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Energy transitions in Europe: 1600-2000

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Keywords: : energy, coal, historical transition, England, Sweden

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Astrid Kander, Paolo Malanima and Paul Warde

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Introduction

The employment of particular ‘energy carriers’ and the technology associated with their use have always lain at the core of most economic activity. Both phases in economic growth, and the prevalence of key (and general purpose) technologies have frequently had a strong association with the employment of particular energy carriers: steam engines with coal, internal combustion engines with oil, and ICT with electricity. It has however also been the case that some of these technologies could have been developed, or initially had potential substitutes, in a way that did not depend on the same carrier (electric cars have existed for example for almost as long as petrol-driven ones). It is clear therefore that a key issue in our understanding of the history of technology, and processes of economic growth (and its social and environmental impact), is why consumers shifted from the use of one energy carrier to another. These energy transitions, fundamental changes in energy provision systems, are also high on the political agenda today, when the world is facing the threats of global warming and geopolitical struggles over remaining fossil fuel reserves. The driving forces behind historical energy transitions may be of importance for understanding also current and future attempts to change energy systems.

This paper will examine the nature of energy transitions in Europe over the past four centuries, providing an overview of possible theoretical approaches, and some empirical data on levels of primary energy consumption, and price. The first part of the paper discusses possible explanations for transition, and the core approaches of earlier literature. The second part of the paper will, in the light of these approaches, address consumption trends in a range of European countries, and examine in more detail the transition from wood to coal of two of those: Sweden and Britain.

Theoretical framework and previous studies

Technological discontinuities and transitions may be perceived of as two sides of the same coin. While the literature on technological discontinuities stresses, sometimes rather exclusively, technology-push-interpretations, with a supply side focus (Van de Ven *et al*., 1999; Anderson and Tushman, 1990), the literature on transitions generally takes social application domains as units of analysis, and investigates how ongoing dynamics in the selection environment influence the diffusion of new technologies. Transitions are shifts in application domains, and focus on the demand side (Geels, 2005, 2006). In reality supply and demand are interlinked and the process may be described as *co-evolution* of variation (technology) and selection (society). Evolution is of course not a continuous or necessarily optimal process. Path-dependence, the idea that societies are locked into their previous and possibly sub-optimal choices, may play a role for explaining different energy transition patterns among countries in Europe. Path-dependence is not necessarily a lock-in in the sense of inertia, but may also be the development of particular competencies that cannot easily be shifted.

We will outline a fourfold framework in which transitions can be understood, encompassing both supply-side and demand-side models. The first of these is perhaps the most profound in historical energy transitions: the shift from dependence on ‘organic’ energy carriers that were derived directly from photosynthesis in plants, and hence limited available supply to a *flow* of photosynthetically-converted energy, to fossil fuels, which consist of a very large *stock* of energy laid down over millions of years. The first significant transition of the modern period (and, one could argue, perhaps its defining characteristic) was an escape from the inherent limitations of the organic energy regime, which can be modelled as a process driven by the steeply increasing marginal costs of employing organic energy carriers. The profound structural difference between organic and fossil-fuel based energy regimes does not however mean that rising marginal costs were necessarily the *proximate* cause of the transition.

A second approach to energy transition is to see it as being primarily driven by *quality* or *performance* characteristics of each carrier. Some scholars have described developments in energy use as a simple linear progress, where inferior energy carriers (such as traditional fuels) are substituted for better (modern carriers such as fossil fuels). This model may be described as *the twin model of serial substitutions and energy ladder*, climbing up to better energy sources, depending on whether the emphasis is on the supply side or the demand side.

A third approach is to see transition as primarily being driven by innovations in *technology*. Both technological transitions and energy transitions may be seen as primarily driven by economic incentives, and thus as an *endogenous* process. Christensen (1997), for instance, sees technological discontinuities primarily as economic process, driven by R&D investments, learning, and price and/or performance improvements. When new technologies become better and/or cheaper than old technologies, they will replace them. This argument assumes, however, that 'better performance' can be easily established. We will argue however that the complementarities of certain technologies, infrastructure and factor goods can lead to *development blocks* that promote transition in a model encompassing both the demand and supply side.

A fourth approach is the *evolving-cost preference* model. This relates the costs of using particular carriers to wider developments in the economy that determine preferences and relates more to the demand side. As income or the relative prices of different factors of production shift, so too will preferences related to perceived risks, or the opportunity costs of using particular carriers. Influence can be exercised on consumption pattern directly through consumer choices or via the regulatory regime, which may take into account factors such as environmental costs, security considerations and the taxation regime.

The 'organic constraint' model

This conceptualisation of energy transition is derived from the work of Tony Wrigley (1962, 1988, 2003, 2006). For most of human history nearly all the energy available to humans was derived from plant products, themselves the result of the process of photosynthesis by which solar radiation is used for cellular growth. Wind and water power are exceptions to this rule, but in aggregate terms provided only very small proportions of total consumption. This meant that energy consumption was subject to an 'areal' constraint, as it had to be proportionate to the land on which the plants grew: levels at any one place were limited by the ceiling set by local biomass growth and the possibility of transporting fuel and fodder from elsewhere. Transport costs however were relatively high because the energy required for transporting bulk goods represented a significant proportion of the energy content of the goods themselves. Given the finite amount of energy that could be obtained from pre-industrial agricultural regimes, development had to proceed on a territorially extensive rather than intensive basis, and was subject to steeply diminishing marginal returns.

Being able to tap into a stock of coal changed this regime utterly. Large amounts of energy could be employed at specific points in space, and thus what Wrigley calls 'punctiform' growth could ensue. It is only after this epochal development (a phenomenon only of the twentieth century in many parts of the world) that modern levels of economic growth, and further energy transitions, became possible. It should be noted however that at its core the 'organic constraint' model does not imply any *necessary* technological development. Rather, the limits to growth imposed by dependency on organic resources will eventually raise the cost of traditional energy carriers that compete for space (such as food, fodder and wood) to such a level that where possible, substitution for fossil fuels (initially substitution of wood by coal) becomes attractive if they are available. However, with no technical change, the ability to employ fossil fuels to provide dependence on traditional carriers to provide *kinetic* energy (i.e. transport), and thus 'punctiform' could only be imperfectly developed.

