Rachel Carson Center
Perspectives

Energy Transitions in History

Global Cases of Continuity and Change

Edited by
RICHARD W. UNGER

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The Twentieth Century and Beyond

Richard W. Unger

Introduction

In the last two hundred years human beings have come to rely on ever-increasing quantities of energy to fuel their rising numbers and improving standards of living. As demand has increased, sources have changed. It is often said that what made the Industrial Revolution was a shift from organic to fossil fuels as an energy source. First it was coal, from the late nineteenth century it was crude oil, and then it was natural gas. The reasons for shifts from one energy source to another are complex. The changes to new carriers were slow. Older forms of energy use persisted alongside new ones. What is more, despite the massive quantities of energy from fossil fuels consumed in modern industrial economies, the simplest forms of energy use, from hunting to walking to collecting foodstuffs, survive and even thrive. The mix of energy carriers shifts constantly in the global economy, with only the scale and the pace of those changes increasing in recent centuries. The coexistence of varied energy carriers and the resurgence, in a few cases, of older forms, have many explanations. Indications of what forces determine the choices people made and are making can be found in the transitions that have taken place over the course of the last millennium. It was exactly those explanations that participants in the "Continuity in Energy Regimes" conference explored.

The colloquium met at the Institute for Advanced Study of the Technical University of Munich and at the Deutsches Museum from 27 to 29 October 2012. The meeting brought together 15 scholars from Austria, Canada, Denmark, Germany, Great Britain, Italy, and the Netherlands. Over three days they examined transitions from the use of one dominant source of energy to another, offering bases for comparing differences in performance at different times and in different regions. Papers and discussion ranged from the eighteenth through the twentieth century and from food to peat to coal to electricity and to natural gas as sources of energy. Speakers showed that the changes in energy carriers have not been sudden or complete. Transitions in consumption and in energy regimes in general have been mixed.

Reasons for quick changes and for delays (both short and long term) in adopting new carriers were central issues of the meeting. Economic reasons for retaining earlier practices often seem obvious explanations. The specifics of economic relationships, of supply and demand, and of the technologies connected to the use of certain types of energy have always shaped shifts around the world. Delivery systems and the use of different energy sources continue to influence the speed of change in energy regimes and the survival of traditional carriers.

Alternative or additional ways to account for apparent tardiness based in politics, psychology, social contexts, and environmental considerations all appeared in the varied explanations offered for the choices of energy sources. The sustainability of certain energy regimes was put forward as an explanation for the retention of earlier practices, though evidence to support any such hypothesis proved weak. The implications for any project aiming to revive traditional sources to replace fossil fuels are serious, and warn against overconfidence in bringing back abandoned practices. Governments can mandate action, influencing moves toward or away from fossil fuel use depending on the political circumstances. Such acts can and have been impeded, however, by technical or economic forces beyond the control of the state.

Food, the oldest form of energy for humans, has survived, and provides roughly the same amount of power per person as it did centuries ago. This has not stopped people from exploring ways to increase the supply of food energy and to shape environments to increase the available energy. A very personal act, food consumption falls into patterns with deep social and psychological roots. It is obvious in examining a variety of cases that, as with food, people have preconceptions about alternative energy carriers and regimes. Ideas about energy supplies vary over time and across cultures. Shaping existing ideas about what is best to use has proven difficult. In some cases governments and suppliers have enjoyed success in promoting energy transitions. Once again, the pattern is a mixed one.

The opening address of the conference, given by Bob Allen, explored the role of energy availability and economic transformations, and more specifically the roots of the Industrial Revolution of the eighteenth century, setting the context for the subsequent discussion. The closing roundtable, followed by a discussion among all participants, laid out the general conclusions to be drawn from the different studies discussed by speakers. The participants, in their papers and in the discussion, expanded the range of explanations for failed or delayed energy transitions. Environmental considerations such as pollution and the social acceptance of forms of environmental damage have been influential, and not just in the last few decades. The pricing of energy carriers matters, but so does the psychology of pricing. Government policies have enjoyed an increasing role over time for reasons strategic as well as fiscal. Gender can influence decisions. So can a crisis, a sudden emergency, or even the belief in the existence of a crisis. While neither the papers at the meeting nor the roundtable discussion at the close produced definitive answers to the original questions, they pointed to the complexity of forces at work, suggesting that simple expectations about changing the pattern of energy use in the future will not be easily realized.

