as the housing it replaced, within the resolution permitted by the data.

The former is consistent with the observed plateau in coastal coal shipping after 1670. If the majority of London homes had converted to coal by that point, and industrial growth had shifted to the Midlands or the North, coal demand would have been suppressed. The widespread adoption of coal is interesting given the apparently weak price signal presented by coal demand. Better indices of industrial production in London would have helped distinguish the suppression of coal demand growth owing to industrial flight from that of residential energy behaviors.

Alternatively, If the latter explanation holds, the results here suggest that a relatively weak price energy signal relative to incomes and capital investment may generate relatively slow progress in adopting alternative energy sources. Though the price of a btu of coal was on average only 63% of the wood price during the 17th century, wood appears to have remained popular as a fuel source. At the very least, we can say that Londoners did not find the lower variable costs of wood a sufficient incentive to switch to coal *en masse* when rebuilding their homes after the Great Fire.

Beyond the distinction between one-time and variable costs in influencing investment choices, several other explanations may support a slow pace of energy source switching. Political disruption was a common problem in 17th century England. The years from 1640-1660 saw the Civil War and the Commonwealth followed by the protectorate under Cromwell. During that period, coal shipments from Newcastle were disrupted by blockade. The political tensions at the heart of the Civil War began in the early part of the century. Hatcher (1993) records frequent changes to the taxes and shipping arrangements on coal consequence of the Crown trying to finance itself independently of Parliament. These disruptions may have retarded the adoption of coal as a fuel source independent of its near-term price advantages.

Second, the ownership structure of London real estate might have informed against making improvements. As the long tenure of the Fire Court suggested, control of property in London in the 17th century was contested. Many of the units would have been rentals as well. Those who owned would have been less willing to improve their lodgings if they couldn't be assured of capturing the value of those improvements. Landlords didn't pay the energy costs incurred by their tenants, and tenants couldn't improve the lodgings themselves. Thus while decaying housing would have been replaced with new technology, the standing housing stock would not have been touched.

In either case, the estimates here suggest that the state of coal technology adoption in London was not significantly influenced by the destruction of a substantial amount of capital stock. This informs against the view that only high fixed costs prevented energy source switching. Those costs would have been immaterial in new construction. Instead, the ambiguity that motivated this paper remains. The pace and form of residential coal energy adoption in London at the dawn of the industrial revolution remains unclear. That it mattered to the progress of conversion to a coal energy system is indisputable, but where and how that switch occurred requires further investigation.

A Data notes

The wood and coal price data provided in figure 1 derive from two sources. Beveridge (1939) provides prices for coal bought at Westminster Abbey by the London chauldron. A London chauldron was apparently equivalent to $\frac{8}{15}$ of a Newcastle chauldron, which was equivalent to approximately 1.7 tons of coal. Thus a London chauldron weighed around 0.9 tons. Coal contains in the neighborhood of 25 million btu per ton. Wood price indices have been calculated by Clark (2004) and are provided in s./100 faggots. That price was probably actually s./120 faggots. A cord of wood contained approximately 134 faggots and around 17 million btu.

	Estimated shock to coal consumption, 1672-1666 (tons coal)	2.5% CI	97.5% CI
OLS	64392.99	14008.60	114877.04
OLS, with controls	19176.09	-24965.62	63107.16
OLS, imputed data	4990.96	-34218.30	44526.87
OLS, imputed, omitting 1666-1671	24108.84	-23155.96	71614.30

Table 1: Estimated effects of the Great Fire shock, 1672-1666. Confidence intervals computed via parametric bootstrap. Discontinuities with controls were estimated with the controls set to zero.

Table 2: OLS regression results for unsmoothed data

	Original	With controls	Imputed	Omit 1666-1671
Intercept	-5137872.94^{*}	-6685746.52^{*}	-6852539.50^{*}	-6861376.77^{*}
	(692872.46)	(678055.70)	(551298.26)	(572693.48)
t	3346.33^{*}	4306.41^{*}	4410.36^{*}	4416.26^{*}
	(425.92)	(417.73)	(338.89)	(352.31)
D	5820942.84^{*}	5052432.63^{*}	7677062.77^{*}	9080071.88^{*}
	(2016986.67)	(1798089.69)	(1604857.02)	(2038095.94)
T	-3457.37^{*}	-3025.75^{*}	-4606.09^{*}	-5436.22^{*}
	(1202.94)	(1071.85)	(957.14)	(1212.17)
Temp	8789.24	241.67	5260.17	6724.74
	(6252.50)	(5632.14)	(4974.93)	(5353.17)
Plague		-198739.54^{*}		
		(58980.03)		
War		-62209.89^{*}		
		(18434.25)		
N	69	69	69	63
R^2	0.77	0.84	0.85	0.86
adj. R^2	0.76	0.82	0.84	0.85
Resid. sd	63879.63	54777.06	50827.14	50933.57

Standard errors in parentheses

* indicates significance at $p < 0.05$

	Estimated shock to coal consumption, 1672-1666	2.5% CI	97.5% CI
OLS	46864.98	15159.23	77575.11
OLS, with controls	28212.23	-4198.26	62643.72
OLS, imputed data	1139.01	-13462.18	16120.06
OLS, imputed, omitting 1666-1671	44137.85	17375.51	70416.58

Table 3: Estimated effects of the Great Fire shock using 5-year moving average data for coal consumption. 95% confidence intervals calculated via bootstrap.