The twin model: Serial substitution and the energy ladder

From the supply side, the pattern of energy carrier substitution is frequently presented as linear and simple. New energy carriers are introduced because of their superiority and that they replace inferior energy carriers. Wood is replaced by coal, which is in turn replaced by oil, electricity and gas. This may be perceived of as a kind of 'technology-push' idea, since new, better energy carriers are discovered and then replace the old traditional ones, simply because they are better. This differs from the 'organic constraint' model outlined above in that in the former it is the *quantitative* rather than *qualitative* nature of the carrier that forces transition. Obvious reasons for the belief in the serial substitution idea is its appealing simplicity and the fact that fundamental transitions have occurred. However, we must remember that the employment of new energy carriers often occurs in a *supplementary* fashion that does not eliminate or even reduce the use of other carriers. As we will see the degree to which certain carriers to sets of carriers became dominant varied significantly from country to country. Equally, some carriers of lower 'quality' will retain niche markets because of particular consumer preferences (such as for domestic wood fires or for particular cooking purposes) where the carriers are imperfect substitutes. In themselves these exceptions do not invalidate the general applicability of an argument that transition may be driven by carrier quality

The mirror of the supply-side serial transition model on the demand side is the *energy ladder* model. This model has mainly been used for explaining fuel switches in developing countries. The energy ladder proponents share a simple view on fuel switching among households (Hosier and Dowd 1988, Smith 1987, and Leach 1992). The switch takes place from biofuels to modern fuels, and is influenced by factors such as equipment costs, reliability of and access to modern energy carriers and to a lesser extent relative prices. The idea behind the energy ladder model is that households only use biofuels if they are poor and have limited access to modern energy carriers, such as gas and electricity. Essentially this is a variant of the serial substitution model that takes into account the difficulties in diffusing new carriers throughout the economy.

Energy carrier quality

There are two ways in which energy carrier quality can be established. One is by employing the *exergy* concept and the other is by means of *physical grades*. Exergy is one aspect of the quality of energy, and the definition of exergy in general terms is 'the ability to perform work'. Indeed, strictly speaking when we talk of 'energy consumption' we are attempting to analyse exergy, because 'energy' in its own right cannot of course be 'consumed', but only changed into another form. However, exergy values tend to fall within a very narrow range for fuels and exergy is also an extremely rough measure. Consequently it is of little use in attempting to explain transitions.

Another attempt to assess energy carriers from purely physical aspects is by means of physical grades. Reynolds classifies energy sources according to four different physical grades:

a) Weight-grade, which is the same as energy density (or energy/mass)
b) Volume-grade, which is the energy/volume
c) Area-grade, which is energy/area
d) State-grade, which defines the state in which the resource occurs: gas, liquid or solid.

All four aspects are connected to the costs of handling the fuels. Fuels that have high energy density as well as high-energy volume have comparatively little dead weight and volume, which is an advantage for transportation and storage. Coal, for example, has a greater energy density than wood and thus a coal-fired steam engine either can be considerably smaller than a wood-fired one, or does not require such regular stoking. A geographically more concentrated energy carrier is cheaper to handle than one that is dispersed. The area grade distinguishes between fossil fuels and firewood. A geographically concentrated energy resource, like coal and oil, has the advantage of scale, because the extraction capital can be stationary and large. Long before Reynolds, Wrigley had emphasized the relevance of the area-grade in relation to the 'organic' economy. The notion of an ‘area-grade’ is more limited than Wrigley’s conception, however, as it does not embrace the limit imposed on the growth of supply by photosynthetic processes.

The liquid state is the optimal condition of a fuel, because liquid fuels are easiest to transport and to use; second best is the gas form, and third best is the solid state. Reynolds makes no attempt to combine the four grades into one energy grade index, but since oil comes out well in all grades, coal is in the middle and firewood has the lowest quality, he concludes that mankind has advanced historically from low-grade to high-grade energy. He even suggests that phases of economic development have been based upon technical innovations in combination with energy carriers of higher grade than the previously dominant energy carriers of the time. Reynolds accordingly believes that a future change to oil-substitutes is likely to impede economic development, although improved technology could outweigh some of the disadvantages of lower grade energy carriers.

Even though there is a lot of sense in viewing long-term transition patterns as linear, we will argue that an economic, rather than a physical approach is necessary for understanding the transitions, which relates to technology and demand-side factors. For consumers, one important aspect of energy carriers is their different number of special applications. An energy carrier which can be used for several purposes, such as light, motion and heat, is naturally of higher value for consumers than an energy carrier which can only be used for one or two purposes. Energy carriers thus compete in different markets where the price elasticity of consumer demand differs in line with the number of competitors. Energy carriers are not perfect substitutes for each other. Equally, the picture becomes more complex with the rise of electricity, which is indeed the highest quality energy carrier, but that is a *secondary* product, generated by inputs of primary energy carriers. Thus primary energy consumption is not directly guided by qualities that can be enjoyed by the final consumer. Thus while we can discern a rough progression in transitions between energy carriers on the basis of quality, we will see that the shares which each carrier achieves of the aggregate total are in fact quite variable between countries.

Technological change and the Development Block model

‘Technology-push’ models of energy transition can be developed that relate more to developments in the *converters* that confer economic value upon energy carriers, rather than in the quality of the energy carriers themselves (it is of course true that energy consumption must always be exploited by means of some kind of converter, even if the main process of consumption does not employ any intermediaries. A fire does not require the use of a converter to have effect, but someone must light it). A key development of the last three hundred years is the rise to dominance of *mechanical* converters of energy rather than *biological* ones. Until relatively recently, although mechanical converters existed (such as water-mills), most conversion, especially to provide motion, had a biological basis: people, horses, oxen, and so on. The ability to replace these converters with mechanical ones such as steam engines, combustion engines and electric motors has been a key part of modern growth, and allowed labour productivity to rise dramatically: effectively we are each now able to employ many ‘energy slaves’ to supplement our own labour.