Financial support for speakers' travel, accommodation, and meals while in Munich came from the Peter Wall Institute of Advanced Study of the University of British Columbia. The director, Dianne Newell, enthusiastically urged all of us along and was sad that she could not participate because of other commitments. At the University of British Columbia, Tuya Ochir dealt with critical financial matters, and the assistance of the university's history department was invaluable. The Deutsches Museum offered a venue for the opening session as well as extensive assistance with the organization and preparation of conference materials. All participants were very grateful to Nina Möllers for the efficient way in which she looked after so many aspects of the meeting. The Institute of Advanced Study of the Technical University of Munich supplied the space for the sessions as well as organizational support. The director, Patrick Dewilde, was influential in overseeing the whole process, and Sigrid Wagner provided effective on-site assistance. After the last session, participants enjoyed a tour of the Deutsches Museum, led by the director of research, Helmuth Trischler, who also has been a central figure in the development of this contribution to *RCC Perspectives.* To all of them I and the speakers at the meeting owe our thanks.

The Long View

Robert C. Allen

Energy Transitions in History: The Shift to Coal

In the Middle Ages, the main energy sources were firewood, charcoal, animals, and human muscle power. By 1860, 93 percent of the energy expended in England and Wales came from coal. The transition was slow and much of it happened before the Industrial Revolution: Coal's share of energy generation in England and Wales rose from 10 percent in 1560 to 35 percent in 1660 and reached 64 percent in 1760, a date that is often taken to be the start of the Industrial Revolution. Why did the transition occur when it did and why was it so slow?

The answers to these questions have four parts. First, the transition required the invention and use of new technology in almost all cases. More rapid technological change sped up the transition. Paradoxically, however, in some instances improvements in traditional technologies extended their useful lives and thus slowed down the transition. Improvements in "old-fashioned" technology were thus one reason why the transition was not faster.

Second, the invention and adoption of new technology were economic decisions that responded to economic incentives, namely prices and wage rates. This is self-evident for adoption, but it was also true of invention. While there are creative aspects to invention, it should not be regarded purely as a result of flashes of genius. In many cases, the ideas behind important inventions were banal. In all cases, time and money were required to convert the idea into an apparatus or a procedure that could work reliably in a commercial setting. Research and development (R&D) was the crux of invention, and it required the allocation of resources to the activity. That was an economic decision that depended on economic incentives. If an inventor imagined that the invention would be worth using, then there was a case for allocating resources to its development; otherwise, there was not. The balance between the potential revenue from the invention and the costs of the R&D determined whether an invention would be made.

Third, between 1500 and 1800, wages and prices in Britain evolved in a unique fashion. Wages rose relative to the price of capital while the cost of energy fell. These changes made it profitable to use new technology that substituted capital and energy for labor. By the eighteenth century, Britain, like the Netherlands, was a high-wage economy. Unskilled workers earned four times the World Bank's subsistence wage of $1.25 per day. In other parts of Europe and in Asia, wages were close to the poverty line. In addition, energy prices on the coal fields in northern and western Britain were the lowest in the world. The relatively low cost of energy used for heating distinguished Britain from the Netherlands.

