Firewood consumption and energy transition: a survey of sources, methods and explanations in Europe and North America

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KEYWORDS: **firewood, environment, labour, energy.**

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This article surveys current literature on historical wood fuel use in North America and Europe. It focuses in particular on the quality of national-level data, highlighting and examining the different methods employed by official bodies to collect this; and in turn, the different assumptions used by historians to use partial data in models to estimate overall consumption. Problematic differences are revealed, along with the likely over-estimation of commonly-used data on the United States in the nineteenth century. It is shown that generally aggregate firewood consumption did not decline in many countries until after World War Two, and remained significant especially in rural domestic uses. The article concludes with a discussion of drivers for different levels of consumption and transition to substitute fuels, highlighting the limitations of price data and the importance of local labour markets for understanding the propensity to use wood fuel or switch to alternatives.

Consumo de leña y transición energética: un estudio sobre fuentes, métodos e interpretaciones en los casos de Europa y Norteamérica

PALABRAS CLAVE: **leña, medio ambiente, trabajo, energía.**

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El artículo revisa la literatura actual sobre el consumo de leña en Norteamérica y Europa. Se centra, en particular, en la calidad de las estadísticas nacionales, poniendo especial atención en los métodos utilizados por los diferentes organismos para recoger la información. También analiza las asunciones realizadas por los historiadores en sus reconstrucciones del consumo total de leña que, generalmente, están basadas en información parcial. Observamos diferencias importantes en los criterios y métodos descritos, que resultan, entre otras cosas, en la muy probable sobreestimación de los datos tradicionalmente usados para el caso de los Estados Unidos en el siglo XIX. *Mostramos que el consumo de leña no cayó en muchos países hasta después de la Segunda Guerra Mundial, y que siguió siendo muy importante en el consumo rural doméstico. El artículo concluye con una discusión de los determinantes del nivel del consumo y de la transición en la sustitución de combustibles, enfatizando las limitaciones sobre los datos de precios y la importancia de los mercados de trabajo locales a la hora de entender la propensión al uso de leña o la búsqueda de alternativas.*

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1. INTRODUCTION

In recent years the quantification of firewood consumption has shed new light on the timing and scale of historical energy transitions, following the pioneering work by energy analysts Schurr and Netschert (1960). International comparison has highlighted the enduring importance of "traditional carriers" for the energy mix even of many developed countries long into the twentieth century, and indeed more recent revivals (Kander, Malanima & Warde, 2013). Today, wood is reckoned to provide around 6% of total primary energy consumption by the FAO, but also to be depended on by around two billion people as a household fuel, or over a quarter of the world's population[1]. If we include all biofuels, whether harvested commercially or by households, these proportions might be substantially higher. This makes the position of firewood in energy transitions doubly interesting: both in understanding the historical transition to modern economies with much greater use of fossil fuels, and its role in the current and future energy economies, most especially in the developing world but also as a potentially desirable renewable fuel for high income households and industries. Indeed, having been framed as a problem since the 1970s due to feared shortages, and the health effects of indoor pollution, firewood and biofuel use now occupy a more ambiguous position (*e.g.* Eckholm, 1975; Agarwal, 1986). Rather than being an atavistic fuel destined to disappear, firewood can now be figured as a component of the bioenergy of the future. There is rich potential for comparison between literatures and across time and space, not least to call into question purportedly universal models of transition and highlight that benefits and costs were, are, and will remain specific to context (see for example Serrano-Medrano, Ghilardi & Masera, 2019).

However, any sound comparison depends on the quality and equivalence of data. The scale of use or the timing of transition between firewood and other fuels cannot yet always be identified with exactitude, even in well-documented countries. Indeed, because of the character of wood fuel whose supply is often highly dispersed and localised, escaping official statistics through household auto-consumption, exactitude may well be impossible. A first step in the comparison of levels and forms of consumption, and processes of transition, is to establish what data is available, how it has been compiled and thus what it *can* tell us. Without due care in this regard, the results of comparison could easily be spurious. This article examines such questions of data quality and method in regard to a range of historical examples and transitions covering western Europe and North America. The reason for choosing these particular examples relates partly to the author's own field of expertise, but also to the fact that the wider literature on biofuel use has largely

1. http://www.fao.org/forestry/energy/en/

concentrated on household and community-level studies in the developing world where firewood is more predominant, and the historical cases from Europe and North America are much less well known among contemporary scholars (although firewood use has by no means disappeared in the developed world). As well as contributing to a diversity of cases, some of the issues that arise in considering these historical transitions, especially at the national level, may be more widely applicable.

The first issue this article tackles is method. How do we know how much firewood was consumed? It is clear that official estimates in different countries were based on rather different methods, and in many cases severely under-estimated levels of consumption (*e.g.* Henriques, 2009: 38; Serrano-Medrano, Ghilardi & Masera, 2019). In turn, historians have adapted this information or generated their own proxies and estimates where official information is lacking. This was especially the case for rural household consumption, which both in the past and in the developing world today accounts for the majority of firewood use. The different methods employed in the historical cases will be considered in some detail. It is clear that consumption varied geographically within countries and between income groups. National averages, or share of wood use in total energy consumption, thus only present us with a limited understanding of the local importance and experience of fuel use (see Serrano-Medrano, Ghilardi & Masera, 2019; Infante & Iriarte, 2019). Equally, local case studies cannot be considered to be representative of a national picture.

It is only with this understanding of the quality of the data that we can move to considering both the scale and pace of transition; and the drivers of change. Here, even within a set of developed economies where fossil fuels have come to predominate in the energy mix to a greater or lesser degree, considerable variation can be found in the timing and nature of transitions. We do not find any standardised "energy ladder" by which consumers move monotonically through different energy carriers as income increases (Reddy & Reddy, 1994). Rather, a diverse range of factors may come into play. The importance of particularities of context have been emphasised in literature on the diffusion of new household technologies, especially the wood-burning stove and the failure of attempts to promote its use (Agarwal, 1983; Saatkamp, Masera & Kamen, 2000). One context that stands out in this survey of cases which has however received relatively little attention in the literature on Europe and North America is the importance of the *opportunity cost of labour* in determining household fuel choice. It may be that labour markets, with strongly gendered dimensions, only loosely connected to the availability of fuel, technology, and infrastructure, have played an under-appreciated role in driving transitions.

