Without coal in the age of steam and dams in the age of electricity

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An explanation for the failure of Portugal to industrialize before the Second World War

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Abstract

We provide a natural resource explanation for the divergence of the Portuguese economy relative to other European countries before the Second World War, based on a considerable body of contemporary sources. First, we demonstrate that a lack of domestic resources meant that Portugal experienced limited and unbalanced growth during the age of steam. Imports of coal were prohibitively expensive for inland areas, which failed to industrialize. Coastal areas developed through steam, but were constrained by limited demand from the interior. Second, we show that after the First World War, when other coal-poor countries turned to hydro-power, Portugal relied on coal-based thermal-power, creating a vicious circle of high energy prices and labor-intensive industrialization. We argue that this was the result of (i) water resources which were relatively expensive to exploit; and (ii) path-dependency, whereby the failure to develop earlier meant that there was a lack of capital and demand from industry.

JEL codes: N1, N5, N7, O13, Q4

Keywords: Industrial Revolution, natural resources, coal, electrification, energy prices

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1. Introduction

The present work examines the role of energy resources for Portuguese economic underperformance before the Second World War, something which has often been neglected in previous accounts, which have focused for example on the role of trade policies, institutions, and a lack of physical and human capital (see for example Costa et al 2011; Lains 2002, 2003; Miranda 1991; Palma and Reis 2016; Reis 1986, 1993). By 1850, Portuguese GDP per capita was already just forty percent that in the UK, between sixty and seventy percent of that in France, Italy and Germany, and almost ninety percent of that in Spain and Sweden, although it was slightly higher than the Finnish level. By the turn of the century, however, income per capita had slipped to just 29 percent of that in England, to around 45 percent of that in Germany and France, 63 percent of that in Sweden, and between seventy and eighty percent of that in Italy, Spain and Finland. Moreover, Portugal's relative standing failed to improve much during the interwar period, so that by 1935 the gap in GDP per capita was more or less maintained in relation to the UK, Germany and France, but had declined further to around 65 percent of that in Italy and Spain, 54 percent of that in Finland and to just 37 percent of that in Sweden. In fact, it was only after the Second World War that Portugal began to converge on the rest of Western Europe (Bolt and van Zanden 2014). We draw on a wealth of primary sources to demonstrate that access to energy provides an important supplementary explanation for Portuguese economic failure before the Second World War.

For the nineteenth century, it has been argued that the availability of coal was crucial for industrialization and development given the technologies of the ”first industrial revolution”.[2] This divided the world into two parts: coal-rich countries such as the UK, and coal-poor countries, such as Portugal. Although the latter fell behind, an opportunity for catch up presented itself in the twentieth century as a ”second industrial revolution” and hydropower allowed countries well-endowed with water to electrify and even to leapfrog the coal-based economies, who were left with outdated technology and were relatively slow to electrify their economies. Although this simple narrative has been nuanced by other work (partly due to the existence of international trade, as we discuss below), we argue that it has some relevance for understanding the case of Portugal, and demonstrate that Portugal actually missed both industrial revolutions: she neither succeeded in the age of coal nor in the age of electricity.

[2] See the literature review by Fernihough and O'Rourke (2014), who find some support for this hypothesis.

Although Portugal had ample water supplies, these were relatively unexploited before after the Second World War, for reasons including geography, lack of access to capital, and institutional factors.

Portugal, in contrast with all other western European countries, never had coal as its main energy carrier. It was in fact available relatively cheaply in the major Atlantic ports of Lisbon and Porto, mirroring the example of Denmark, a country in which nowhere is further than 52km from the coast, which we have previously shown to have developed through coal despite no domestic reserves (Henriques and Sharp 2016). In contrast, however, in the interior of Portugal overland transportation costs made the use of coal prohibitive. This meant that industrialization almost exclusively occurred in the coastal cities, which did indeed witness a greater uptake of steam-based technology. However, this was limited by a lack of demand in the countryside, where we demonstrate that both coal and alternative fuel sources were expensive, with the end result being a generally unbalanced regional growth path (Badia-Miró et al 2012). Portugal was thus unable to emulate the economic growth of the leading European countries, which was to a great extent based on iron and steel, and there were therefore no opportunities for the sort of multiplier effects to the rest of the economy experienced elsewhere, especially through the supply of materials for railroad construction, the manufacture of machinery, or shipbuilding. Instead, relatively high energy to labor costs directed Portuguese industry towards a labor-intensive type of industrialization.

After the First World War, we argue that this lack of industrial demand led to a sort of path dependency, which in part meant that Portugal was also unable to take advantage of the opportunities presented by the second industrial revolution and electrification. To understand this, we should note that coal-poor countries with an early electrification had at least one of the following factors in common: first, a tradition of water-power use and small or medium resources that could be used without any large capital investment; and second, the pre-existence of energy intensive industries that ensured a demand for power and the capital that large investments in hydropower would require. In Portugal, due to irregular rainfall and thus the need to store energy, as well as a lack of smaller-size water resources (i.e. for example streams rather than rivers), the full exploitation of hydro-resources required particularly large amounts of capital as well as a guarantee of demand. The labor-intensive path chosen during the first industrial revolution implied however low levels of energy demand and prevented capital accumulation. Access to capital was moreover additionally constrained by a variety of institutional factors. There was therefore neither capital to attract demand nor demand to attract capital. The solution was thus thermo-power stations fueled by coal which were more adaptable to the small size of demand and had less capital requirements, but which implied that the difference in energy costs in relation to coal-endowed countries was maintained and the resultant electrification was poor. It was an understandable choice, but created a vicious circle of high energy prices and poor industrialization.

Our argument is structured around the remainder of this paper in the following way. Section 2 reviews the relevant literature and presents the history of energy in Portugal in a comparative perspective, demonstrating that the Portuguese economy was using relatively small amounts of coal before the First World War and relatively small amounts of hydropower in the interwar period. In section 3, we explain why Portugal was without coal in the age of steam. Prices were too high everywhere except on the coast, and alternative energy sources were also relatively expensive. High coal prices relative to wages in turn gave less incentive to invest in labor saving machinery, with industrialization mostly limited to the port cities of Lisbon and Porto, which constituted a small fraction of the population of the country. In section 4, we argue that path dependency led to Portugal being without dams in the age of electricity. We first show that Portugal was not lacking in water resources, but that nevertheless less hydropower was employed and that electricity prices were higher than in other countries. The end result was that electricity prices were relatively high compared to cheap labor, perpetuating the labor-intensive and unbalanced industrialization path from before the First World War. Section 5 concludes, and provides a brief explanation of what allowed Portugal to escape the low-energy, labor intensive trap after the Second World War.

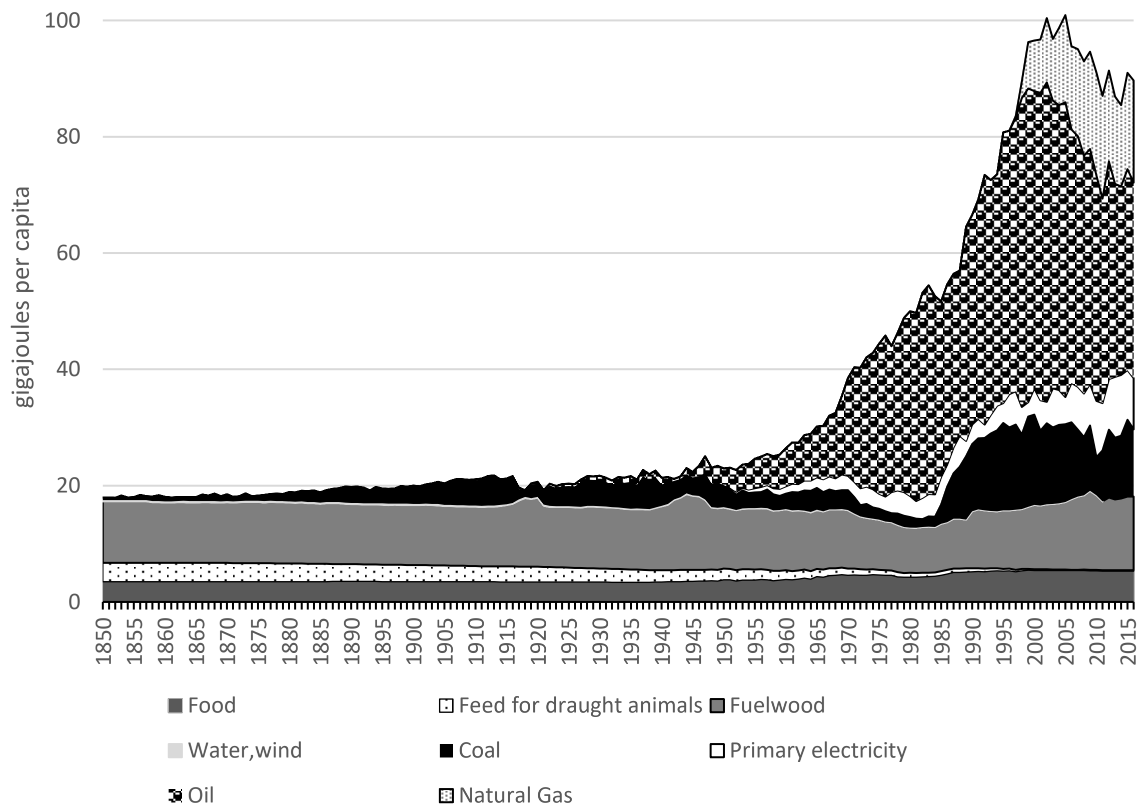
2. The history of energy in Portugal in a comparative perspective

The history of energy in Portugal (see also Henriques 2009) is summed up by figure 1. Until the Second World War, there was little increase in energy consumption over time, and the majority of energy came from fuelwood (57 percent in the 1850s and 46 percent in 1938). After the war, energy consumption took off, along with economic growth as mentioned above, and wood was rapidly substituted with oil[3] as the main carrier. From this, two particularly striking

[3] We largely abstract from oil in the present work, since it was not widely adopted by any country – experience its 'breakthrough' – until after the Second World War, when prices dropped substantially (Kander et al 2013, p. 256).

facts stand out. First, coal plays a relatively insignificant role, apart from for a brief period after the oil crisis of the 1970s. Second, it took until after the Second World War before there was a real acceleration in energy consumption per capita.