However, recognising the essential importance of technological change does not tell us how or why technological innovation occurs, nor why the take-up of technological innovations proceeds at very different rates in different times and places. How closely are these processes related to the availability of particular energy carriers, their price, the infrastructure necessary for their use and aspects of demand? It is these questions that are at the heart of the *development block* model. The Development Block concept was coined by the Swedish economist Erik Dahmén (1950, 1970, 1988) and has been used by scholars like Schön (2000, 2006), Lundquist et al (2005, 2006), Enflo et al (2007). The ideas of Hirschman (1958) of forward and backward linkages in the economy are of a similar character. Hirschman emphasized that growth was unbalanced among sectors and that strategic investments should be done in certain sectors that may propel the growth of others because of strong complementarities.

Dahmén’s development block concept relies on Schumpeter’s idea of innovation proceeding by ‘creative destruction’, and on Gerschenkron’s ideas on the evolution of relative prices and value-added in different sectors of the economy. Thus both radical innovations and complementarities are central to the concept. Complementarities arise because of functional interdependence between core technologies and supplementary activities. In most cases a development block is plagued with imbalances, or bottlenecks, mainly stemming from the incapacity of the supplementary activities to provide sufficient support to the core technologies. One can build wood-fuelled steam engines, for example, but in many parts of the world limited wood (as opposed to coal) supplies would soon curtail their use. Supply bottlenecks will result in demand pulls on complementary sectors and give rise to relative price increases compared to the products of the core technologies, which in turn will put pressure on the complementary sectors to come up with cost reducing innovations. Once they have succeeded in this the bottleneck is widened and growth may be swift. New and desirable technologies can thus prompt a wider wave of innovation.

In the analyses of Dahmén and Schön the development block is however a much more encompassing concept than one that simply stresses linkages between core and supplementary sectors. Their analyses also stress complementarities between production, infrastructure and institutions. In an economy characterised by development blocks, two main processes generate transformation: *market widening* and *market suction*. Market widening is the more dynamic of these. It means that certain products are supplied at the market at a lower price and will consequently be used more, frequently finding employment in new areas of the economy. Market suction increases the demand for complementary factors, such as services, raw materials or energy. Generally the elasticity of supply of these factors is such that market suction leads at least in the short term to increases in the relative price of these goods. With successful complementary innovations the relative price of the complementary factors, such as energy, eventually falls. If no such extension of the ability in supplying key inputs (such as energy) appears, this dynamism may be cut short.

A development block gives rise to a situation of limited substitution opportunities. Complementarities mean that certain things work together, even if substitution is theoretically possible: combustion engines use liquid fuel and historically the most effective liquid fuel has been petrol. Although it is possible to design alternative forms of motor vehicle the success of the petrol-driven vehicle has generated a large set of interdependencies in the development of the road network, the provision of filling station, oil pipelines, refineries, and so on. Petrol cannot easily be substituted for another energy carrier, neither wood nor electricity.

In particular cases technical innovation at the heart of development blocks are *general purpose technologies* and may display *modularity*. General purpose technologies simply have a very wide range of applications and usually generate significant complementarities (such as computers in the organisation of workplaces). *Modularity* is a particular design aspect and refers to technologies that have multiple applications, but where adjustments to the use of the technology had ramifications and requires change in complementary technologies or forms of organisation, which inevitably make its use more complex. That is, they have *modular* rather than interdependent design characteristics. Steam power, for example often requires the design of very specific engines for particular uses, and any alteration of engines' parameters would also affect the design of its surroundings. Electricity, on the other hand, is strongly modular. Once a supply is connected many different things can be plugged into the electricity network that requires no alteration as a consequence. Equally, it is possible to generate electricity in many different ways, without altering the basic form of the network. This *modularity* Allows makes the use of electricity, already a high quality carrier, widely attractive, but also means that it becomes relatively easy to adjust the primary energy carrier by which electricity is generated.

The development block model implies that major technological inventions are at the core of explaining energy transitions. Technological breakthroughs will lead to market widening, which in turn will lead to demand-induced growth of energy provision markets (market suction), and rising prices of energy in relation to the technical equipment, which will put an innovative pressure on energy markets and lead to complementary innovations there. This will in turn reduce the relative price of the energy carrier that is complementary to the core technology of the new development block. In turn this fall in relative prices can lead to widening in the use of the carrier in areas where there are clear substitutes, in part because of economies of scale associated with the infrastructure of the development block. However, for the purposes of analysis the manner in which relative price shifts relate to energy transitions may be complex. The relative price of energy carriers is not clearly related to the Rostowian relative price pattern, where market widening and market suction changes the price relationships between machinery and inputs (such as energy). As an economy is likely to have overlapping development blocks with their own specific energy carriers. Indeed, processes of innovation in the energy sector could occur that simply keep the relative prices of carriers level in a situation where without innovation one might expect rising marginal costs for the new carrier. However, we could also suggest that the rapid advance of a particular carrier that *does not* show any relative cheapening compared to other carriers, or indeed, that becomes more expensive, is also evidence of the development being ‘locked-in’ to a particular development block associated with that energy carrier. Nevertheless, its is reasonable to expect that in most cases the relative price of a carrier undergoing transition will fall at some stage, though this could take place either before, or during the main phase of the shift.

One would also expect to observe relatively rapid growth in both the supply sector for that particular carrier, and in closely associated sectors (for example in the case of the development block associate with steam, we would expect to see well above average advances in coalmining, iron production, engine production, and the transport sector including railways and steamships), although the correlation may not be very close where the carrier has many uses. The transport sector may be a key variable in this regard as specific transport technologies are usually associated with specific carriers.