2. ESTIMATING FIREWOOD SUPPLY AND CONSUMPTION: DIRECT DATA

Fossil fuels are extracted from the ground at a relatively limited number of points, by identifiable commercial enterprises, and are taxed by governments at various points between extraction and retailing. Consequently records of fossil fuel consumers and producers are widespread. Britain's mineral statistics stretch back to 1853, for example, and numerous commercial and customs records allow estimation of coal supply right back to the sixteenth century. In contrast the supply of wood was diffuse, episodic, largely untaxed outside urban contexts, and often supplied through auto-consumption or informal markets. Thus any records give only a very partial picture of the total use of woody fuels and rarely rest upon large-scale collection of direct data before very recent times. As supply brought them no direct revenue, its enumeration was of little use to authorities. Even though fears of "wood shortage" were widespread across Europe from the sixteenth century, remedies very rarely aspired to a detailed quantification and balancing of supply and demand, but rather a combination of prohibiting of what were considered excessive levels of use by individual households, or stimuli to raise wood output (Warde, 2006a, 2015). Although control of levels of consumption by municipal or communal authorities was widespread, one must exercise caution in generalising such evidence.

As a result no direct national-level statistical information on firewood consumption of any kind was collected anywhere before the twentieth century. Although one can find estimates of deforestation and wood use for the United States stretching back to 1630, which have often been used to chart the course of American "energy transition", all pre-WWII data is actually based on occasional and partial surveys in the 20th century, and largely of farms (Song *et al.*, 2012; Clawson, 1979; Reynolds & Pierson, 1942). Before that time firewood consumption estimates for the United States were made for only one year, 1879. This was done by the forester Charles Sargent collating written reports of varying quality from correspondents in a range of cities across the country (Sargent, 1883, 1884)[2]. Nothing like a systematic survey was ever undertaken, and there seems to be little realization among later scholars as to how thin the data actually is. Later, more formal censuses of firewood use usually remained partial. Wartime shortages and efficiency drives resulted in the setting up of Fuel Commissions in Sweden during both World Wars, and war also prompted the report of the United States Department of Agriculture (USDA) after fuel shortages and a rise of firewood use in 1917-18 (USDA, 1919: 1-2; SOU, 1922, 1948). Brazil was among the countries that suffered from scarcity of coal during Second

2. Clawson also utilised estimates from the US forest service from the year 1930, published in 1946 and 1958.

World War leading to a surge in firewood use by industry and railways, and interest in data collection (Brannstrom, 2005: 402-3). Denmark included woodfuel consumption in its industrial censuses from the 1910s (Danmarks Statistik, 1959), whilst Portugal's industrial statistics of 1943, 1948, 1953 and 1958 give partial coverage (Henriques, 2011), as do Spain's from 1958 (INE, 1960-80). Often such surveys focused on supplies to industry, even though it typically had little more than a tenth of the market share in countries where we have data, with the relative inefficiency of wood-burning furnaces and costs of supply militating against the development of large-scale heavier industries in the absence of fossil fuels (see though Lindmark & Olsson-Spjut, 2019). 1920s Brazil may have been a twentieth-century exception where it rose as high as a quarter, if we include the extensive use by railways (Brannstrom, 2005: 412)[3]. Thus industrial censuses, which might also cover charcoal, represent only a particular segment of the market.

More widespread were farm surveys, often taken as part of agricultural censuses seeking to determine the overall pattern of farm incomes. For example, wood production and consumption was incorporated into decadal agricultural censuses in Canada from 1920. The most comprehensive estimates for Canadian firewood consumption were developed by Urquhart (1993) as part of national income accounting. Urquhart considered all pre-1900 estimates of consumption unreliable, but employed the 1920 and 1930 censuses that gave firewood production per farm and on-farm consumption, but not off-farm production; and that of 1910 that gave farm production but not sales; and of 1900, giving estimates of farm and non-farm production. Wood supply estimates from the Dominion Bureau of Statistics used by Urquhart were largely based on these agricultural censuses. It was not recorded where wood sent off-farm went (whether to cities, or non-farm rural households). Equally, in the Canadian case considerable amounts of wood were sold from Crown forests (which was faithfully recorded, in theory), or non-farm owners of woodlots (which was not). A startling drop in in official figures for firewood consumption between 1954 and 1956, from 11 million cords to 3 million cords, probably relates to a switch from using estimates based on the older agricultural census data to official forestry production figures (Unger & Thistle, 2013: 36). The economist Davis, in his survey of national energy consumption in 1957, reckoned on 7 million cords being consumed *per annum* but this may simply represent a mid-point between the two alternative available estimates (Davis, 1957).

The Canadian case illustrates a more general truth: fuel data in agricultural censuses was not generally universal, but aimed to survey some kind of representative sample of a

3. This is based on a household consumption of one ton per capita added to Freise's estimate from 1926 for 1920.

narrower population of interest to the enumerators of the time. The earliest rural survey of Sweden, for example, comprised only 667 households in the region of Värmland in 1921 (SOU, 1954: 29, 94). Some partial surveys also sought to capture fuel consumption across all kinds of households, with the Canadian census of 1941 seeking to assess the fuel predominately burned in 20% of all households (McFayden, 2016). Notably, this was a wartime survey and may not reflect fuel use in the period before or after the war. There was very great regional variation, a reminder that national averages calculated using assumptions about static household consumption may be driven by the regional distribution of population rather than changing habits among any particular households (see Serrano-Medrano, Ghilardi & Masera, 2019). American officials sent out 48,000 questionnaires to *county and crop correspondents of the Bureau of Statistics* including questions about fuel in 1908, but for smaller urban centres relied on the testimony of coal and wood merchants (Pierson, 1910). Such methods are likely to miss the poorer sections of the population. Equally, it may also be, as modern Nepalese surveys have found, that people tend to exaggerate their levels of consumption (Fox, 1984). In Portugal, rural firewood consumption was included in household investigations from 30s to the 50s (Henriques, 2011: 39).