Figure 1. Portuguese energy consumption by source 1850-2016 in gigajoules per capita



Source: 1856-1959: Henriques (2009), with revisions to exclude bunker fuel. 1960-2016: Henriques and Borowiecki (2017), IEA (2015), FAO (2017), DGGE (2017) and PORDATA (2017). Primary electricity expressed by its heat content. See Appendix.

The lack of significance of coal is striking, in particular because it plays such a central role in explanations for why the ”first industrial revolution” began in England, and for why early industrialization and economic expansion followed in similarly well-endowed countries. The importance of coal has been highlighted particularly in the work of Cipolla (1962), Wrigley (1988, 2010), Pomeranz (2000), and Allen (2009), the last of whom argues that England’s high wage economy (fueled by London and trade), combined with cheap coal, meant that inventions were focused on testing coal in a range of industrial processes, eventually leading to macroinventions which would drastically change factor proportions by substituting energy and capital for labor. The ensuing period until the outbreak of the First World War witnessed, in addition to a revolution in the process of making steel (the Bessemer process and the Siemen-Martins open hearth) in the early 1850s, the widespread use of steam in most economic sectors. This was accompanied by a transportation revolution as the spread of railroads and steamships led to a few leading industrialized countries supplying the rest of the world with coal, steel and manufactured products in exchange for food and raw materials (Grübler 1998; Kander et al. 2017).

Thus, prior to the First World War, the widespread adoption of coal marks to a great extent the onset of industrialization, given the technologies available, leading scholars including Kander et al (2013) to argue that the availability of coal was a necessary condition for industrialization at this time, with Portugal a clear laggard, like many other coal-poor countries. Coal could of course be traded, but being a bulky commodity transportation costs could significantly increase its price, thus frustrating the foundation of key heavy industries where energy costs were important. Consistent with this, Pollard (1981) noted that industrialization happened first in areas which had similar factor endowments to England, such as in Belgium and the Ruhr, although its use spread around Europe due to the increased efficiency of steam engines (Allen 2009) and the steam-driven transportation revolution itself (Kander et al 2013), ultimately allowing even coal-poor countries with easy and cheap access by water to the coal mines of England, such as Denmark, to industrialize (Henriques and Sharp 2016). In recent work however, Malanima (2016) stresses, in a comparison between England and Italy, that, although industrialization was certainly dependent on the labor-augmenting innovations surrounding coal, these innovations themselves were the result of technological advances connected to developments in institutions and social structure. Thus, as he puts it "Energy is a main determinant [of growth], but the determinants of this determinant are multiple and diverse." Nevertheless, it is not disputed that a supply of coal was important at this time.

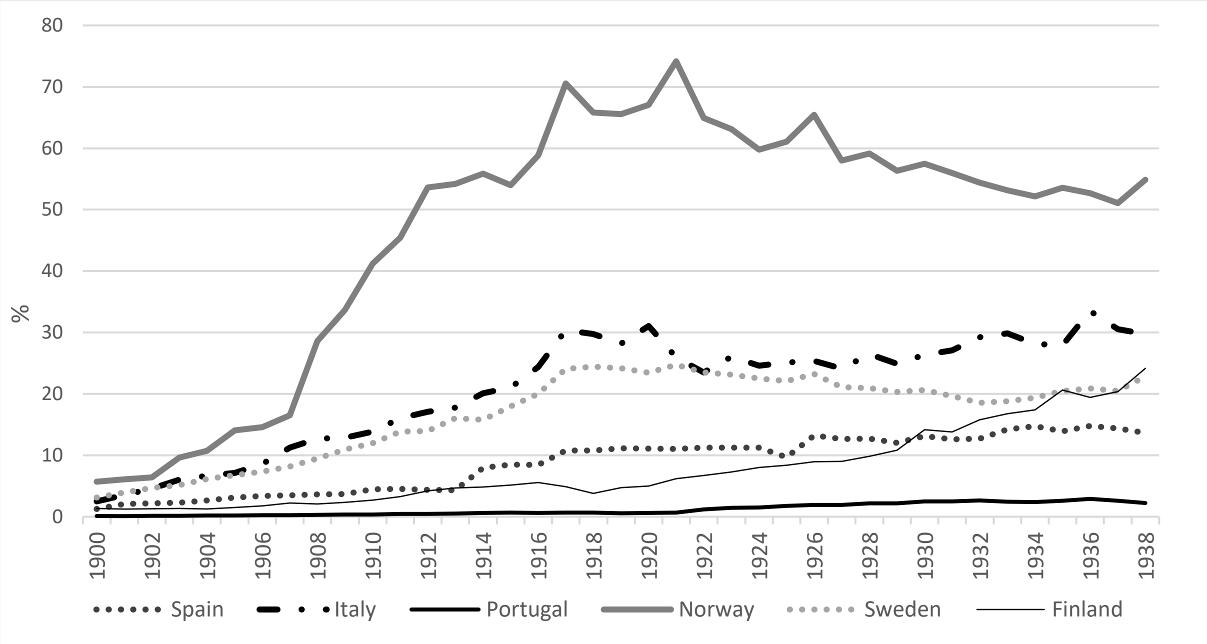
We will explain why Portugal found it difficult to access coal in the following section, but even without it, it has been argued by others such as Clark and Jacks (2007) as well as environmental historians, that industrialization might have been, and in some cases was, possible using alternative sources of energy. The case of the US is a famous one, where wood was an important energy carrier, used for both steam engines and transportation, during early industrialization (Melosi 1982; Schurr and Netschert 1960). Similarly, in Sweden, differences in relative prices were enough to make it worthwhile fueling the extremely energy-intensive Swedish mining industry with charcoal until as late as 1900 (Kander 2002). Water was another alternative to coal, and at half the price of steam power in the United States in the 1840s, it became dominant in the cotton, paper and wood industries as late as 1870, though not in the heaviest industries (Christensen 1981, p. 322). In Europe, Alpine regions such as Switzerland, part of Italy, and the south of Germany also benefited from extremely low costs of water power and, in the case of Barcelona, the high costs of coal made industrialization with water power a strong alternative for the textile industry of the region (Carreras 1983; Nadal 1975). The low level of growth of per capita energy consumption in Portugal reveals however that not only was coal not used in a country with little domestic endowments, but that alternative sources of energy for industrialization were also scarce until the First World War, a point which will be important for our argument for why she then failed to exploit other alternatives in the interwar years.

In other coal-poor countries, by contrast, water power, specifically hydroelectricity, began to play a crucial role. This “Second Industrial Revolution” gained momentum in 1890 and was based on a new energy carrier (oil – which came to dominate after the Second World War) and a new form of secondary energy (electricity), along with their converters: the internal combustion engine and the electric motor. For industrial power, electricity started to be considered as an alternative source of power to steam in around 1900. Electrification brought a host of advantages compared to direct power: it could be produced with any primary energy carrier; the ease of transportation of electric current made the point of consumption independent of the point of production; it allowed for a more efficient use of motive power; and it meant that factories no longer had to be organized around a central steam engine, allowing for better organization of the factory and an improved working environment, among other things (Devine 1983). Coal-poor countries probably had the greatest incentives to develop hydropower technology, which in turn presented them with more opportunities to gain technological leadership or to catch up (Bétran 2005). Not only were relative prices more advantageous for these countries, but also coal-intensive countries had comparatively more vintage capital to depreciate and could not as fully take advantage of this promising new energy form. Thus, a number of authors have stressed path dependency of energy systems, for example Unruh (2000), who put forward the idea that ”carbon lock-in” might result when fossil fuel-based advanced economies experience technological and institutional co-evolution driven by path-dependent increasing returns to scale, thus preventing the diffusion of carbon-saving technologies despite their apparent economic and environmental advantages.[4]

The end result was that much of the Nordic region and parts of southern Europe were able to catch up with the early industrializers through hydropower, both in terms of energy intensity and standards of living. Figure 2 gives the share of hydro-power in energy consumption (excluding muscle power) for a number of coal-poor countries using the ”partial-substitution method”, which quantifies hydro-power in terms of the fuel that would otherwise be used to generate the same amount of electricity in thermal stations. This allows us to illustrate the importance of hydro-power in the energy system in terms of saved fuel (mostly coal), which is not captured otherwise since hydro-power enjoys a far greater resource to end use efficiency (close to 100 percent) than thermal-power. Clearly, all of these coal-poor countries, except Portugal, were receiving a significant share of their energy from hydro-power by the end of the period.