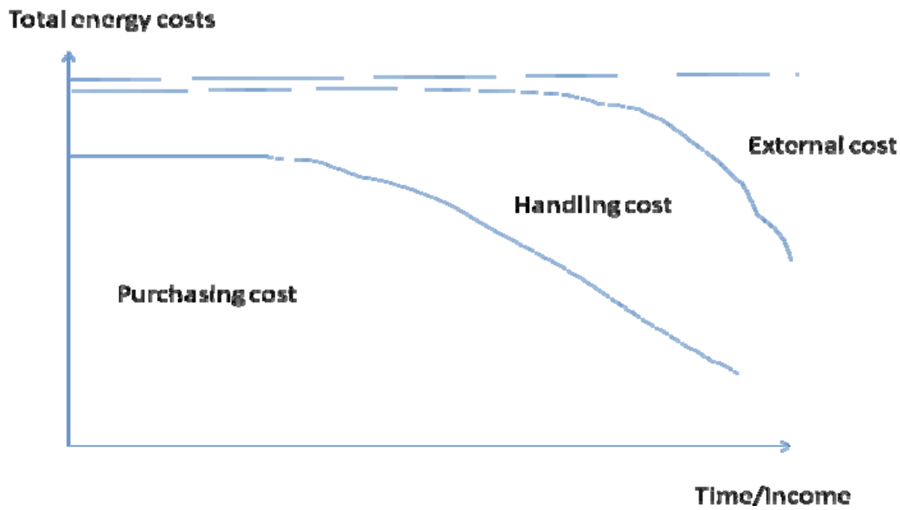
The evolving cost preference model

Kander (2002) proposed an economic-historical model for understanding energy transitions over time based on changes in people’s preferences as they get richer. Energy use entails different costs and it may be argued that there is a shift in cost emphasis as income rises. People will give different weight to the varying cost components. The three kinds of costs involved in energy consumption are:

1) the purchasing costs (the price of energy carrier and its related equipment)
2) the handling costs (mainly time),
3) the social costs (or external costs).

Handling costs, or time costs, are important both for final consumers (for instance. Households) and when energy is an intermediate input used in industry or transport. Two shifts seem to take place over time. First there is a shift in people’s assessment of the importance of costs from purchasing costs towards handling costs. This is because time costs rise with income: for both companies and households income increases have an effect on the time costs. For companies this relation is more obvious, because time costs increase with wages, and as wages go up it will be more expensive for companies to use labour for handling time-consuming energy carriers. People will then find it worthwhile to instead buy an energy carrier with a somewhat higher purchasing price. For households the time costs are not quite as explicitly linked to income, but there is an indirect effect, which consists of their assessment of alternative uses of their time (this may also relate to the household division of labour: for example, if two adults in the household have paid employment or not). The time-constraint imposed may be immediately related to energy consumption (for instance, the choice between lighting a coal fire and flicking on a switch), or related to technology driven by a particular carrier (part of the attraction of cars is that they can save time in reaching locations relative to public transport which is constrained by particular routes and timetables). Such preferences do not always develop in a linear fashion: for example, high-income groups who also enjoy longer leisure may develop preferences for using traditional energy carriers like firewood because of their pleasant smell, or cultural associations.

Figure 1 The evolving cost preference model



These issues relate too to a long-term phenomenon which is not necessarily related to rising income, but historically has generally been so: the divergence between energy and wage costs. These diverged radically around 1830 in Britain when the introduction of the railways removed the constraint of the 'organic economy' on transportation. Real energy costs have for the most part remained low ever since, while wages have for the most part progressively risen. The long-term increase in relative wage costs against energy costs creates an incentive for employers to economise as far as is possible on wages relative to energy intense forms of production (or put another way, to increase labour productivity). This naturally favours time-saving technology, compounding the process by which higher incomes also lead consumers to develop new preferences for reducing handling costs.

Preferences also alter with regard to what economists refer to as 'externalities'. These might include the wider impact of consumption that is not generally encompassed in the basic cost (such as environmental impacts), or relate to security and political issues (such as a preference for reducing dependency on imports, especially from unstable regions of the world, or the desire to support domestic interest groups and producers). Here new preferences may evolve that are articulated either through changes in consumer taste, but more influentially, through regulatory and especially taxation regimes (most notably in the very high level of tax on petrol). Externalities have tended to become more significant over time, both as income has risen, but also scientific knowledge about the consequences of consumption (i.e. of pollution) has improved.

A major test of the evolving cost preference model is to relate consumption of different carriers to their relative prices. Following Kander (2002) one can look at relative prices of competing energy carriers and see if there is a correlation between when they reach the same level per energy equivalent, which one would expect to be related to major transitions. If transitions take place despite the new energy carrier still being more expensive, then people are paying for something else (for instance reduced handling costs). In order to check whether external costs are being internalised, one needs to look at energy and environmental taxes and assess to what degree this has been a driver of relative price shifts and consequent transitions.

How do we test these ideas?

In our future work we will seek ways of testing the hypotheses and theoretical perspectives outlined above with economic historical methods. Chronology must be a key aspect of course: something cannot cause something else unless it occurs beforehand or simultaneously. It is essential to identify the major transitions and whether they happen simultaneously or not in countries across Europe (i.e. whether they relate to country-specific or general trends to do with technology or world markets). This is a starting point to understanding how transitions diffused across the continent and whether a transition in a 'leader' country or region determined the course of future developments elsewhere. Equally, the energy carrier mix and resource endowment prior to transition means that 'transitions' happen in radically different contexts and one must be careful about attributing them to the same basic processes. For the example, the rapid post-WWII rise of oil use in the UK occurred at a time when about 90% of energy consumption came from coal and the period of the steepest rises in consumption already lay a century in the past. In Italy, the post-war explosion in oil consumption came when 'traditional' energy carriers still made up over half of all consumption and where per capita levels of consumption were not radically higher than they had been for centuries previously.