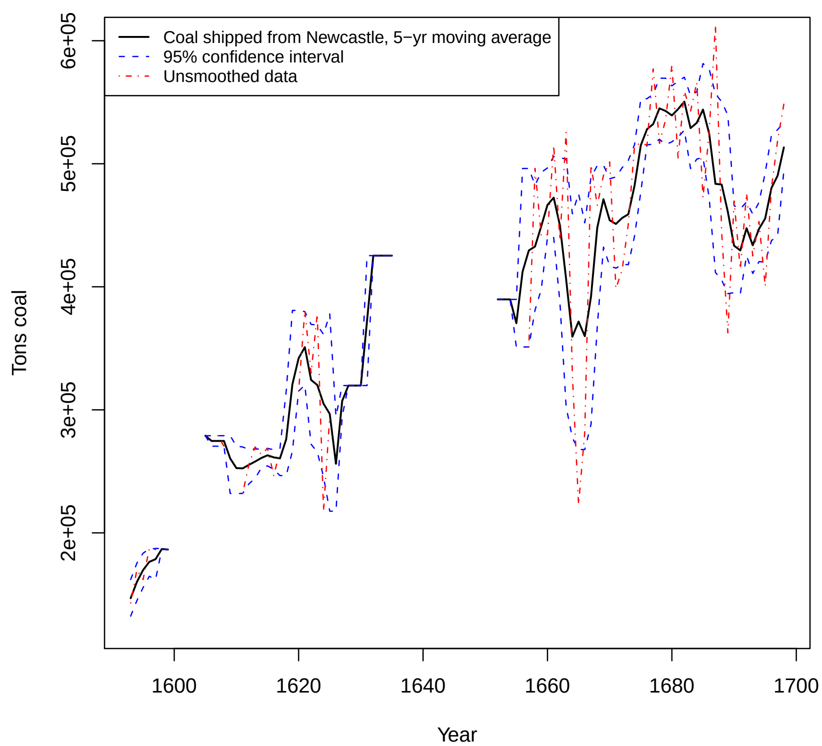

Figure 4: Smoothed coastal shipping data, 5-year moving average, with bootstrapped 95% confidence intervals.

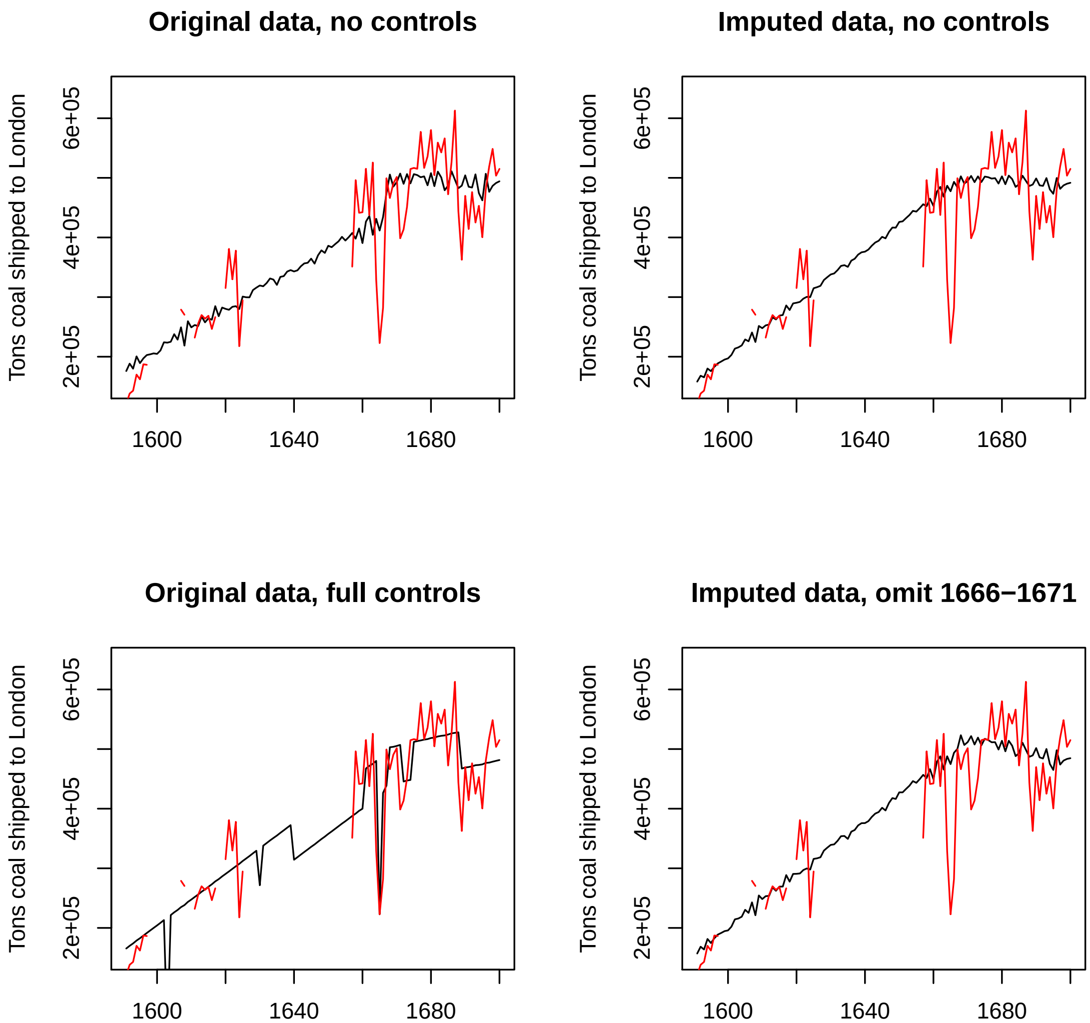

Figure 5: Regression estimates on the unsmoothed data. Original data in red; predicted values for each regression estimate in black.

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