Forestry authorities also provided data on firewood supply, sometimes from their own directly-managed stands, and sometimes also from commercial operators. Both these and agricultural censuses can be shown in the Spanish case to have greatly understated real yields (Infante *et al.*, 2014). Firewood was frequently a by-product of more valuable logging operations and not necessarily recorded in full. These supply-side records can be considered as bare minima of actual supply. However, in certain circumstances, the data is of relatively high quality, especially if the area of privately-owned woodland was relatively small. National data on wood (including firewood) production was recorded in a German census of 1899-1900. Previously, the forestry yield statistics of individual German states covered a large percentage of the wooded area, differentiated according to the type of wood harvested, and in landscapes generally without extensive growth of woody plants outside of managed woodland. This provides us with a reasonable estimate of supply at the scale of the region that can be aggregated to a national dataset, but is less valuable for telling us about the experience of particular localities (Endres, 1905).

There is a greater amount of information on fuel entering urban centres in many parts of pre-industrial Europe. Customs points on gates or wharfs were carefully monitored and urban authorities often paid careful attention to the supply of such a staple commodity. Hence information on the import of wood and charcoal into cities such as Paris, Madrid, Berlin, Lisbon and others is very good. Taxes on charcoal entering Madrid 1860-68 allow an estimate of 1.8 kg/person day being consumed in 1860, a little lower than provided by data for the late 18th century (Bravo, 1993: 20-2). Lisbon maintained a firewood and charcoal tax from 1854-88, and charcoal only until 1922. In her study of the city Sofia Henriques argues that domestic fuel was largely charcoal, with consumption being around 1.8 kg/day per capita in wood equivalent to the 1880s, falling to down to below 1 kg by 1922, compared to 2.4 kg in the countryside in 1930s surveys. The problem remains in relating this data to wider patterns of consumption when the bulk of the population was rural; official data appears to have been underestimating this demand even in the 1980s and 1990s in Portugal (Henriques, 2011: 36-40). Sometimes it is not even clear whether rural consumption was lower (as one might expect given higher urban incomes) or higher (as one might expect given the cost of delivering fuel to the city).

Given these circumstances it is not surprising that historians have almost universally until very recently employed more anecdotal data about the scale of wood use, a "hit and miss" approach that certainly has some value in developing plausible impressions of the scale of use. Overviews have been significant pioneers in the field but relied on a small number of rough estimates from secondary literature, without necessarily investigating their origins (see for example, Malanima, 1996: 54; Braudel, 1981: 367; Toutain, 1961: 132-33). And the problem is, of course the "miss". While we can enumerate numerous estimates or testimony of wood use in particular households in many parts of Europe, the bias of information is most likely towards wealthier members of the population. Equally, regional variation was clearly high, and in establishing per capita usage, we are also faced with considerable differences in the size of households. It is also the case that such information, lacking any broader statistical basis or clear comparability over time, cannot tell us much about *transition*, but rather focuses on giving a broad impression of the importance of wood to households that did use that fuel. The range in a broad European sample runs from households consuming around 0.5 m^3 (a cubic metre of wood typically containing around 600 kg, but with considerable variation) of solid wood each year to forested regions estimated to consume up to 8 m^3, although most fall in a much narrower range of 1-2 m^3 (many dozens of works could be cited in this regard; for some broader surveys of this evidence, see Warde, 2006a, throughout Schmidt, 2002, and Malanima, 1996: 52-5).

3. ESTIMATING FIREWOOD SUPPLY AND CONSUMPTION: MODELLING

In attempting to move beyond the limitations of the "hit and miss" approach, historians who have attempted a more statistically-based analysis have resorted to modelling under certain assumptions. This can be done on the basis of the demand side, or the supply side. In areas with very extensive wooded areas, or access to a supply of woody off-cuts, the supply-side potential may far exceed annual demand and gives little helpful information. However where wood fuel supplies are relatively limited, and yet there is no evidence that they rapidly disappeared, the possible range of supply is constrained between figures for sustainable annual yields per hectare from similar kinds of woodlands we can measure today, and data on wood supply per area available from contemporary sources (generally lower than the level now achieved). This was the method applied to England and Wales by Warde, though having to take into account the widespread provision of wood from individual pollarded trees and hedgerows; such a method establishes, we should stress again, a plausible range of possibility rather than an exact figure (Warde, 2007; on the importance of pollards and hedgerows, see Williamson, Barnes & Pillatt, 2017: 59-68). Work on Spain employs a more sophisticated version of this approach, using data of forest surface and firewood productivity by hectare for eleven benchmark years over the twentieth century (Infante *et al.*, 2014). This could give a maximum of firewood potential production coming from forests. To this is added firewood coming from woody plants growing in farms outside of the forests (vineyards, olive trees and fruit trees). Such supply-side estimates have been combined with demand-side to estimate woodfuel use as a residual when other uses can be quantified, and taking into the account the distribution of population that did not have affordable access to alternative fuels (Infante & Iriarte, 2019).

Other attempts have been cruder. Hoffmann took data on firewood supply in Germany from 1900 and 1912 and projected a trend between these two points backwards to 1888, and then assumed it remained static before that date with no close reference to incomes, prices, or the availability of alternatives. Hoffmann estimated that prior to 1888, total firewood production was stable at 32 million m^3 (Hoffmann, 1965). Instead, Warde used a weighted estimate from regional statistics for state-owned forests, assuming that yields across types of ownership (state, private and communal) were equal, and applied them to data on the extent of woodlands in each region. Warde's German series show, in contrast to Hoffmann, total firewood production rising from under 25 million m^3 (solid) *per annum c.* 1800 to peak at 37.7 million m^3 in 1874. By 1888 it had fallen to 33.5 million, by 1914 29 million and was a similar level in 1939. The level had fallen to 15 million in 1948 and was *c.* 5 million in 1960 (based on data in Endres, 1905; and later German national statistics)[4].