With long time series of energy carrier prices (that we partly have collected) we can make a simple test of 'do prices explain everything', or whether quality premiums are paid for new energy carriers. In other words: do we need the evolving cost preference model to understand transitions? Crucial for the usefulness of such energy price series is that they are retail prices rather than wholesale prices and come from the same location. Another thing which is important in regard to prices is that variations may be large for different consumers (for example with electricity, households pay much higher price than industry) and among different products derived from the same source (petrol is much more expensive than fuel oil).

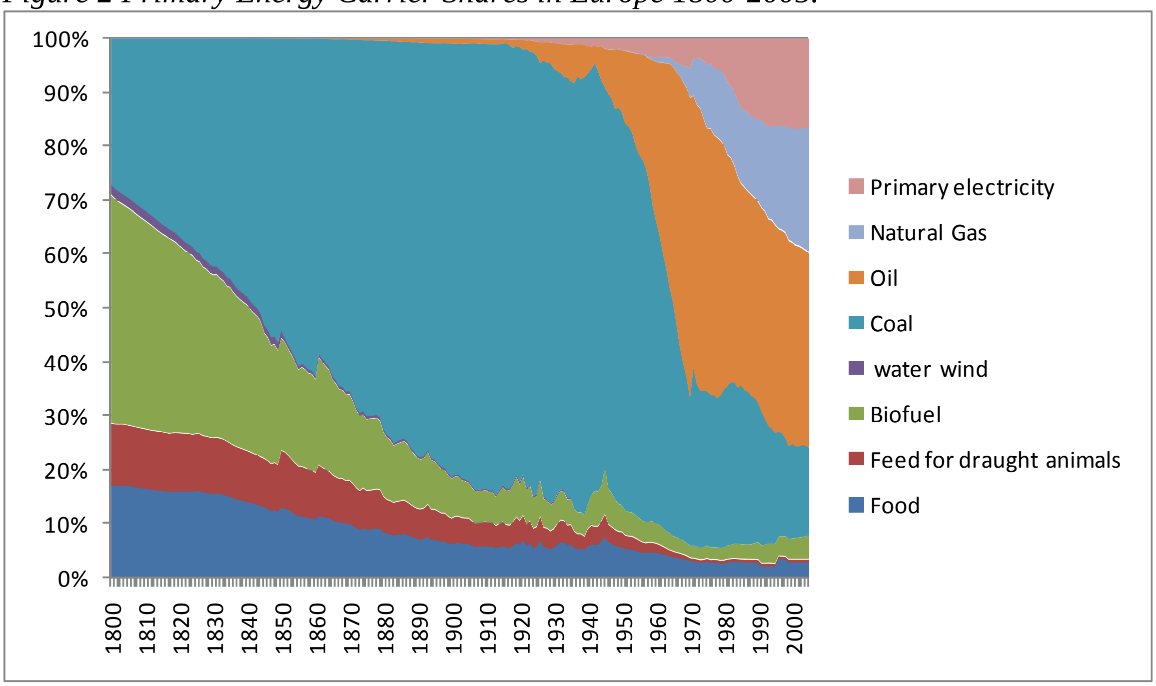
What especially needs further investigation is the degree to which general transitions 'piggyback' on particular development blocks that create market widening. We merely think of this approach as a perspective rather than as a hypothesis. Indications of its usefulness as perspective would be if transport takes a clear lead in the consumption of the new energy carriers (coal and oil), and that only after a drastic relative price fall of the new energy carriers the actual transitions take place. For example, in the 1930s by far the largest share of UK petroleum consumption was as motor spirit (petrol), but after the war this share steadily declined and was eclipsed by fuel oil. But would the development of fuel oil as a substitute for coal ever have occurred without the incentives provided to develop the oil industry by motor vehicles? Alternatively to looking at sector consumption (such as transport) we could try to find data on consumption for key technologies (steam engines and internal combustion engines). This requires time series on the diffusion of such technologies in Europe.

Some tentative observations on transitions

In the LEG (Long term Energy Growth) network we have worked to establish the historical consumption of primary energy carriers, including the traditional carriers, across Europe. To date we have completed series for England & Wales, Italy, the Netherlands, Spain and Sweden. Tentative series are also ready for Portugal, Norway, France and Germany. The energy transitions at the West European level 1800-2005 are depicted in figure 2.