[4] Related to this, more recently Fouquet (2016) has argued that although government intervention can allow the adoption of cheaper energy and economic growth in the short run, it can potentially lead to the economy being locked into energy-intensive patterns, thus increasing the country’s vulnerability to energy price shocks, inflation, trade balance deficits, political pressure from energy companies, and environmental pollution.

Figure 2. Share of hydropower in energy consumption (excluding muscle power) in coal-poor countries, partial substitution method, 1900-1938



Note: The figure includes fossil fuels, firewood, direct water (except Finland and Norway), and hydro-electricity. **Sources**: Own calculations with the data from Henriques (2009), Henriques and Borowiecki (2017), Kander et al. (2017); Malanima (2006), Mitchell (2003), Myllyntaus (1991), Statistics Norway (1955), Statistics Finland (2007), and Rubio (2005); Water-power is expressed in fuel equivalents using the historical efficiency of Portuguese thermal plants for Portugal (Henriques 2009, 2018) and the US thermal plants for the remaining countries (US Department of Commerce, Bureau of Census 1975).

The process by which innovations in energy technology can allow countries to catch up or even overtake earlier innovators has been referred to in the literature as "energy leapfrogging", following Goldemberg's (1998) seminal work in which he argued that the environmental consequences of the development of poorer countries could be averted by the adoption of modern and efficient technologies, for example in the production and use of biomass, early in their development process.[5] To a certain extent, this idea was anticipated already by the work of Bardini (1997)[6], who argued that the precocious Italian electrification which can be seen in

[5] This has however been disputed in recent work by van Benthem (2015), who, based on an analysis of 76 developing countries today and industrialized countries in the past, finds that despite dramatic improvements in energy efficiency, economic growth in developing countries is not less energy-intensive than past growth in industrialized countries. According to him, therefore, some of the potential environmental benefits of leapfrogging are absent.

[6] The title of Bardini's paper, 'Without Coal in the Age of Steam', is of course the inspiration for the title of the present work.

figure 2 proved a poor substitute for steam before the First World War, given the advanced, power-intensive production technologies of the time, but provided one of the bases for the eventual catching up of the Italian economy. By contrast, Rubio and Folchi (2012) and Rubio and Tafunell (2014) have demonstrated that Latin American countries leapfrogged from coal to oil in the first half of the twentieth century, around thirty years earlier than most developed countries, although in terms of hydroelectricity, Latin America was more of a laggard, taking off mainly after the oil crisis of the 1970s.

In panel (i) of table 1 it can be seen that coal consumption per capita in all countries was relatively low compared to that of the UK between 1870 and 1935, although the Nordic countries used more coal towards the end of the period. Panels (ii)-(v) show the leapfrogging, as electricity consumption per capita and electricity intensity (electricity consumption divided by GDP) are for many countries already in 1900 in excess of that in the UK. Portugal, and to a lesser extent Spain, are clear laggards in this regard, with the latter at just 26 percent of the UK consumption per capita in 1935 (having fallen since 1900), and the former never exceeding ten percent of the UK level. Finally, in panels (vi) and (vii) the difference between the other coal-poor countries and Portugal becomes clear. All besides Portugal were producing the vast majority of their electricity with hydropower, and all besides Spain and Portugal were at some point producing hydropower equivalent to the substitution of over seventy-five percent of their actual coal consumption.

Table 1. Comparison of coal and electricity development in Northern and Southern Europe 1870-1935

	Sweden	Norway	Finland	Italy	Spain	Portugal
			(i) Coal consumption per capita, UK=1			
1870	0.03	0.01	0.04	0.01	0.02	0.01
1900	0.15	0.02	0.19	0.04	0.07	0.03
1935	0.34	0.18	0.30	0.10	0.09	0.05
			(ii) Electricity per capita, UK=1			
1900	2.42	2.15	0.59	0.44	0.53	0.03
1920	2.21	8.16	0.46	0.63	0.28	0.05
1935	1.94	4.78	1.03	0.58	0.26	0.09
			(iii) Electricity intensity, UK=1			
1900	6.0	5.8	1.8	1.1	1.5	0.1
1920	3.6	1.2	14	1.1	0.6	0.2
1935	2.8	2.1	8.1	1.1	0.6	0.4
			(iv) Electricity per capita, KWh			
1900	26	24	6	5	5.8	0.4
1920	441	1630	92	126	55	10
1935	1103	2717	586	327	147	50
			(v) Electricity intensity, GWh/$1990			
1900	13	12	4	2	3	0.3
1920	147	50	595	47	25	9
1935	246	189	715	100	57	31
			(vi) Hydro in % of electricity production			
1900	60	na	71	69	49	30
1920	73	na	46	96	87	17
1935	68	99	79	97	93	33
			(vii) Coal saved by hydro-power in % of coal consumption			
1900	8	9	19	6	2	1
1920	77	301	219	103	26	4
1935	44	168	95	60	29	8

Sources: Italy: Malanima (2006); the UK: Warde (2007), Mitchell (2003) and Etemad and Luciani (1991); Sweden: Kander (2002); Spain: Bartolomé (2007), Rubio (2005), Mitchell (2003),1950; Finland: Myllyntaus (1991); Norway: Etemad and Luciani (1991); Portugal: Henriques (2009, 2018). Coal saved by hydro: own calculations based on efficiencies of US thermal stations for all the countries (US Department of Commerce, Bureau of Census 1975) except Portugal, where country-specific efficiencies were used (Henriques 2009, 2018). See Appendix.

Portugal thus emerged as a clear laggard in consumption of both coal and electricity (with extremely low electricity intensities), of which the latter was mainly based on thermo-power from coal. Elsewhere, particularly Norway, but also Sweden and Finland are well-endowed with water resources, with the former quickly attracting foreign capital and technology due to the low marginal costs of electricity production, after which it became an important producer of various alloys for example (Kaijser 1995; Thue 1995). Although Sweden's water resources were largely located far away from the consumer centers, the high cost of energy in pre-existing heavy industry was a strong incentive for the development of hydroelectricity, first funded by mining capital and then by the state from the 1910s, giving rise for example to an important electrochemical industry (Kaijser 1995; Myllyntaus 1995; Jakobsson 1995). Finally, the Finnish state supported the development of hydropower after independence in 1917, again induced by the demands of pre-existent energy-intensive industries such as wood, paper and pulp (Myllyntaus 1991; Myllyntaus 1995; Kaijser 1995). At the other end of Europe, Italy, with similarly large water resources in the north of the country, also rapidly developed hydropower. By 1911, the percentage of electrification in Italian industry was already 48 percent, as compared to England with only 13 percent (Bardini 1997, p. 640). In Spain, electricity was introduced early on in Madrid (Aubanell 1992), and more widely around 1900 when a boom of hydroelectric plants started, financed mostly by Basque mining capital (Antolin 1999; Sudrià 1995).

The First World War accelerated the process of electrification around the world by cutting off coal supplies. As coal and gas prices rose steeply in relation to electricity, household and industrial consumers rapidly switched to the latter and Sweden, Norway, Finland and Canada thus became the leaders in electricity intensity (see panel iii of table 1). This switch to such highly intensive electrical systems was due not only to substitution in manufacturing, households and even railroad systems, but also to the development of entirely new industries based on extremely cheap hydropower. This could not be achieved to the same degree in all the countries. For example, the development of Italian electrochemical and industrial electricity consumption during the interwar period was financed by extremely high tariffs on household consumers (Storaci and Tattara 1998; Bartolomé 1995). For Spain, it was already clear by 1930 that it was not possible to pursue the intensive path of the Nordic countries, since given the technologies of the time the possibilities for expansion were smaller (Bartolomé 2007). Spain thus began to fall behind other countries in terms of electricity intensity: see panels iii and v of table 1.

To sum up, the emergence of electricity changed the allocation of energy resources between countries: since power could be cheaply produced and transported, there was hope for a more intensive industrialization for countries with more difficult access to coal. Portugal, however, failed to exploit hydropower despite the fact that, as we will demonstrate below, energy prices remained high compared to other countries, but where they were apparently not sufficient to motivate the widespread adoption of hydropower. Our explanation for this is the central contribution of this paper, and relies first on understanding how and why Portugal failed during the age of coal.