More common is modelling from the demand side, but it is important to realize that historians have made very different assumptions in their models. The most widely-employed model (often by people who will have no idea that it is a model) was produced by Pierson and Reynolds in their report of 1942, estimating US fuel wood consumption back

4. The series is provided at www.energyhistory.org

to the seventeenth century. They linked agricultural census data collected by Pierson with estimates of regional consumption from 1930 in a model to project firewood consumption far back in time. Unfortunately, they did not specify how they calculated any of the variables, so there is no means of assessing the reliability of their approach. They simply state, *The rates used are intended to include both domestic and industrial consumption and take into consideration the climate, the timber, the characteristics of the population, housing conditions, the shift from fireplaces to stoves and the displacement of wood by mineral fuels* (Reynolds & Pierson, 1942: 9). If we examine historian Bill Cronon's estimates of New England houses burning an astonishing 30-40 cords annually in the colonial period, we find that he is, in fact, simply citing the unsubstantiated estimates of Pierson and Reynolds (Cronon, 1983: 120-21). We will have cause to discuss the plausibility of the results further.

Recently Josh McFayden, in seeking to improve the quality of information on Canada, made the assumption that, *Occupied dwellings required a relatively consistent amount of energy for heat regardless of the number of occupants* (McFayden, 2016; see also Urquhart, 1993). This implies there is no price or income sensitivity to fuel, which would affect the number of rooms heated or the length of the heating season. Certainly *some* case studies have found that household size affects consumption levels, for example in Costa Rica (Lemckert & Campos, 1981). Habits certainly differed between populations, even with comparable climates. The Swede Per Kalm was astonished to find American households heating *for nearly half the year*, a length of time confirmed by Samuel Breck in Philadelphia in 1808 (Cronon, 1983: 121; Peterson, 1950: 22). If we assumed, as some historians have done, that household demand for firewood is relatively constant, they imply that the income elasticity of demand is zero. This is problematic for a number of reasons, and not only because higher real income might lead to higher fuel consumption (in which case income elasticity of demand might be closer to 1, if the share of income spent on fuel remained constant). It is quite possible that *nominal* increases in income, if accompanied by a loss of rights and marketisation of fuel, could in fact lead to *falls* in fuel consumption. Furthermore, we must guard against the assumption that the demand is purely for heat energy, that is, the consumer will purchase the same amount of heat irrespective of energy carrier. It does seem that some income groups paid a real premium to consume wood above coal. Were this the case, whoever made the switch from firewood to coal could immediately greatly increase the heat energy consumed if they did not reduce the amount of money that they spent on fuel. Rather limited evidence from English labourers' budgets suggests that coal users actually paid a much larger share of their *wage income* on fuel than their peers who used turf or wood (Eden, 1797; Davies, 1795). This is probably because they had to purchase coal on the open market, while wood or turf costs for many poor in the countryside actually largely comprised the labour of going to cut or gather it.

It is thus clear that simply assumptions used on modelling fuel consumption carry implicit, and frequently unreflected, implications for household economic behaviour. It is important to think about the realism of such implications (which may be more or less appropriate in different cases). Fuel consumption also features in estimates of household budgets which are widely used to estimate trends in real income over time. These often make the assumption, for obvious reasons of clarity and simplicity, that the price elasticity of demand for fuel is zero, or completely inelastic[5]. This is, of course, improbable. Thus these models consider real fuel consumption to be constant over time, resulting in fuel taking up a rising share of household income as prices rise. This is not very compatible with the idea of unitary income elasticity of demand, because rising fuel prices in that case depress real income and should reduce demand. Neither are these assumptions backed by the limited empirical evidence we do have of shifts in average consumption levels, although for reasons already outlined, these do not trace changes in the consumption of *individual* households, and thus may arise from changes in *distribution* of kinds of households, among other factors. To these complications we may add variations in supply and *availability* that clearly do shape consumption when viewed on a regional level.

The distributional issue is highlighted in Table 1, presenting what are almost certainly exaggerations of firewood requirements per household from a Prussian survey conducted in 1799-1800, given that the figures are much higher than those found in most others sources for central Europe (Gleitsmann, 1989: 202; but see Schmidt, 2002; Warde, 2006b). What is of concern however with this example is not *levels* of consumption but the *differences* between households.

TABLE 1

Firewood consumption per households in Prussian sample, 1799-1800

Group	Firewood consumption (stacked m^3)
Poor	2.0
Workers and more lowly artisans	11.4
Retailers and artisans	16.7
Cotters	20.0
Smallholders and smaller farmers	26.7

Source: Gleitsmann (1989: 202).

While it is possible that some differences are caused by variations in household size, these figures suggest higher rural wood use, and consumption differentiated by income. Clearly

5. There of many of these but they follow the same basic procedure; hence they are not referenced here.

any aggregate or average consumption figure will be in part driven by the social structure of a given society. The gap between the fuel consumption of workers and more prosperous artisans here suggests that an income elasticity of demand for fuel of 1 may be reasonably accurate, but the huge gap between the poor and other workers' households suggests that at a low level of income the figure may be rather more than 1. Thus wood fuel may be a good for which elasticity of demand varies over the income scale.

Historians of Sweden, such as Kander and Lindmark, have adopted different assumptions: that room heating varied over time, with the amount of space heated rising with income, but that this increasing demand was counterbalanced by the spread of more fuel efficient stoves (Kander, 2002; Lindmark & Andersson, 2010). This mimicked post-war official data that produced assessments of firewood use separated out into space heating (differentiated according to whether centralised systems for apartment blocks were used or not), heating water, cooking, or equipment that could combine these services (SOU, 1948). Given that there is no Swedish data beyond the anecdotal from before the 1920, Kander and Lindmark have developed models of national consumption based on back-projecting figures from that date, combined with demographic data on regional populations and the rural urban divide given that these clearly did affect fuel use. McFayden, in contrast, includes an efficiency parameter by assuming a slow decline in average household fuel use of a cord a decade from around 1870 (McFayden, 2016). We may consider these very different approaches more or less plausible, but in the current state of knowledge they cannot move beyond broad assumption. A more unusual method has been employed in Belgium, experimentally heating older buildings to calculate changes in efficiency of heating space since 1800. This however rested on the assumption that the full living space was heated to a "comfort" temperature of 18 °C for 12 hours per day, when necessary, across the year. This is almost certainly a huge overstatement of the daily temperatures actually achieved or indeed desired in households where much labour took place outdoors (*e.g.* Brewer, 2000: 16, 41; De Vooght *et al.*, 2006).