Fourth, British wages were high and energy costs low because of the country's success in the globalizing economy of early modern Europe. Wages in the Netherlands were also high for the same reason. These countries succeeded in creating large, commercial empires and trading connections that generated high volumes of trade and high demand for the standardized products made in rural and artisan industries. As trade grew, so did the cities. London was the most rapidly expanding city in Europe. Its population rose from roughly 50,000 in 1500 to 200,000 in 1600, to 500,000 in 1700, and to 1,000,000 in 1800. Rapid urban growth led to tight labor markets and higher wages. The growth of rural industries tended to raise wages in the countryside, as did migration to London.

Equally important, the growth of London led to rising demand for fuel in the city center. In the later Middle Ages and into the sixteenth century, the principal sources of thermal energy were charcoal and firewood. As the city grew, prices rose, since the supply region had to be extended to meet the increasing demand, and transport costs for wood fuels were very high. Small quantities of coal had been shipped from Durham and Newcastle to London in the late Middle Ages. Coal sold at about the same price per energy unit as wood through the Middle Ages, but coal use was limited almost exclusively to lime burning and blacksmithing. Its sulfur rendered it undesirable in all other uses or required expensive ways to limit the tendency of coal to pollute. However, as the price of wood rose, wood became a more expensive source of heat than coal. Once the price of energy embodied in charcoal or firewood was twice the price of energy in coal, people tried to substitute coal for wood. This unleashed the process of invention that led to the transition to coal.

We can trace the process of invention in many activities. The focus here is on only one: the use of coal to heat houses. Indeed, this was the most important application, since residential heating and cooking was the single largest use of energy in the eighteenth and nineteenth centuries. The shift to coal in domestic heating occurred in the seventeenth and eighteenth centuries and explains why more than half of England's energy consumption consisted of coal at the beginning of the Industrial Revolution.

As the price of wood in London rose in relation to coal, the incentive to use coal increased. Converting from wood to coal was not, however, simply a question of chucking one fuel rather than the other onto the fire. Switching fuels, in fact, presented complex design problems.

These began with the layout of the house. The typical medieval house had a large hall or room that extended from the ground to the rafters. The fire for heating and cooking was built on a low hearth in the center of the room. Smoke from the fire filled the space above the hearth and exited the dwelling through a hole in the roof. The smoky atmosphere was useful for curing bacon but not entirely salubrious. This design did have two advantages, however. First, the family could gather round the fire, and, second, the fire was away from the flammable walls, making it less likely that the house would burn down. Had one put coal rather than wood on the fire in this house, two things would have happened. First, the sulfurous fumes of the coal smoke would have rendered the structure uninhabitable. Second, and much more likely, the fire would have gone out. For efficient combustion, coal must be confined to a small, enclosed space, unlike the open hearth of the medieval house.

Burning coal, therefore, first required a new style of house. Chimneys were essential, and they were being built in great houses by the thirteenth century. Initially, stone or masonry walls were built in the house, and the open fire was lit against them. A hood above the fire gathered the smoke and led it out through a chimney. Often a small room was built around the fire to husband the warmth. Building chimneys proved expensive and so for centuries they were only in use in the houses of the well-to-do.

The hooded fire was a first step towards coal burning, but it was not sufficient. Fireplaces remained large as long as wood was the main source of fuel. The design was not effective for burning coal, however. An enclosed fireplace or metal chamber was necessary to confine the coal for high-temperature combustion. The coal had to sit on a grate so a draft could pass through. A tall, narrow chimney rather than the wide chimney used with wood fires was needed to induce a draft through the burning coal. This was necessary both to increase the oxygen supply to the fire and to vent the smoke upwards and out of the house, rather than having it blown back into the living quarters. To work well, the chimney had to narrow as it got taller. The termination of this design trajectory was the house designed around a central chimney with back-to-back fireplaces on the ground and first floors. They could burn coal and warm the house without filling it with smoke.