3. First Industrial Revolution lost: without steam in the age of coal

Relative prices and the choice of energy carrier

The decision regarding which energy carrier to use for industry would have been limited to for example coal, charcoal or water in the nineteenth century. The discussion above suggests that the choices economic agents made between these would have been largely based on relative prices. A country such as England, with expensive labor and cheap coal would have an incentive to develop labor-saving, energy-intensive technologies[7]. Coal-poor countries with limited other energy options such as Portugal on the other hand would have more incentive to specialize in labor-intensive production methods, although coal-poor countries with alternative energy sources, such as plentiful wood in Sweden or plentiful water in northern Italy, might develop industry using these carriers. Countries which industrialized using wood or water would not necessarily have less-energy intensive industry, although industrialization was likely to be less extensive than in coal-rich countries. A country like Portugal, however, would be expected to have little industry.

[7] Although the early industrial revolution in cotton was mostly powered by water until 1840s.

Figure 3. Energy choices during the first industrial revolution

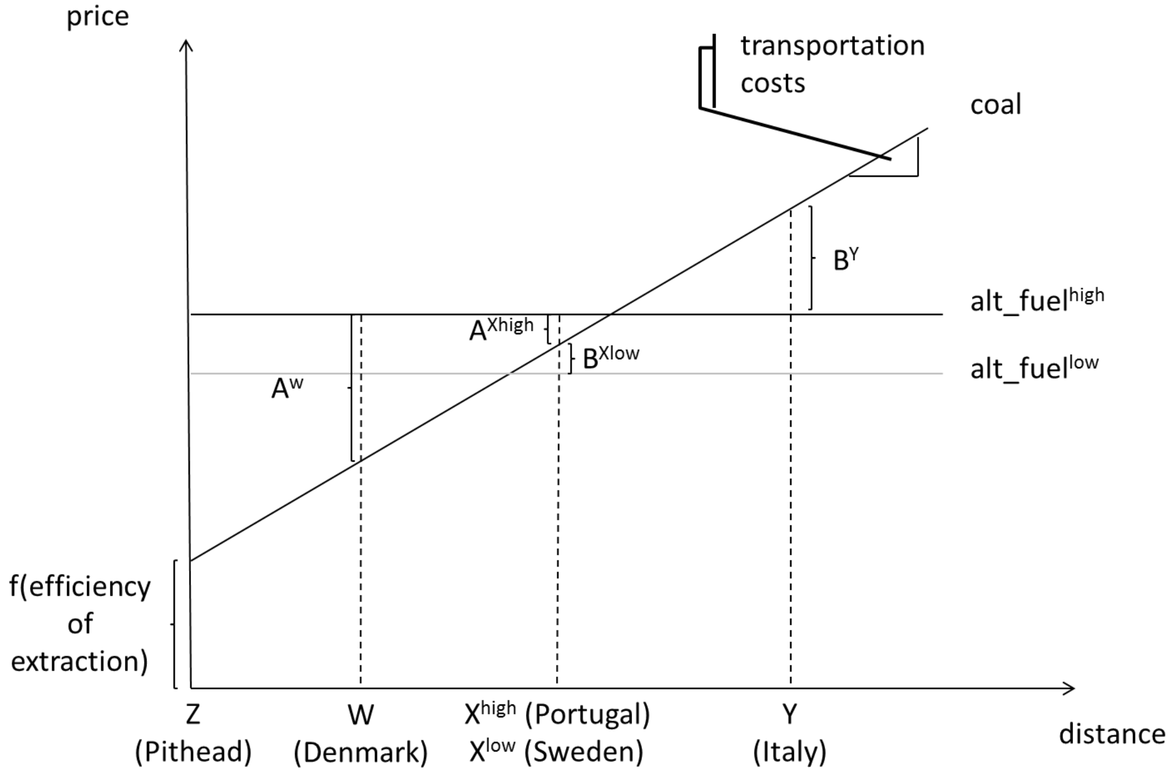


Figure 3 gives a stylized illustration of the energy choices available before around 1900. At the pithead (Z) the price of coal is a function of the efficiency of extraction. Further from the pithead, the price of coal increased by the transportation costs according to the law of one price, meaning that importers had to pay higher prices than producers, with the gap particularly high in the early period. We imagine that alternative sources of energy are available at each location, but in some places it is expensive (alt_fuel^{high}) and in others it is relatively cheap (alt_fuel^{low}). A country like Denmark (location W), with expensive alternative sources of fuel, and cheap access to British mines would have a strong incentive to develop using coal (A^{w}), measured by the gap between the price of the alternative fuel and that of coal. This would be expensive relative to coal-producing areas, however, suggesting a less energy-intensive industrialization. By contrast, a country further away from the pithead like Italy (Y) would have an incentive to develop using the alternative (B^{Y}). Two countries such as Portugal and Sweden, on the other hand, which are roughly equidistant to the pithead (X) could develop in two different directions, depending on the price of the alternative fuel. We imagine that in Sweden this was cheap, giving an incentive to develop using the alternative (B^{Xlow}), whereas in Portugal it was expensive, giving an incentive to use coal (B^{Xhigh}). In fact, if the price of the alternative in Sweden was low enough, energy-intensive industrialization would be possible. In Portugal, however, prices would be even higher than in Denmark, and industrialization would be limited and non-energy-intensive. Of course, as the efficiency of extraction increased, and transportation costs declined, the coal schedule would shift downwards and become flatter respectively, giving more locations an incentive to shift to coal.

Table 2. Coal prices in North and South Europe and energy prices in different regions of Portugal 1879-1881 and 1909-1911 as multipliers of UK pithead price (UK=1)

		Denmark	**Italy**	**Spain**	**Sweden**	**Portugal**
		Imports	Imports	Pithead/Imports	Imports	Imports
1879-1881	Coal	2.4	4.4	1.7-3.9	2.7[a]	3.7
1909-1911	Coal	1.8	3.2	1.5-2.4	1.9	1.9
		Lisbon	**Porto**	**Portalegre**	**Castelo Branco**	**Guarda**
1879-1881	Coal	3.4-4.9	4.1-7	7.5-9.1	19	
	Firewood[b]	6.6-10.2	5.4-19	6.6	8.2-9.9	4.7-8.5
		Lisbon	**Porto**	**Aveiro**	**Castelo Branco**	**Viseu**
1909-1911	Coal	1.6	1.9	3.8-4.2	4.3	5.7
	Firewood[b]	6.9	7.2-7.7	3.5-5.9	3.1-3.3	2.3-4.1

Source: UK pithead = Bardini (1998) 5.4 shilling/t in 1879-1881 and 8.1 shillings/t 1909-1911. 1879-1881. Denmark, Italy, Spain and Portugal coal imports information from Henriques and Sharp (2016),Bardini (1997); Coll and Sudrià (1987) and Henriques (2011). Sweden: 1879-1881 estimation from Astrid Kander, 1909-1911 from Ljungberg (1990); Regional prices: 1879-1881: MOPCI (1881). High-bound firewood prices in Lisbon and Oporto are from Henriques (2011), p.304 and Pereira (1983). 1909-1911: Coal, Lisbon and Oporto: INE, Comércio Externo. Firewood, Lisbon and Oporto: Henriques, 2011 and Pinheiro (1983). Aveiro: Cabido (1911 a, b, c, d, 1912b), Castelo Branco: Pinto Júnior (1911), Viseu: Cabido (1912a). Notes: [a] railway fuel price. [b]1 ton of coal is considered to be equivalent to 2.3 tons of wood (DGE, 1993), except for the districts of Castelo Branco (3) and Portalegre (4), according to information reported in 1881 industrial survey.

The top panel of table 2 gives some supporting evidence for this. The price of coal varied widely between European countries, and was generally cheaper closer to the pithead. Although coal arrived at the Portuguese ports at double the price of exports from the United Kingdom and three and a half times more than pithead prices in 1880, by the end of the decade, the use of steam navigation meant that maritime freights represented only twenty percent of the final costs, although Portuguese coal prices at the port were still double English pithead prices, a differential which was more or less maintained until the First World War. However, due to its proximity to England by sea, coal prices were still relatively cheap in Portugal when compared with Mediterranean ports. Moreover, import prices in Portugal were by 1910 not much higher than those in Copenhagen, which begs the question as to why Portugal failed, and equally coal-poor Denmark succeeded to industrialize using coal-powered technology.

To explain this, we illustrate in the lower panel of table 3 all the information we could gather on prices in various parts of Portugal. Coal could become extremely expensive in some inland industrial centers, despite the small size of the country. Just outside the limits of Lisbon, the price went up from 3.4 to 4.9 times the UK pithead price in around 1880. The same happened in the suburbs of the Porto region where coal increased from 4.1 to 7 times the UK pithead price in 1880 for the 52 km of railroad transportation. There was also a railway line connecting Lisbon to Alentejo (200 km), but Portalegre wool industries faced coal prices more than double those in Lisbon. Coal would have been even more expensive in the mountainous regions of Guarda and Covilhã in Castelo Branco, where railroad construction was not yet complete, about four to five times the Lisbon price and almost twenty times the British pithead price. Although prices of coal in Portugal declined relative to the UK pithead price between 1880 and 1910, it remained significant for inland areas in particular, even if the price in Lisbon declined to less than twice that at the UK pithead.[8] Thus, similarly to how our investigation of Denmark nuanced the idea that it was location of the pithead which mattered, by demonstrating that it was economic distance to coal rather than physical distance which counted, we argue that Portugal nuances further the "coal-poor" versus "coal-rich" dichotomy, since the country comprised areas with both access to coal and those that did not, or at least not at a reasonable price.