4. COMPARISONS

Our results can only be as good as the data we have. Supply side methods of accounting attempt to set a ceiling on possible consumption, while demand side estimates face the question of the representativeness of reporting. Of course, all are prone to error, and we must stress that we are not examining the consumption of non-traditional fuels generally, which would include peat, turf, gorse, and in some instances even dung or straw. In addition, comparisons can only be approximate because of different measurement practices and qualities of wood. Most wood consumption was measured as stacked –a volume measure that contains a considerable amount of air. This alerts us to the important distinction between *Raummeter* (stacked) and *Festmeter* (solid) in German, or what are called cords "superficial" and solid in English. Measures typically use a multiplier of 0.6-0.7 to reduce stacked to solid timber but the figure might vary depending on the size of the wood and density of stacking. To convert this into standard energy measures such as calories or joules, or a solid mass, then we must deal with the problem of different types of wood having differing specific weights and energy content, even when dry. Poplar, for example, weighs around 0.45 g per cm^3 when dried (down to 12-15% moisture). Hornbeam on the other hand weighs 0.87 g per cm^3. National statistical bodies have used differing estimates of the energy content of wood, from 5.45 gigajoules (GJ) per cubic metre in Italy to nearly 9 GJ in some Swedish cases (Kander, 2002)[6]. This matches the range of possibilities in that different woods may contain anything from 13 to 23 GJ per cord. Canadian historians have reckoned on a cord of drywood being equivalent to the heat content of a ton of coal, although generally the maximum content of a cord of wood can be considered only two-thirds of that of a ton of coal (29-31 GJ/t). American railroad companies reckoned 2.5 cords to be the heat equivalent of one ton of coal; post-war Swedish authorities, dealing with northern softwoods, that just under two cords were equivalent to a ton of coke (McFayden, 2016; Cole, 1970: 353; SOU, 1948)[7]. Some woods like the preferred hickory were calculated in the nineteenth century to approach the heat content of coal, but most fell far short of this. The precise yield may depend on the use to which the fuel is put (Bull, 1830: 23, 60). It is unclear whether national differences reflect differences in the mix of wood being burned, or simply variation in measurement practices.

With these caveats most evidence, or perhaps more frequently arguments, present a comparatively narrow range of per capita consumption. At the top end would be American Canadian estimates for 1870 and earlier at an annual level of around 4 cords per person –up to 10 m^3 of solid timber or 16 kg/person/day. By the 1920s and 30s Urquhart sets the level in wood-burning households at a little over 1 cord per person off-farm and 2 or more cords on-farm, that is, around 5-6 cords and 9-10 cords for each type respec-

6. Data on Italian estimates was kindly provided by Silvana Bartoletto of the Parthenope University of Naples.

7. A ton of coke has slightly more heat content than a ton of coal, although it has a higher primary input in the coal from which it is produced. McFayden and Unger and Thistle's figures imply a cord of dry wood being 28 GJ, but this seems very high. In fact it seems to imply that it is solid rather than stacked wood. Reynolds and Pierson also addressed this question from US forestry data, finding only in a few exceptional woods such as hickory did a cord of wood (90 ft^3 dried) come close to the value of a short ton (2000 lb) of coal (Reynolds & Pierson, 1942: 7). On Canadian wood heating values, see http://www.seymourarm.net/docs/heat%20values%20of%20wood.pdf

tively (McFayden, 2016; Unger & Thistle, 2013; Urquhart, 1993)[8]. These latter give a rough range of 5-10 kg/person/day, but would translate however to an average of only one cord per person *nationally*. McFayden believes in higher levels, based on 14 cords being consumed per reporting farm household (perhaps 3.5 per person) in data from as late as 1951, and as much as 18 cords in 1931 (nearly 4 cords per person) (McFayden, 2016)[9]. McFayden's figures imply wood-using farms burning on average as much as 65 m^3 of stacked wood *per annum* as late as 1931, an estimate which must stand at the very top of the range of possibility, and requires farms reporting extensive use of their own woodlots being treated as representative of wood-using farms in general. In contrast, wood-dependent farms surveyed in inland Norrbotten, near the Arctic Circle in Sweden, consumed only around 37 m^3 of stacked wood in the 1940s (SOU: 1948).

Thus depending on which figures we choose, comparison between Scandinavia and Canada might suggest rough equivalence, or a much more fuel intensive domestic life in North America. 1920s surveys of Sweden suggest a national average consumption of 2.6 m^3 (solid) per head in the countryside (4.6 kg/person/day), although the rural north used some 4.7 m^3 per head (8.7 kg/person/day), close to Urquhart's estimate for Canada in the same period. We have seen that interior farms in the sub-Arctic north would have burned rather more. By 1950 the national average had fallen to 1.1 m^3 and 0.37 m^3 by 1965 (Kander, 2002). Pierson and Reynolds' estimates for the United States range from around 12-18 kg/person/day for the highest levels of per capita consumption in the first half of the nineteenth century, but was under 2 kg/person/day by 1950. As a *national* average across the whole of the United States these are very high. As we have seen they have no direct empirical basis and the model used is unknown. By 1900 these figures were much lower at around 3.2-4.5 kg/person/day (comparable to early twentieth-century Sweden), although by this time coal had made major inroads into the American energy supply. By 1920, this had fallen to 1.9-2.7 kg/person/day (Reynolds & Pierson, 1942). In the nineteenth century rural Brazilians are estimated to have used around 2.7 kg/person/day, mostly to keep a constant kitchen fire and process crops, but the dwellers of Rio only half this in 1888 (Dean, 1995: 195).