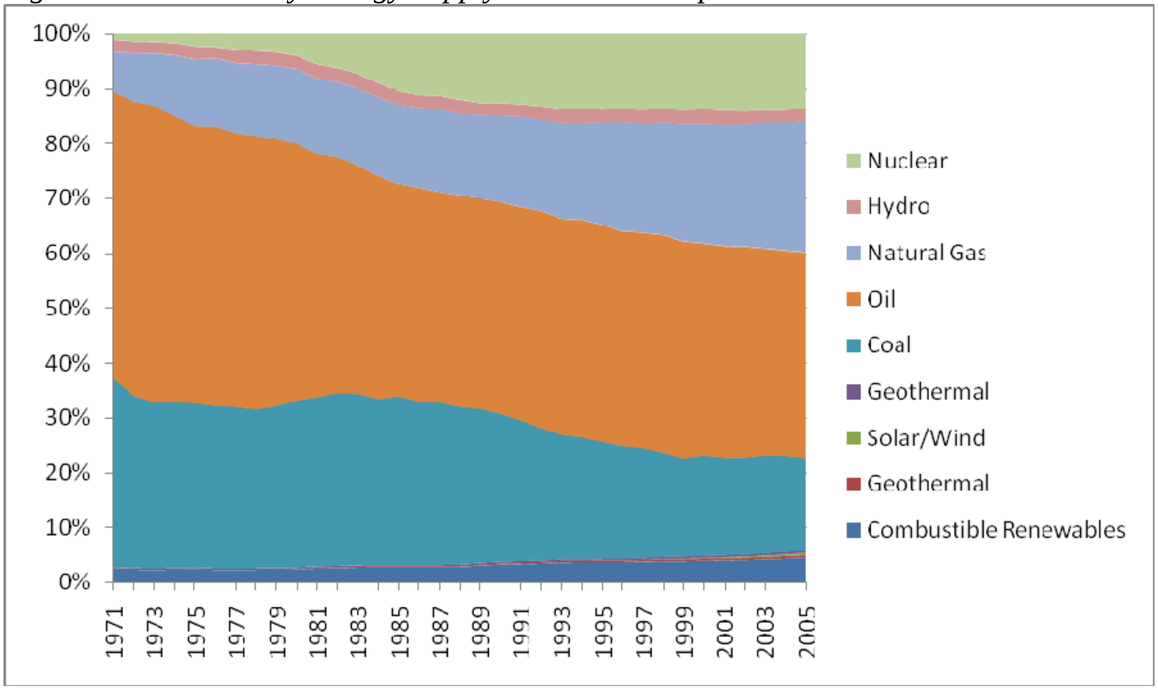
The escape from the constraint of the organic economy had already come some way in 1800. Coal then made up 30% of total primary energy supply, and this is all due to England. Then the diffusion continued over more than a century. In contrast the breakthrough of oil consumption took place very rapidly after the Second World War. After the oil crises of the 1970s oil stabilised its share, and natural gas and uranium were the main winners in relative shares. Renewable energy rose in importance, but as figure 3 shows this is still rather modest. .

Figure 2 Primary Energy Carrier Shares in Europe 1800-2005.



Sources: The Netherlands, Sweden, Spain and Italy: Gales et al 2007, England & Wales: Warde 2008, data for Germany, France and Portugal tentative series from the LEG (Long Term Energy Growth) network, IEA: OECD Europe 1971-2005.

Figure 3 Total Primary Energy Supply in OECD Europe 1971-2005.

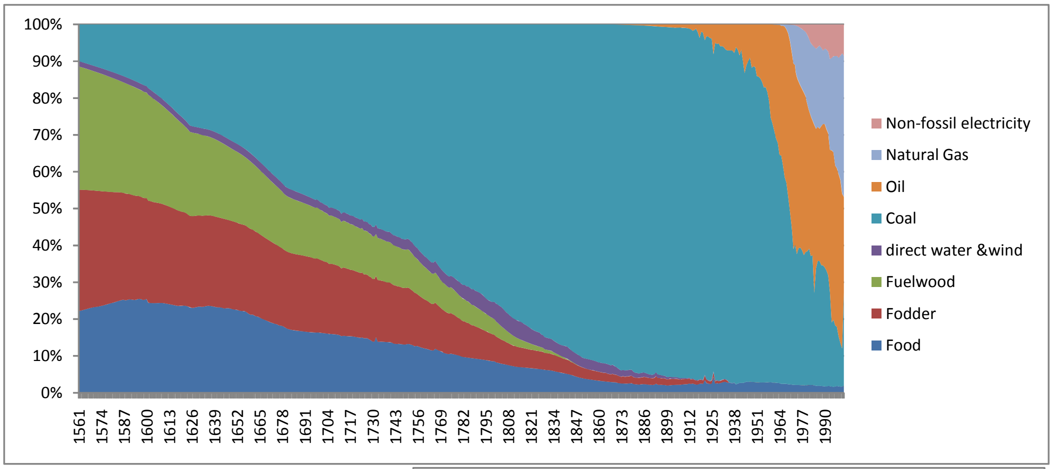


The variations in the energy carrier mix among European countries are rather large. Natural resource endowments (and relative prices) play a large role in this. For instance countries with domestic coal have a much larger share of that carrier in their portfolio, and countries with ample waterfalls have much larger shares of hydropower than the average in figure 3.

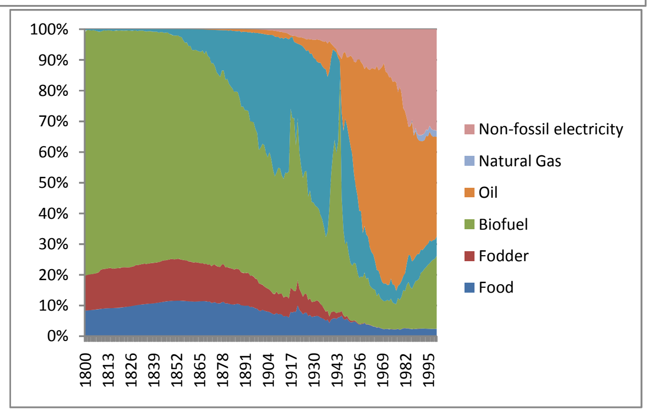
Two countries with very different resource endowments and energy composition stories are England and Sweden. Their stories are not only different, but also interlinked, especially through trade in coal. Figure 4 gives the British energy transitions since 1560 and right below we find the Swedish energy history from 1800.

Figure 4 British versus Swedish energy transitions

England



Sweden



British energy consumption has followed an exceptional path in that it has been dominated by fossil fuels from a very early date. (1) The first significant transition saw coal become more important than wood as a provider of thermal energy by the 1620s, and by the beginning of the eighteenth century coal provided more than half of the nations' energy needs. The coal to wood transition was a long, drawn out process but the key period lay between 1560 and 1620. However, the transition between 'traditional' and modern carriers more generally (moving to a point where coal took over 90% of total energy consumption) took three centuries. (2) A second transition took place *within* coal's era of dominance, and lasted from around 1830 to 1870. This saw a dramatic rise in per capita coal consumption and energy intensity in the economy, associated with steep falls in the relative and nominal price of energy, following the development of the railway network and the proliferation of steam engines. Coal remained the dominant energy carrier until after the Second World War. (3) At this point oil rapidly expanded its share. This was associated with a steep rise in total energy consumption however, rather than (on a national level) substitution for coal. In absolute terms coal use did not decline until around 1970, when (4) a new phase of transition and diversification began, associated with the rise of gas to have the largest share by the late 1990s, and to a lesser extent, new forms of electricity generation (mostly nuclear power).