Finally, table 2 also gives information on the price of wood, the main alternative energy source in Portugal, at various locations, where we have converted its price into coal equivalents for the sake of comparison. Unlike Sweden and Finland for example, where firewood competed with coal in the early phases of industrialization, coal arriving at Portuguese ports was significantly cheaper than wood, in particular by 1910. Outside the coastal cities, the price of

[8] A relevant question is why the Portuguese government did not simply regulate rail prices, thus giving cheaper access to coal in the interior of the country. In common with many governments of the time, a generally *laissez faire* attitude was adopted, although subsidies were offered to rail companies, which were sometimes nationalized if the subsidies failed to rescue them (Mata 2002). Without this intervention (presumably limited in scope also due to capital constraints), we can speculate that transportation might have been even more expensive.

firewood was cheaper than coal which was transported to those areas, but far higher than coal in Lisbon or Porto. Thus, although there was enough non-conventional forest (e.g. on common land) to fuel rural household needs, there was certainly not enough to sustain a wood-based industrialization, of the type that occurred in Sweden and Norway with the use of charcoal for production, as mentioned above. In Portugal just 14 percent was covered by conventional forest in 1867 and 22.1 percent in 1902 (Lains and Sousa 1998, p. 21), whereas in Sweden well over half of the country was and is covered (Heckscher and Gerschenkron 1954, p. 225).

Although water power might have been an alternative, it is of course a natural resource that cannot be moved, so any advantages of water power would have to be measured relative to the distance to ports (for imported raw materials) and to the major centers of consumption. The only Portuguese regions where water is preponderant are Guarda and Covilhã in Castelo Branco, which were the preindustrial wool centers, and an area where coal arrived at exorbitant costs. However, the quality of the water resources was poor by international standards. In Covilhã, the waterfalls are on average only 4 to 7 meters, and the volume of the water is no more than 100 liters per second; enough for only some tens of hp per factory. Moreover, during the summer, the water power went down considerably making it necessary to work during the night, and even then this was not enough. As we will see below, all the factories requiring larger amounts of power thus needed complementary steam power, but steam itself was an expensive solution.

Limited industrialization and an unbalanced growth path

We might expect then that coastal areas of Portugal would be more like Denmark in the sense that they had access to relatively cheap coal, and would follow a more coal-intensive development path, whereas inland areas would have little industry, since they only had access to expensive energy sources. We can see some evidence of this in the Industrial Census of 1881, which is the first that gives a comprehensive picture of how the diffusion of steam had proceeded around the country. We have summarized some of this information in table 3, from which two major points stand out. First, the low use of power, and the limited diffusion of mechanized industrialization in general, which is given by total installed power and the number of motorized factories. The Portuguese power market was small, at the level of less than one percent of the English power market in 1870 (Musson 1978). Second, however, the coastal cities Lisbon and Porto (to a smaller degree) followed the British steam model, with 93 and 73 percent of power coming from steam alone. Third, unlike other coal-poor countries, cheaper alternative power sources were largely unavailable in Portugal: wood and water were thus unable to compensate for the lack of coal.

Table 3. Steam and waterpower, manufacturing and mines, around 1880

	Lisbon[a]	Porto[b]	Castelo Branco and Guarda	Other regions	Mining[c]
Factories[e]	67[a]	47	98	49	
Hp	4 146[a]	1 619	1 384[g]	1 680	1 952[d]
Steam,% hp	93%	73%		19%	77%
Steam/Water, % hp	7%	27%	41%	61%	
Water, % hp			59%	20%	23%
Steam users, from whom	67	47	11	34	
Firewood users	5	1	11	11	
Coal users	66	46	0	6	
Unknown	0	0	0	17	

Sources: MOPCI, *Inquérito Industrial de 1881*.

[a] Includes the power of steam cereal grinding factories (7/1021 hp) that were not visited in 1881 but are included in MOPCI, *Inquérito Industrial de 1890*.

[b] Small industries are not included.

[c] INE, *Anuário Estatístico de 1885*.

[e] Number of factories with motors.

[f] Missing data for Guarda was corrected by the average of the power of other wheels in the region.

Table 4 breaks down the Portuguese coal consumption into sectors and compares it to the structure of coal consumption in three other coal-poor countries, Portugal, Sweden and Spain, as well as the UK, around 1870- 1880. The diffusion of steam in Portugal's two main cities was mainly due to the introduction of cotton textiles manufactures, which enjoyed the duel benefits of relatively cheap access to both coal and cotton imports. Coal also became relatively important in other textiles, cereal grinding mills, machinery and tobacco. All but one steam user for each region (Lisbon and Porto) reported the use of imported coal as the first choice, although wood was used in some boilers and ovens, especially in ceramics or glass making. Outside Lisbon and Porto there were 54 steam engines accounting for little more than 1,000 hp distributed by 45 users, but use of steam as the only power source was rare, although even more rare was the use of coal. The census only mentions six coal users and they all correspond to locations where coal arrived at the low range of national prices (6 escudos, i.e., 150 percent of

Lisbon prices). Thus, for the production of steam there was only wood, which was cheap relative to coal outside the cities.

Table 4. Coal consumption (PJ) in some sectors, UK, Portugal, Spain and Sweden circa 1870-1880

	UK c. 1870	Portugal c. 1880	Spain c.1870	Sweden c. 1870
	Coal consumption			
Sectors	PJ	PJ	PJ	PJ
1. Railways	59	1.0	5.7	1.2
2. Gas	185	1.3	1.5	0.8
3. Industry	1905	0.3	21	1.3
3.1.Pig Iron, Metals and steel	976	0.0	13.2	0.0
3.2 Mines	212	0.3		0.0
3.3 Manufactures	717	2.4-3.4	7.9	1.3
from what, Textiles	20%	42%	22%	na
Sum(1+2+3)	**2150**	**5 to 6**	**28**	**3.3**
% firewood in industrial fuels	0	25-30%	na	95%
Coal per capita (GJ)	86	1.2-1.4	1.8	0.8
Solid fuels per capita (GJ)	86	1.4-1.7	na	16
GDP per capita ($1990)	4 000	1 000	1 200	1345

Sources: Data excludes agriculture, navigation, and household sector. UK: Warde (2009); Portugal: own calculations based on Pinheiro (1986) for railways and CLIG (1880) for gas and MOPCI (1881) for industry [a]Low coal values for manufacturing are based on the numbers in MOPCI (1881) and high coal values is the value obtained after deducting coal use for navigation, railways, gas and mines. Spain: Coll and Sudrià (1987). Sweden: coal based on Kander (2002) and firewood on Kander et al. (2017).

Putting Portugal into a comparative perspective, it can be seen that all the coal-poor countries seem to have lost out on the first wave of steam that succeeded in countries such as the US, Germany, France or Belgium. Coal per capita would have had to increase by a factor of around 60-70 if Portugal was to emulate the coal-dependent industrialization path of the UK, but this was not much different to Spain, where it would have involved an increase of a factor of almost 50, or Sweden, where it would have required over one hundred times the coal input. For these countries, railroads represented a much higher proportion of coal consumption, despite the much lower density of the rail network relative to the UK, which seems to imply that the diffusion of coal was more concentrated in sectors where it could not so easily be substituted such as transportation. Still, the structure of Portuguese industry was more affected by the lack of coal endowments than Sweden or even Spain. In the case of Sweden, while coal consumption per capita in the sectors above was probably as low as for Portugal in 1880, firewood compensated for the lack of coal, especially so in the heat intensive iron industry, and amounted to about 95 percent of solid fuels in industry, with the implication that energy input rather than being one hundredth as stated above was actually more like one fifth of that in the UK. In the case of Spain, industrialization was more inclusive. Despite the high costs of domestic coal in the coastal areas, where it could barely compete with imported coal, it was important for the railroads and the mainland regions. And even with imported coal, the Basque iron reserves were of such good quality that they managed to be competitive with the English in some branches (Sudrià 1995).

On top of having little coal, Portugal also lacked ore (and other metals), and this had an additional impact on railroad investments and mechanization in general. Since it was necessary to import all the iron and steel from abroad, the expansion of the railroad network had little impact on boosting the metal and engineering sectors (Pinheiro 1988). Machinery, working with imported iron and imported coke, could only be internally competitive in small market segments, and even then it was only used for the less energy intensive final phases of metal transformation (Santos 2000). Portugal thus specialized in industries with lower energy costs of which textiles employed about half the workers and power. This preponderance in one sector was mainly based on the domestic market and made possible by internal protection of cotton and wool textiles. By 1890, the protected textile market already satisfied 90 percent of the demand for linen and 75 percent of the demand for wool and cotton (Reis 1993, p. 171). However, in the external market lower wages in the textile sector did not compensate for the higher cost of raw materials, energy and capital. Thus, Lains (2003b) estimates that value added per worker in woolen and cotton textiles would have been around 15 percent and 25 percent of that in the UK in a situation of free-trade. One important reason for such low labor productivity was the nature of biased technical change in favor of capital (and energy) in relation to labor across most of the traditional sectors of the first industrial revolution. The average power per worker, in the 1871 British cotton and woolen factories, was about 0.7 hp and 0.5 hp (Musson 1978), whereas the 1881 Portuguese Industrial Census gives a mean power per worker of 0.5 hp and 0.4 hp for the same sectors, differences that would be higher if we took into account the duplication in capital of mixed systems of water and steam.