In Germany, official statistics suggest "firewood" *(Brennholz)* consumption per capita at 0.77 m^3 (solid) in 1872-75, falling to 0.5 m^3 by 1900. However *Brennholz* is a quality category of wood and if we assumed that all smaller diameter wood was also burned, this would raise the amount by 0.2-0.3 m^3, to around 1 m^3, or around 1.7 kg/person/day (Endres, 1905). This was decades after Germany's rapid transition towards coal use that took

8. In 1921 average rural household size was 4.6 in Canada (Basavarajappa & Ram).
9. In 1951 average rural household size was 4.1 in Canada (Basavarajappa & Ram).

off in the 1850s, but even in the century before that transition, *average* consumption was probably little different (Warde, 2006a). Most European estimates fall into this range, and are clearly far lower than norms in North America. The most recent Spanish series, higher than previous estimates, begins at 3.1 kg/person/day in 1860, declining slowly to 2 kg/person/day by the 1910s and marginally less by 1950, before reaching 1 kg/person per day around 1960. Portuguese figures are in a similar range (Infante & Iriarte, 2019; Henriques, 2011). Urban Sweden, where wood stoves were used, also used a similar amount in the 1910s (almost certainly rather more efficiently than rural counterparts): 0.9 m^3 per year or *c*. 1.6 kg/person/day. National estimates of early modern Italian consumption and sixteenth-century England, before the take-off of coal use, come in similarly between 1 and 2 kg/person/day (Warde, 2006a, 2007).

What is clear, and of course unsurprising, is that firewood use varied enormously regionally, and national averages may disguise as much as enlighten. This aggregate of demand does not tell us much about individual household use of wood if alternative fuels are available. As McFayden notes, *Only Southern Ontario, the treeless districts of the prairies, and the coal-rich districts of Newfoundland, the Southern Gulf of St Lawrence, and the Southern Rocky Mountains were home to more dwellings heated by coal*, as late as 1951 (McFayden, 2016). During Second World War nearly half of all households in Canada still relied predominately upon wood. Similarly, and unsurprisingly, wood consumption was much higher in the more forested southern regions of Germany than the north, where peat and turf was available as a substitute fuel. Modelling suggests very varied access to woodfuel in Spain associated with variations in woodland cover but also cultivation of woody crops (Infante & Iriarte, 2019).

The estimates of Pierson and Reynolds for the United States are built up on a state-by-state basis and can be converted into per capita regional estimates. Surprisingly, they imply that it was the southern (and warmer) states of the old confederacy that took the lion's share of national consumption, from 46% in 1879 to 61% in 1918. This reflects in part the earlier penetration of coal into eastern and northern markets, but is also a result of per capita firewood consumption in the south being very high: over 20 kg/person/day in 1879 in Tennessee, Kentucky, North Carolina, Arkansas, and even, allegedly, on the coast of the Gulf of Mexico in Mississippi and Alabama. Georgia and South Carolina are not far behind[10]. These are similar to levels found in Wisconsin and Michigan, and are

10. Pierson and Reynolds must have assumed equally high levels of consumption in the north-east in the early nineteenth century to reach such a high national average, although in the Boston region around 1829, no more than 1 cord per person was consumed, or 2.35 m^3. Based on a population of 92,989 in Boston in 1830, with 120,000 cords being consumed in the Boston-Cambridge-Charles-

much higher than Dakota or Montana and, indeed, the most fuel-intensive provinces of Canada (Reynolds & Pierson, 1942). Although halved by 1908, they remained notably high in these southern states. It is possible that consumption *per farm* in twentieth century surveys is exaggerated, leading to overstated aggregate figures in the south because, as noted in 1908, there was a *large number of tenant houses and cabins on the large plantations* and multiple households may have been reported as a single farm unit (Pierson, 1910: 3).

Why would such southerly regions consume so much wood, and why would on-farm consumption half between 1879 and 1908 if no substitute fuel had been introduced on a major scale? Perhaps the likeliest answer is that the earliest estimates from 1879 are wrong. Gary Nash's work on rural Virginia reckoned an "average laboring-class" rural family to use 5-10 cords annually; Williams reckoned on 15 for an "average farmer". Estimates assembled by Jones for Philadelphia show a range from 24 cords annually for a wealthy household to eight cords being typical, and two and a half cords for heating for the poor around 1830. In other words, an annual cord per person represented the average (*c.* 2-2.5 m^3 solid). Other contemporary estimates reckoned on 5-6 cords per fireplace. Even allowing for urban scrimping, these are very much lower than the Pierson and Reynolds estimates, and also match better observations that fuel could be expensive in urban America, albeit this took up only a tenth of the population at this time (Brewer, 2000: 28, 31, 39, 64; Jones, 2014: 47; Peterson, 1950: 22; Williams, 1980: 9). In contrast a farming magazine exhorting readers to economy reckoned two fires burning year-round (itself profligate by global standards) could be fed by ten cords of wood (Green, 2006: 387). Yet even as an idealized goal, this again stands well short of the 4-5 cords *per person* for the entire community, rich and poor, implied by Pierson and Reynolds or reckoned by Sargent for 1879. Indeed in Sargent's case there is a very large gap between his extrapolated figure for demand, and on-farm production that would cover only a third of this sum (Williams, 1987: 110).

If we may make some tentative generalisations, in Europe, it seems that outside of the cold north, annual consumption during early industrialisation fell between 1 and 2 m^3 per capita each year, equating to a similar range in kg/day. North American consumption was certainly much higher but regionally differentiated and there must be some doubt regarding the higher estimates. Such doubt must also affect our view of aggregate firewood supply. Nevertheless we can make some clear statements about chronology. There were

town region in 1829. Williams claimed 1.2 million cords being consumed in Boston but this seems a simple error, especially given that only 2.8 million cords were reckoned to be sold along the entire eastern seaboard in 1840 (Cole, 1970: 348; Williams, 1980: 9).

apparently peaks in total firewood consumption in the USA and Germany around 1870. War tended to lead to revival in firewood use. But most notably, rapid decline was rare in our sample of countries until much later, during the 1940s and 1950s. Thus in aggregate, firewood does not disappear with the rise of coal, even though it declines in relative importance and direct substitution was widespread in places where coal became cheap, as in Britain, parts of Germany and urban North America. Indeed urbanization was a major driver of changing *share* of woodfuel in the residential energy mix. As late as 1945, wood provided 23% of total residential energy consumption in the USA (Song *et al.*, 2012: 2117). One set of estimates is that in 1950 wood still provided 16% of *total* primary energy in Spain although the latest data suggest a higher figure; 22% in Italy; 23% in Sweden; 44% in Portugal; and 10% in France (Kander, Malanima & Warde, 2013)[11]. This was probably largely for rural domestic use. It is the rise of oil, gas and electricity in the countryside that really impacted on absolute levels of firewood production in the post-war period.