The Swedish energy system and transition shares some characteristics with the British, but there are distinct differences as well. Sweden did not possess much domestic coal, but had large forest areas as well as several large rivers, suitable for hydropower. As a consequence electricity was implemented relatively early and diffused more rapidly than in many other European countries. Electricity produced from other sources than fossil fuels (called primary electricity in figure 3) was early on more important in the Swedish energy system than in Europe as a whole and very much more so than in England. The transition to coal took place much later than in England and coal never reached such dominance. Coal shares peaked in the interwar period, but never quite reached 50% of total primary energy supply. In the early 19th century firewood made up 80% of primary energy provision, and after almost being phased out of the system by the early 1970s it has regained some of its historical role. A common feature for Europe is that oil had a rapid breakthrough after the Second World War. The Swedish case is no different, but the British remained dependent on coal and the oil transition was less substantial in relative terms there. In a more general way the Swedish transition pattern may be perceived of as traditional areal bound energy sources paving way for punctiform energy sources (fossil fuels and uranium), and a partial retrogression to the areal bound energy sources in the last couple of decades. This retrogression is much stronger in Sweden than in Europe in general and England in particular. Biofuels to date make up roughly 20% of the primary energy supply in Sweden, but half of that biofuel consists of spent pulping liquor, which is a rest product in the paper and pulp industry, which is employed for its internal usage. The still rather impressive expansion of fuel wood has partly been related to the refinement of raw firewood into wood pellets and wood chips, making the wood fuel more like fossil fuels in being easier to handle (lower handling time costs). Still, the most important reason for the proliferation of fuelwood in this period is the internalization of external costs. Tax regimes have favoured domestic firewood for reasons of secure energy supply and later also environmental reasons (putting on CO_2 taxes from the 1990s).

One transition: from wood to coal

While ‘punctiform’ growth was a feature of the British economy from the sixteenth century, the transition to coal use was slow. This was because away from the coalfields supply was dependent on a transport sector wedded to traditional forms of energy consumption: muscle power and wind power. Prices from central London show a clear cheapening of coal relative to wood in the period c.1570-1620, when fossil fuel did indeed conquer the London market. Hence the incentive to use coal initially appears without any technological innovation, and may have been driven by general rises in agricultural rents raising wood prices than any specific scarcity suffered by wood supplies.

However in London for most of the period between 1620 and 1830 there was no real divergence between the price of thermal energy and the price of *labour*. This limited demand for the development of a more energy- and capital-intensive economy. A large set of technological innovations had to take place before the thermal energy from coal could be used for kinetic energy, and thus market widening remained limited (and tended to pull activity towards the coalfields themselves). Thus there could be no radical restructuring of the economy. After the railways begin to develop we see rapid rises in per capita and aggregate consumption of energy, in this latter case clearly driven by new technology that then helped coal prices to remain very, very low. In real terms coal prices remain much lower now than in 1830. Both consumption and production were linked to the employment of the steam engine, the development of which was strongly linked to the mining industry during the eighteenth century and its use to drain deeper mines. Steam power was thus initially a key aspect of the expansion of coal supply, but after 1770 began to exert a strong pull from the demand side as its use entered the industrial sector. However, the steam engine only became generalised in the 1830s, and thereafter drove much of the expansion in the use of fossil fuel. Once steam engines became sufficiently sophisticated to be used for transport and to substitute for water and human power in textiles, their diffusion was very rapid (facilitated by a rapid drop after 1785 in the price of high quality iron which was a major raw material cost of the capital equipment.) In this case the 'complementary organic sector' became radically less important rather than innovative of itself, although improvements in productivity in agriculture were in fact quite impressive in the 18th and 19th century.

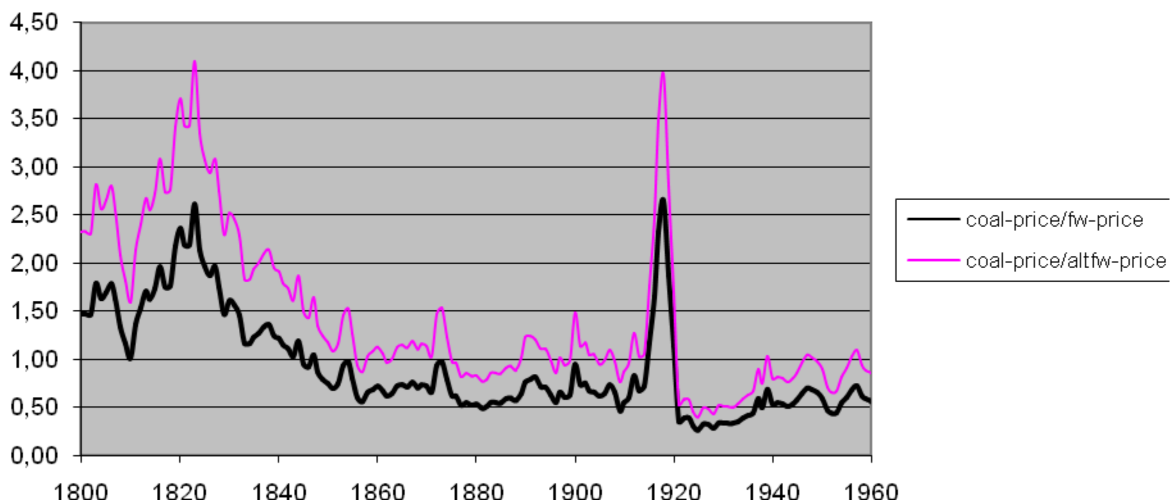
For European countries that lacked domestic coal the situation and driving forces were different. The main advantage of coal compared to firewood is its high energy density. The main drawbacks are its smell and environmental effects. Because coal has less dead weight (less water) than firewood, there are comparatively low time costs in dealing with it. When coal was first introduced in Sweden the only consumer category willing to pay a premium for the high energy density of coal was transport. In transportation the high energy density not only saved labour costs, but also space. It is difficult to know the energy content of firewood consumption historically, as it differs with the kind of wood and how dry the wood is. We have used two alternative firewood energy content figures for our comparisons (6.9 GJ/solid cubic metre versus 8.97 GJ/ solid cubic metres).[1] These alternatives will matter for determining when the price of coal was the same as the price of firewood (per energy unit), and when consumers no longer had to pay a quality premium for coal. Between 1820 and 1860 the price of coal fell to approximately the same level as the price of firewood and then stayed on par until WW1. During the war imports were restricted and the price of coal rose tremendously, it peaked at a level around 3 times the price of firewood. In the 1920s the price of coal was down at historically low levels, and then in the 1930s rose to roughly the same level as firewood again.