A second problem with the lack of coal was caused by the spread of industrialization and determined in part by the high costs of coal in any city other than Lisbon or Porto. The end result was an unbalanced growth path, reflected in the estimates of regional GDP per capita presented by Badia-Miró et al (2012), which suggest that Lisbon in 1890 had 158 percent of the average income for all of Portugal, with the second richest region being Porto, with just 117 percent. These cities constituted just a small proportion of the population, however: under ten percent before 1900, increasing to just under fifteen percent in the interwar period. More inland areas were considerably poorer, again reflecting the correlation between energy prices and development. With such a small domestic market to absorb the products being produced in the cities, any specialization, which was not based on exports, faced limits in their capacity to attain the levels of growth that were needed to catch up with the leading economies. In fact, the only relatively successful manufacturing exports were based on indigenous natural resources and in almost exclusively manual methods of production, such as cork and fish preserves. However, these exports were very dependent on the fluctuations in international markets and never permitted sustained capital accumulation.

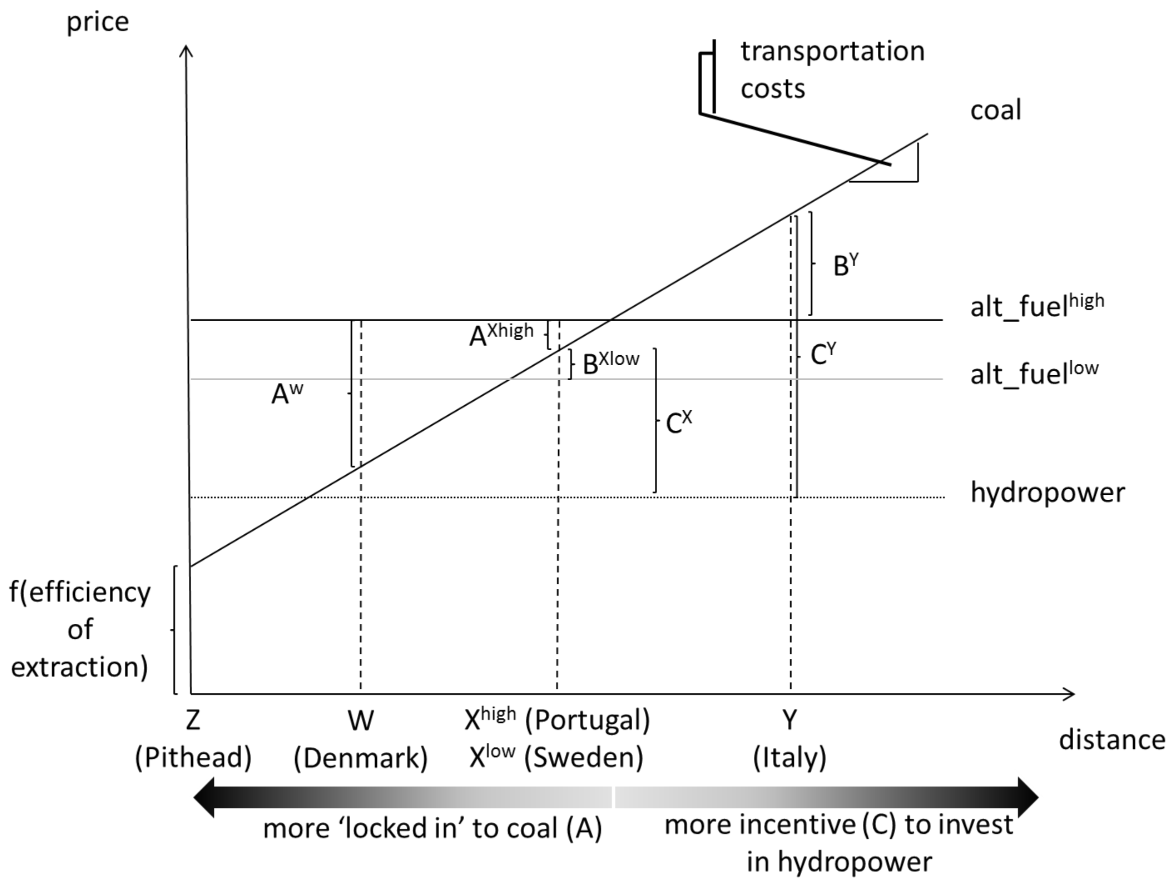
The pattern of energy prices and the lack of alternatives to coal thus left Portugal before the First World War a relatively backward country, with limited industry which was neither capital- nor energy-intensive, in contrast to other coal-poor countries like Sweden and Italy which achieved some industrialization based on alternative sources of energy, or like Denmark, whose geography allowed relatively easy access to coal throughout the country. Even the most advanced parts of the country, where imports of coal were cheaper, only witnessed moderate industrialization, which was constrained by a lack of domestic demand, despite trade protection.

4. Second Industrial Revolution lost: without dams in the age of electricity

Relative prices and the choice of energy carrier

Around the turn of the twentieth century, technological progress meant that the age of electricity began to supplant the age of steam. This new, versatile power source could in theory be produced by all manner of fuels, but in practice the choice was often between coal (in thermo-power stations) and water (hydroelectricity). Since hydroelectricity had the potential for dramatically lower prices of energy, as well as a relative independence from geography, new opportunities thus opened up for coal-poor countries, or those where cheap energy had previously only been available close to the coast. Figure 4 builds on figure 3, and illustrates the potential for dramatically lower prices of energy with the “hydropower” schedule. This would have given countries like Italy or Sweden massive incentives (C^Y and C^X respectively) to choose hydropower over coal – and thus to leapfrog the coal-rich countries. An extra dimension complicates this picture, however, as suggested by the discussion in section 2. Coal-rich countries had invested in the equipment and infrastructure for a steam-based economy and thus might have experienced”carbon lock-in”. This path-dependency would be reflected by the previous incentive to invest in coal (A), meaning that they might not move to hydropower even if it gave the potential for considerable savings. Of course in practice, some countries had almost no opportunity to turn to hydropower, like Denmark, where the water resources were simply not available. In this framework, we would expect that Portugal would have experienced some lock-in in the coastal cities, but that elsewhere the incentives to develop hydropower should have been significant.

Figure 4. Energy choices during the second industrial revolution



The evolution of the ratio between electricity and coal prices has been employed in previous work as a measure of the incentive to electrify (Svennilson 1954; Antolin 1988,1990; Sudrià 1990b; Bétran 2005). Often, household or average electricity prices relative to coal are used in order to make cross-country comparisons, although this is probably not the most appropriate measure since they can be dramatically different in level and trend compared to industrial prices[9]. Table 5 thus uses the ratio of industrial electricity prices to coal for several countries and in the two main Portuguese cities, Lisbon and Porto. The relative prices, expressed in MWh/ton, indicate how much coal in metric tons can be bought for the price of an industrial MWh of electric current.

Table 5. Relative prices electricity versus coal MWh/ton for industrial consumers

			Portugal			Spain	
	US	UK	Lisbon	Porto	Sweden	Bilbao	Italy
	Thermo	Thermo	Thermo	Hydro	Hydro	Hydro	Hydro
1910	21	16.1[a]	14.1		1.4	1.7	8.6[c]
1917	9.3		6.9		0.2	0.1	
1925	6.9	5.2	5.5[b]	2.6-5.5	1.6	1.4	
1928	7.1	5.2		3.6-5.2	1.5	1.6	1.8
1935	6.8	4.3	4.2	5-6.6	1.2	1.8	2.1

Notes and sources: Thermo and Hydro words below the countries/regions entries express the source of electric power: from fossil fuels in thermo and from water in hydro. [a] 1905-1908; [b] 1923 [c]1908. Own construction from following sources: UK: 1908: Bardini (1998), 1925-1935: Svennilson (1954), average industrial uses. US: (US Department of Commerce (1975)); Melman (1956); average industrial prices. Portugal: Henriques (2011) for coal. Porto: SMGEP, *Relatório...* (1917-1938). The highest series refer to High Voltage prices charged by the municipality for industrial consumers, and the lowest refers to the price charged by the distributor of the municipality. Lisbon: Matos et al (2004), lowest industrial tariff (1910-1917), and CRGE, *Relatório*… (1920-1935),average industrial prices. Italy: Bardini (1998);Storaci and Tattara (1998); average industrial prices. ISTAT (1958). Spain: coal due to Bilbao, imports (1910) and domestic (1917-1935) from Coll (1985), electricity: Antolin (1988), Garrues-Irurzun (2008) from average prices from Hidroeléctrica Ibéria who mostly supplied industrial consumers (95%). The series of prices used relates to the price of kWh produced, so the price is adjusted to incorporate 15% losses in transmission. Sweden: Ljungberg (1990). The series is for high intensive uses in industry, due to its large share in consumption.