5. EXPLANATIONS

What might explain the different levels between countries, between different regions within countries, and over time? It is unlikely the data will ever be of sufficient quality to be usefully subject to a statistical analysis. We can draw on the literature surveyed however to consider shortlist of possible explanations that might operate independently or in tandem.

1. Use in households for cooking and heating (which might be related to both the average number of days of frost and cultural expectations of ambient heat).

2. Other household or on-farm uses, such as heating fodder for animals.

3. Availability of wood fuel (proximity of dwellings to forests or other sources of wood fuel).

4. Availability of substitutes such as peat, coal and later oil and gas.

5. Opportunity cost of labour (both within household, with likely gender differences, on-farm, or in the waged labour market).

6. Price and income effects (that could feed back into cultural habits).

11. The total includes coal, oil, water and wind, but not food or fodder.

7. Urbanisation (although related to price and income effects).

8. Level of industrialisation (scale of industrial sector and related transportation which also affects availability of substitutes).

There is some evidence that fuel availability affected cooking practice. Regularly cooked meals and pottages appear to have been more frequently consumed on the coalfields of England than in some areas dependent on wood in the nineteenth century. Fredric Eden argued that this was why the north of the country ate more meat and the south more cheese in the 1790s (Eden, 1797). Evidence from Europe also points to fuel scarcity encouraging the use of bakeries and food retail outlets when fuel prices were high (*e.g.* Warde, 2006b: 270-74).

Overall our data suggests that there is not a clear-cut relationship between climate and wood consumption. Wood consumption was certainly higher in northern Sweden or Canada than more southerly countries. However, consumption in Quebec was much higher than in the Prairie states; consumption is also recorded as being almost as high on the regions abutting the Gulf of Mexico as the Great Lakes; and German consumption of firewood was no higher, and possibly less in some periods, than in the Mediterranean. These results suggest that the *availability* of firewood is a key and possibly more significant factor than climate; pre-industrial levels are driven by supply rather than demand, which would also explain very high levels of consumption in regions of frontier expansion –so long as they were wooded. Indeed, the stock of wood per farm recorded in the USA in 1910 and 1919 was considerably higher in the southern states where consumption was also higher (Williams, 1987: 112; USDA, 1919: 8). In regions where woody crops such as vines and olives became more commercially important, in much of Mediterranean Europe, the provision of fuel remained complementary to the agricultural economy until after the Second World War when increased labour costs and the availability of cheaper, more flexible fuels in the shape of electricity, butane gas and oil. Their availability was linked to a new transport economy by which fuel acquisition was complementary to engagement with other forms of provisioning and off-farm work. Until the latter part of the 20th century the lack of efficient mechanical means of disposing of waste wood from crops and forestry may also have increased its use as a domestic fuel.

Our understanding of fuel prices remains limited. It was not unusual for wood and charcoal to be more expensive than coal by heat content and weight, where markets for both existed, indicating a consumer preference for wood that also related to having the capital equipment to burn it effectively. However, big city wood prices are not very representative of the country as a whole, because a significant share of the retail price is transport costs –as with coal, and indeed with a higher heat to volume ratio coal is usually cheaper to freight. Calculating prices for *heat* is fraught with conversion problems mentioned above, to which we can add the *quality* of the wood provided. McFayden records that in Canadian cities, greenwood prices were much lower than drywood prices (and surges in demand for wood during cold years must have been met by greenwood). In more commercial markets this differential makes sense given the capital that was tied up in seasoning woodpiles over many months.

In contrast, when a very high proportion of supply was on-farm, the notional level of the *wage* must have been at least as important as the retail cost of fuel in determining preferences, and generally was much cheaper than fossil alternatives until the appearance of the truck and affordable petrol. Then, either the supply of fossil fuels to the farm, or the trip to town to collect supplies could be bundled with a number of other purchases and activities. Household budgets for English labourers from the 1780s and 1790s reveal that it was not unusual for poorer households to pay nothing at all for fuel, either because they received it from welfare authorities, or because they gathered it as part of common rights, or indeed stole it! Although frequently excluded from a share of the common lands, many poor households across Europe gathered their fuel, even in the nineteenth century, rather than purchasing it. This was not of course costless; an opportunity cost for the labour involved is implied. Michael Williams' reading of American farm diaries shows that farmers spent between 14 and 17% of their working days on these processes, and in Upper Canada J. David Wood estimates that as much as 25% of farm work was for this purpose. By way of comparison European urban labourers are commonly reckoned, in household-budget approaches, to have spent between 5 and 10% of their income on fuel (Williams, 1989: 134; McFayden, 2016; Brewer, 2000: 40). Woodcutting was often considered a winter activity because the slack agricultural calendar meant the opportunity cost was low relative to alternative tasks, and in snow-bound countries, removal of cordwood from the forest was easier. American forestry officials in 1919 reckoned that in the case of hardwoods, the total labour time per cord involved in cutting, splitting and "bucking up" the wood into fire-ready logs could take approximately 2.67 days for the least efficient worker to one day for the best woodsman (USDA, 1919: 11-2). On this reckoning, a single, less efficient worker (of which there must have been many) would have had to prepare fuel for at least two months according to the highest estimates of consumption, and more in earlier times if tool quality was lower. Given this we might hypothesise that the appearance of high-quality tools, and especially power equipment, reduced this cost and actually *increased* levels of use as we come closer to the present, contrary to common assumptions based on efficiency of heating equipment meaning consumption was higher the further back we go in time. Lindmark noted that the rising price of labour increased charcoal costs (a relatively labour-intense fuel) in Sweden from

1890s and made coal relatively cheaper (Lindmark & Olsson-Spjut, 2019). Given the large amounts of labour-time required for wood felling and chopping, any rise in off-farm wages or opportunity for more continuous agricultural labour would have made self-supply of fuel less attractive.