As for the sectors that used the coal, in 1870 roughly 40% of the coal was used by households, ships and railways used 37%, industry (including gasworks) used 15%, locomobiles for threshing in agriculture used some 8 % (Kander 2002, p 202). This broad sector diffusion by 1870 could be explained on basis of the relative prices. Once the price levels had been more or less equalized all sectors had incentives to switch fuels, due to the higher energy density of coal. However, the beginning of the story was much earlier than 1870, and we need to understand the start.

[1] 6.9 GJ is taken from Skogsstatistisk Årsbok, and 8.97 from Föreningen för kraft och bränsleekonomi: Koks, kol eller ved för centralvärmeanläggningar, Helsingfors 1924.

Initiating and propelling this transition from wood to coal was the development block around steam engines, railways and iron. Coal would never have reached any impact in the Swedish energy system were it not for this development block. Sweden had hardly any domestic coal at all (only small supplies of low quality coal in Höganäs, South of Sweden). Domestic coal dominated over imported coal until the 1830s, but in 1850 the imported coal made up two-thirds of the total and in 1870 it was 90%. This increasing level of import, at falling relative prices, was due to the cheaper transport of coal to Sweden, by means of steam ships. The Swedish iron industry relied on charcoal, and before 1896 coke use was still negligible (Arpi 1951, p 91). But iron was important for the construction and expansion of railways and ships that facilitated the transportation of punctiform energy carriers like coal between sites of production and consumption. Thus this development block in the course of its evolution led to the relative price decrease of coal, and led to its diffusion to many sectors of society. To start with it only reached the consumers willing to pay a quality premium for the high energy density, but from the 1860s onwards the diffusion was much broader.

Figure 4 Coal to firewood price in Sweden 1800-1960



Concluding discussion

The theoretical perspectives on energy transitions that are outlined in this paper are not necessarily exclusive, but may apply in different historical cases to different degrees.

The least 'economic' of the perspectives outlined in this paper is the twin model of serial transitions/energy ladder. It merely ascribes objective values to different energy carriers derived from measurements made by the natural sciences and neglects demand conditions and technical contexts. Still, on the aggregate level of European energy transitions there is something to the model: people tend to consume ever higher quality carriers over time. Yet there are several deviations, such as the slow substitution of coal for wood and the diversification of energy carriers after 1970 that calls for further explanations. The quality of carriers is clearly important but without having the technology to exploit those specific qualities they do not matter much (for example the liquid properties of oil are not valuable before motor vehicles are developed), so this model explains nothing about the historical specificity of transitions or why they vary between countries.

The escape from the constraints of the organic economy is clearly important for understanding the fundaments of modern economic growth, and industrialisation in Britain. In England the 'land constraint' means that coal is favoured over wood as general costs rise even before technological change occurs, and then that the subsequent technological change of steam power creates a new development block that lowers the price of coal generally and permits the Europe-wide diffusion of its use.

The development block model with technology at the core is a relevant perspective, with its stress on market widening for basic innovations and market suction for complementary resources such as specific energy carriers. The wood to coal transition took place in two phases. A first phase saw shallow coal resources being exploited, and was important in England (only very small deposits of inferior domestic coal were used in this way in Scania, Sweden). Here high relative local prices of wood can explain this use of coal. In Germany there were few coal deposits near the surface that could be used and thus no similar early expansion of coal use as in Britain. The great expansion of coal use (the second phase of increase in Britain) and the diffusion of coal use to more European countries was clearly related to the development block around steam engines, iron and coal: land transportation by means of railways was crucial. Market widening of steam engines led to market suction for coal, which stimulated innovations in processes of extraction, transport and communication around coal, which in turn led to the relative cheapening of coal in all countries, leading in turn to its expansion to areas outside of the development block (household and industrial use for heat). Handling costs became more important as energy became cheaper with the access to deep pit coal (in other words, labour costs rose dramatically relative to energy costs). This further augmented the shift over to coal. In several countries apart from England (Sweden for instance) people clearly had to pay a quality premium for coal, which restricted the diffusion initially to consumers that could benefit much from the low handling costs.

The evolving cost preference model, with its emphasis on time costs and external costs becoming relatively more important over time than purchasing price, is important not only to understand why coal could gain market share in countries where it was still more expensive than wood, but also to understand the diversification of energy carriers that has taken place since the 1970s. In part the dual concerns of energy supply security and the environment have stimulated this diversification, where in some cases such as Sweden there is even a partial retrogression to an organic based energy base. This would not have taken place without the internalisation of external costs through the energy and CO2 taxes. However, the persistence of oil use in the growing transport sector, despite steep rises in relative price, also indicates the resilience of a major development block. In turn, a continued preference for electricity with its very low handling costs but ‘modular’ technology that permits generation through a large variety of primary energy sources has permitted more price-sensitive substitution in industry and power generation, which in turn has facilitated government policy seeking to promote diversification and environmental concerns.

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