It is clear that the relative prices of electricity versus coal declined enormously in all the countries/regions employing thermo-power due to significant gains in the efficiency of thermo-

[9] Due to the frequent practice of consumer price discrimination as well as certain energy policies.

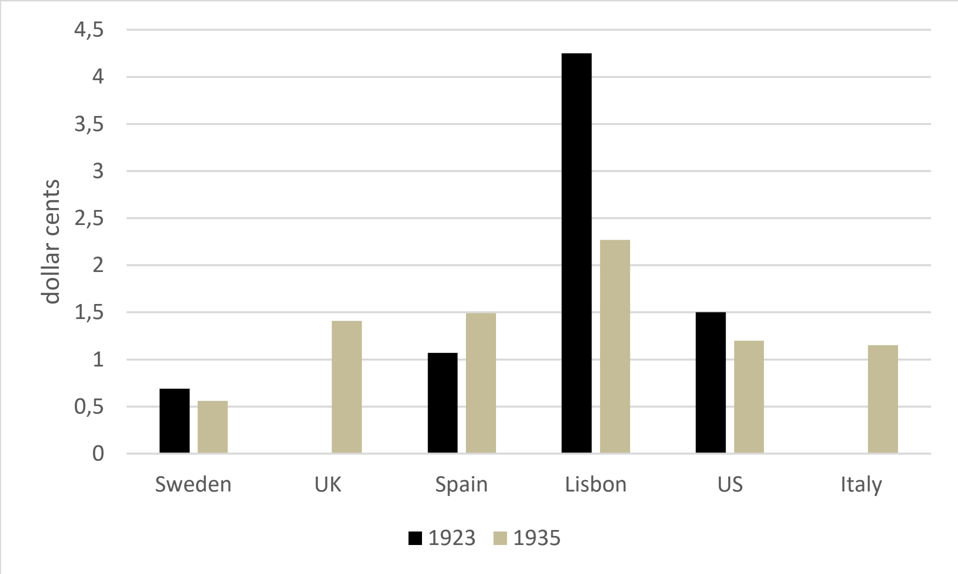
power production among other things[10]. For example, data from power centrals in the US and Portugal shows that efficiencies increased from a mere 5 percent and 4 percent respectively before the First World War to 18 percent and 14 percent around 1935. The story was very different in the early hydro countries, Sweden and Spain, where the fall in relative prices was less pronounced. This has mainly to do with the fact that efficiencies in hydraulic equipment were already very high, and thus had less room for improvement. It is striking that the level of the relative attained prices of electricity versus coal was already much lower in hydro countries than in thermal countries before the First World War. While an industrialist in Lisbon could buy 14 to 17 metric tons of coal in 1910 for the price of 1 MWh, in Sweden or Spain they could buy just 1 to 2 tons, which indicates a much stronger incentive to electrification. As coal prices in the north of Spain and in Sweden were similar to those in Portugal, it is clear that prices of electricity were in fact much lower than in Lisbon and Porto, even though the latter had switched to hydropower since 1923. This can be an indication that hydropower possibilities in Portugal were more limited than in other places but also points to other reasons, such as market power (see Bartolomé 2009 for the case of Porto). In any case, the comparison between relative prices suggests that electricity was not an escape from the burden of pre-war costly energy resources, at least relative to other countries.

Comparing the relative electricity to coal prices in the Portuguese capital with the other thermal countries, we observe that they behaved quite similarly, although the ratio was a little higher in the US. So the incentives to electrify in relation to the steam option did not seem to be worse in thermal Portugal than in other thermal countries, at least not after the First World War. These results are less optimistic than they seem, however – similar electricity to coal prices in relation to the main Portuguese coal exporter, the UK, means that double the coal prices correspond to double the electricity prices. In fact, what is relevant in a cross-country comparison is not really the relative decline in electricity to coal prices but the low electricity prices that were charged in countries with hydropower. In nominal terms, the Basque region in Spain, Italy and Sweden managed to leap-frog in a dramatic fashion during the twenties and thirties, having lower electricity grid prices than the coal-endowed UK, and in the case of Sweden also lower prices than the US. By contrast, industry in Lisbon faced electricity prices

[10] Gains in transmission, transformation of energy and also decline in exploration costs due to the use of larger power centrals. These are variables that can also improve in hydropower centrals.

which were about three times as high as those in the US in the early twenties, and twice as high as the UK in the mid-thirties, as illustrated by figure 5.

Figure 5. Electricity prices in 1923 and 1935 for selected countries, dollar cents



Sources: See Table 5, Exchanges rates are from Officer (2009).

Countries that pursued the hydropower technique managed therefore to supply their industries with electricity at a price that was competitive or even lower than the coal endowed UK or US. Portugal missed an early advantage of hydropower and lagged behind in the electrification of manufacturing, choosing instead to use coal-based thermo-power. As the country eventually became hydro-dependent in the 1950s, it is reasonable to question whether this was justifiable or if in fact represented a missed opportunity which was to have a strong negative impact on the growth trajectory of the country.

Did Portugal miss an opportunity to leapfrog?

Arguments for the missed opportunity might in fact seem compelling when comparing calculations of hydropower potential which became available in the 1950s. Portugal appeared in a better position than Finland, France and Spain, in terms of economic potential per km^2 and with a per capita resource endowment much worse than Nordic countries and Switzerland, but comparable to France or Spain, and in a better position than Italy. Despite this fact, the actual hydropower production corresponded to only 3 percent of the economic hydroelectric potential[11] , contrasting with Italy (43 percent), Finland (28 percent) and France (25 percent), but as table 6 demonstrates also with other countries with 10-15 percent of economically exploited resources, which managed to attain high percentages of hydro production.

Table 6. Hydroelectric potential in some European countries around 1950

	A Technical potential (GWh/y)	B Economic potential (GWh/yr)	C Economic potential (MWh/yr/km²)	D Economic potential (per cap.)	E Hydropower production (GWh)	E/A Technical potential exploited (%)	E/B Economic potential exploited (%)
Spain	76 639	48 220	96	1 724	5 079	7%	11%
Finland	18 100	13 000	38	3 243	3 650	20%	28%
France	100 000	65 000	119	1 554	16 072	16%	25%
Italy	58 000	50 000	166	1 069	21 605	37%	43%
Norway		158 000	487	48 390	16 920		11%
Portugal	**17 000**	**13 500**	**146**	**1 599**	**437**	**3%**	**3%**
Sweden	130 000	95 000	211	13 491	14 394	11%	15%

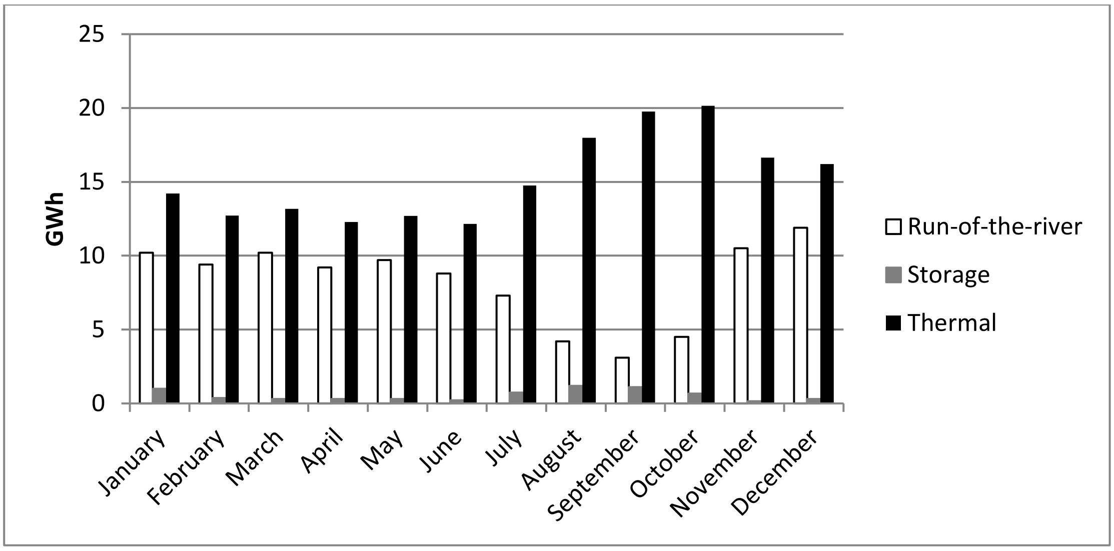
Source: Bartolomé (2005) first three columns and own calculations.