The appearance and dissemination of new technologies widened the choice of alternative "modern" fuels, although most of the new stoves and cookers of the nineteenth century, and steam engines could use both firewood and coal. In the case of the engines, the sheer volume of wood required was problematic, and so widespread use only became feasible with the emergence of more efficient models across the nineteenth century. In many regions however the extension of the rail and navigable waterway network had the effects of lowering the price of coal, but in some periods access to efficient engines or stoves *opened up* the possibility of continuing to use wood with more modern technology. It is certainly not the case, however, that people automatically invested in the most efficient solution. The famous distinction between the open fires of the British Isles and some other parts of western Europe, and the moveable iron or fixed tile stoves of the centre and east of the continent, was replicated across the Atlantic. British emigrants long stuck with their inefficient fireplaces, while Quebecois or Germans in Pennsylvania used stoves (Brewer, 2000: 18-26, 36-7, 52, 60-1; McFayden, 2016). In 1910 Pierson blamed the high fuel consumption of the southern states in part on their preference for the open fireplace over the northern stove (Pierson, 1910: 3). Stoves were frequently substantial investments, however, and beyond the poor. The cheapest examples advertised for cottages in England around 1800 would have required £12 to £20 in coal to maintain a daily fire, when the very best labouring wages would have fallen around £35-£40 *per annum* in the capital. Such expense was clearly beyond the bulk of the population, the cost of a stove aside (Boyd & Son, 1850; Brewer, 2000: 54).

The urban-rural divide appears to have been significant until a late date, which must also have been reflected in the real price paid for fuel, whether this was a monetary price paid on the open market, or labour time foregone in obtaining fuel. Where labour was cheaply available, as was often the case in the off-season on smallholdings, it made sense to cut it on-farm rather than spend cash on purchases. In 1908 no less than 83% of US consumption was reckoned to be "on-farm" (which may be viewed as meaning "rural" given that non-farm rural household must have obtained some of this) when only 55% of the population was rural (Pierson, 1910). The great majority of Canadian consumption was reckoned to be on-farm too by this date, when the country's major cities had largely gone over to coal, as was also the case in Sweden and in much of the eastern United

States[12]. In southern Europe the development of the oil economy especially by the 1950s and 1960s saw easier penetration of rural markets by truck and the use of butane gas cylinders for cooking and heaters, radically transforming traditional woodland management and the use of firewood. Before the widespread arrival of the motor vehicle coal was not easily available as a substitute for wood in many areas, and equally, most fuel was consumed close to source. Indeed, the US forest census of 1840 estimated a mere 5.3 million cords of wood were sold for fuel, while Pierson and Reynolds reckoned that around 65 million cords were burned each year in the 1830s and 88 million in the 1840s, making the recorded commercial market 6-8% of the total although the urban population was already over 10% (Williams, 1980). Even if the total consumption estimates supplied by Pierson and Reynolds are far too high, the supra-local commercial market appears to have been relatively small. In both Canada and Sweden it is clear that urban firewood consumption per household was lower than in the countryside, even before the availability of fossil fuels, or electricity as a substitute (the latter's adaptation for heating coming only after the Second World War).

Thus when we come to understanding transitions, it would be too simple an answer to say that they are explained by changing relative prices of fuels. This truism is only meaningful so long as we can establish both a price and the service being rendered by consuming the fuel, and it is only in certain circumstances that this becomes clear. Seen in national or regional terms, we can see that structural transformation is an important factor in reshaping domestic fuel markets –urbanization and the development of infrastructure, which of course had impacts on price, but also many other circumstances associated with labour and consumption. Aside from relatively compact regions quite close to coalmining districts in the north-east of the United States or north-western Europe, woodfuel remained pre-eminent in many rural regions until after the Second World War.

Above all, we can highlight the *opportunity cost of labour* as a crucial factor in determining both the level and likelihood of woodfuel use. This covers whether the fuel was a complementary good along with other agricultural activity, as in much of southern Europe, or labour was of very low value because the limited amount of wage opportunities over much of the year, as was typical in many rural regions –and perhaps more so when rural industry declined in the face of factory competition. Thus the structural changes outlined above were perhaps as important for widening the *labour market* as providing access to alternative fuels. Equally, an expanded labour market would have raised the price of wood fuel, because heat energy from wood was labour intensive, and effectively pay-

12. McFayden's estimates would suggest either that this was actually greatly under-recorded, or that the commercial firewood market was much larger than supposed.

ing a market wage closer to the urban norm raised the price (whether it was being purchased or cut for auto-consumption), although access to power tools like chainsaws would have had a countervailing effect. Whilst in urban centres a "scarcity rent" driven by general pressures on space in their hinterland drove up prices and incentivised a switch to coal when transport networks made that possible, a process already visible in England in the sixteenth century, the decisive factor in many rural regions the for the post-war transition was probably labour markets, which were linked in turn to new transport possibilities that simultaneously brought oil and gas to the country dweller.

6. CONCLUSIONS

In conclusion, examination of the data available on firewood use and energy transition in western Europe and North America indicates that in many regions, woodfuel remained a significant part of the energy economy, especially in the countryside, until after Second World War. It has of course never entirely disappeared and is experiencing something of a revival today. However we must exercise great caution assessing and comparing general *levels* of consumption, as it is of highly variable quality and several wide-quoted data series do not stand up to scrutiny; whilst it must be appreciated that all those stretching back before the twentieth century rely on models or major assumptions about household behaviour. Equally, when we come to consider the drivers of change, it was often not the fuel market *per se* that was crucial for transition, but the other activities with which fuel supply was bundled, whether involving emerging transport infrastructure, or especially labour opportunities. Transition must be viewed in the round, shaped by wider social and economic changes. Such changes are never likely to be captured by models of change that focus solely on fuel use itself.

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