Of course, however, these calculations are very superficial: they say little about the type, cost and regional endowment of water resources in a country. The bulk of hydro resources in Portugal are concentrated in the north of the country (the River Douro and its tributaries) and in the international stretch of the river, where most of these resources could only be harnessed in a later period after agreements with the Spanish Government and water regulation in the Spanish part[12]. An additional limitation of Portuguese hydropower was the lack of smaller sized resources, which elsewhere in Europe were the first to be harnessed due to the low cost of exploitation using technology which was a natural follow up to early hydro-mechanical technology and to the establishment of long distance transmission. Even in districts other than Lisbon and Porto, where waterpower had dominated, the direct use of steam was becoming more important. Turbines and wheels in those regions declined from 47 percent to 24 percent of total primary motive power between 1890 and 1917 (Santos 2000). Thus, earlier industrialization using water power in Italy, Finland, Sweden and some regions of Spain

[11] Resources that can be economically harnessed in relation to other alternatives.
[12] A contemporary author, Galvão (1928), pointed out that regulation in Spain could improve the potential thirteen times.

became a small advantage for the early appearance of hydroelectricity, whereas in Portugal it was mainly provided by thermal centrals. Finally, even if the technological problems in long distance transmission were solved around 1900-1910, a second bottleneck remained: Portuguese hydro resources had large requirements for water regulation. The type of centrals that existed around 1935 (mostly run-of-the-river, the less expensive type, compared to 2storage" for example in reservoirs) shows the irregularity of the flow of Portuguese rivers. Production varied between 12.2 GWh in January to only 4.2 GWh in September, as shown in figure 6. Regulation was only practiced on a very small scale and only 7 percent of production was through storage, which meant that thermal support was needed during parts of the year, increasing the cost to the consumer.

Figure 6. Monthly chart of Electricity Production in 1935



Source: DGSE, *Estatísticas das Instalações Eléctricas*, 1935.

To increase the productivity of the rivers, significant investments in the building of reservoirs would be needed, especially in the south of the country, where the river flows were subjected to much stronger variation. This meant very large installation expenses and was one of the reasons behind the persistent use of coal in the south. In fact, the Portuguese water resources were more adapted to larger establishments where only large-scale consumption would lower costs. Unlike the Nordic countries, natural lakes for regulation were not available, so to take full advantage of more regular power, artificial reservoirs had to be constructed. Although Spain also had water regulation problems, they seem to have been less serious than in Portugal and occurred in a later period of electrification (Antolin 1999, p. 433, Bartolomé 2005). Moreover, large initial investments in water regulation and transportation were made possible by foreign investment due to an already pre-existent industrial demand (Capel and Urtega 1994). Thus, what seems to explain the Portuguese early choice of thermo-power and general low level of electrification was not simply an inadequacy of natural resources, a point which is consistent with the work of Rubio and Tafunell (2014), who demonstrated empirically using data for Latin America that hydroelectric potential is only a necessary and not a sufficient condition to explain its wide scale adoption.

Our explanation for Portugal's failure to exploit its water resources is that it lacked both the capital and the potential industrial demand to be able to exploit its natural resources, and that this, together with various institutional factors, was a result of path-dependency from its lack of ability to develop using either coal or alternatives in the nineteenth century. On the supply side, capital was already chronically scarce by the end of the 1890s, following a public debt crisis in 1892, resulting from a depreciation of the exchange rate after abandoning the gold standard, when controls were imposed on borrowing abroad and short-term interest rates rose to around 4 percentage points higher than the UK (Bordo 2003). This only worsened after the First World War at a time when Portugal witnessed general financial malaise, including interest rates of 12 percent and one of the highest rates of inflation in Europe in the 1920s (Valério 1985). Indeed, many hydroelectric utility projects were not pursued due to lack of capital (Simões 1997). On the demand side, unlike other coal-poor countries like Sweden and Finland which managed to build up highly energy intensive industry based on alternatives, Portuguese industrialization had resulted in a low intensive use of steam and a high intensive use of low skilled labor. Traditional industries such as textiles, food and ceramics constituted the demand[13] from industry, and even the demand for urban electrification was limited, with the only sizeable cities being Lisbon and Porto.

Moreover, in both Lisbon and Porto, the institutional setting did not favor the establishment of electrical networks. The two gas companies operating in each city had a monopoly (regulated by the municipality) of private and public gas supply, and managed from an early date to secure the same for the distribution of electric current. Thus, they were not particularly interested in creating competition for their main source of revenue, gas, and adopted

[13] DGSE, *Estatísticas das Instalacões Eléctricas*.

a wait-and-see strategy in relation to technological developments in the field of electricity. Thus, they operated small scale utilities without any capacity for expansion and it was only when the municipalities pressurized them into substituting gas with electricity for public lighting that they finally constructed new thermopower centrals, in 1903 for Lisbon and 1908 for Porto. In the capital there was already a latent market for industry, and power had to be increased two times before the First World War to accommodate the expansion of consumption. Thus, even after a late start and with a monopolistic situation, the advantages of electricity in relation to other systems were already present before the war: a study from 1911 suggested that the daily cost of a 10 hp electric motor compared well with anthracite gas motors. Outside Lisbon and Porto, there were very few substantial public power stations installed before the war. After the thermal power stations of Lisbon (6500 KW) and Porto (2516 KW), the next largest facility was a hydropower utility in Serra da Estrela supplying just 370 KW.

The First World War provided a large shock to Portuguese energy dependence, eliminating the constraints of the gas monopolies, and led to a change in the perceived benefits of hydropower. During the war various plans were put forward for moving to hydropower, but most of these projects were never realized. Then, the end of the Republic and the establishment of the dictatorship in 1926 led to a desire for autarchy in energy, and the perception that imported coal was a threat to independence and an unnecessary drain of gold reserves. Rules were laid down to make it mandatory that a certain proportion of national coals should be mixed with foreign coals for railways and manufacturing in general. It was clear that the independence of the energy sector would have to come from hydroelectricity, but despite regulatory attempts and heated discussions, most initiatives remained private and consumption remained mainly thermal, especially in the south of the country.

Without substantial public investment, the low potential demand from industry meant that private actors determined that hydropower was not viable. Although they were more expensive to operate than hydropower stations, thermal power stations were less expensive to construct and more adaptable to the variations in demand which determined the technological choice. In fact, both due to the natural resources and demand, intensity of use was low[14]. By 1931-1935, the use of power in hydro-electrical centrals had not surpassed 2,000 hours, as against 2,786 in

[14] There was not enough consumption in normal exploration conditions but power was successively increased in order to cover for problems during the summer. In many cases this was preferred to water regulation, which seems to point to a lower cost in the first option. (DGSE, Estatísticas das Instalações eléctricas, 1935)

Spain, 3,450 in Canada, 3,800 to 5,400 in Italy, and 4,895 in Finland (Myllyntaus 1991, pp. 71-99). This says much about the relatively high initial power costs of hydroelectric companies. Because prices were higher, consumption was low. This created a vicious circle whereby consumption was low because prices were high and prices were high because consumption was low. This did not help electrification: for the low wage level of the Portuguese economy, industrial prices would have had to be substantially lower to give an incentive to capitalize. While in Sweden and the US, relative prices for electricity versus wages fell by 2.51 and 2.89 times between 1914-34, and 1.41 from 1925 to 1934 in the UK, in Portugal those incentives were less visible, even reversing from 1925 to 1934, as shown in table 7.

Table 7. Relative electricity prices versus wages (1934=100)

	Sweden	US	UK	Portugal
	1934=100	1934=100	1934=100	1934=100
1914	251	289		107
1925	127	110	141	73
1934	100	100	100	100

Source: Prado (2010); Melman (1956); *Boletim do Trabalho Industrial* (1934).

5. Conclusion

We have argued that Portugal's failure to industrialize substantially before the Second World War was at least in part due to limited access to natural resources. The country missed out on most of the advantages of steam before the First World War. In the interior of the country, coal was prohibitively expensive, and alternative power sources were limited, meaning that domestic demand for industry in the coastal areas with cheaper access to coal was constrained. Relatively high energy to labor costs thus directed Portuguese industry to a limited and labor-intensive industrialization, which, combined with water-resources which were relatively expensive to develop, led to a sort of path dependency, whereby, lacking government action, the opportunity for exploiting hydro-power and electrification in the interwar period was lost. There was a lack of capital to fund the necessary infrastructure, and a lack of demand from existing industry. Instead, electricity was supplied by coal-based thermo-power and the difference in energy costs in relation to coal-endowed countries was thereby maintained, thus giving an incentive to maintain the labor-intensive industrial structure.

This vicious circle would only be broken during the 1950s and 1960s, a period not covered here. Neutrality during the Second World War led to an inflow of capital[15], which might be the reason why the state was then able to invest in a vast electrification plan using hydro-power, ensuring cheap energy for both old and new industries. Industrial electricity prices declined impressively and converged with those in other European countries. However, it was already too late for hydropower to make a significant difference[16]: by then the world had entered the age of cheap oil which democratized industrialization in many countries. Endowments of energy were no longer an important prerequisite and source of growth.

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[15] See Amaral (2017).
[16] See also Madureira (2008).

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