It took a long time and a great deal of experimentation to develop this style of house. Each element had to be perfected. That required trying out many variants to see what worked best. Grates, for instance, could be made from metal or brick. Which was better? How big should the holes be? Such prosaic questions arose with all elements of the heating system. How big should the fireplace be? Should it be made with brick or metal? How could it be designed so that heat projected into the room rather than escaping up the chimney? How tall should the chimney be? How wide? Should there be a taper? How many twists and turns could there be in the flues? How could several fireplaces be connected to a central chimney without smoke passing from one room to the next? And so forth. Not only did the individual elements have to be perfected, but they had to be balanced against each other. Records of some of this work have survived, since in a few cases designs were patented and some people wrote books and pamphlets promoting their work. Much experimentation was surely done without any records being kept. Most of this experimental work was done in London, and the architectural results were destroyed when large parts of the city burnt down in 1666.

The one innovation whose adoption can be roughly dated is the chimney. John Aubrey and William Harrison both remarked on the widespread construction of chimneys in rural areas in the late sixteenth and seventeenth centuries. This is not very precise evidence, but it does indicate that the proliferation of chimneys occurred at the same time that the market for coal took off in southern England.

The coal-burning house presented economic challenges that paralleled the engineering challenges. Had a modern economy faced the challenge of shifting from wood to coal, there would likely have been a large and coordinated research and development program to solve the design problem. Nothing of the sort happened in the sixteenth and seventeenth centuries. Design innovation was left to the decentralized market. Since most of the innovations could not be patented—the taper of a chimney was not a legal novelty, for example—no one could recoup the cost of experiments through patent royalties. As a consequence, experiments were piggy-backed onto commercial building projects. Builders erecting houses could change the design of a chimney to see if it worked better without any great cost or risk. Their motive was to build houses that were more efficient to heat and that would not fill with smoke, since they could sell such a house for more money. If a design innovation proved successful, they or others could extend it and try to make it even better. Copying and elaborating on innovations was how the coal-burning house was developed.

In this model, which I have described as "collective invention," the rate of experimentation depended on the rate of house building, since commercial construction was the activity that financed the experiments.

The economics of collective invention highlights another way in which the growth of London was critical to the shift to coal. The first way, of course, was its contribution to the rising price of wood, which motivated the shift. The second was the building boom, which underpinned collective invention and solved the problems associated with coal-burning. In the sixteenth and seventeenth centuries, London grew rapidly, and a large number of new houses were built in a small area. The high volume of construction provided innumerable opportunities to tack design experiments onto projects that were undertaken for ordinary commercial reasons. The proximity of this building facilitated the sharing of information, allowing builders to extend each other's innovations and perfect the coal-burning house. Furthermore, the need to rebuild so many houses after the 1666 Fire of London created opportunities to quickly shift the facilities for fuel consumption to the burning of coal. Despite cheap coal in the ground, this sort of experimental work would not have taken place in small towns on the coal fields since not enough building was going on there. London's boom created the incentive to shift to coal and subsidized the experiments that were needed to solve the technical problems that arose. The adoption of coal for domestic heating drove investment in production and transportation of coal, lowering its cost even further and driving innovation in many other sectors of the economy toward the use of a different and easily available energy source.

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Richard Oram

Arrested Development? Energy Crises, Fuel Supplies, and the Slow March to Modernity in Scotland, 1450–1850

In common with records from many parts of northern Europe through the period 1450–1850, Scottish record sources portray a protracted crisis regarding energy resources generally and the supply of fuel to urban centers specifically, despite the fact that, unlike many European states, Scotland was a relatively energy-rich environment. Several factors hindered intensification of industrial activity and retarded national economic growth: an underdeveloped communications infrastructure for bulk intraregional transportation, strong regional variation in the natural presence or accessibility of particular fuel types, often punitive pricing strategies, and localized fiscal-legal systems that limited the potential or incentive for infrastructure or internal trade development. Lack of capital for investment in commercialized fuel extraction completed a picture of abundant but inaccessible fuel resources. This hampered the development of economic activity, activity that might stimulate demand and so encourage investment in the resource exploitation. Further pressure was introduced by social and cultural factors in the eighteenth and early nineteenth centuries, where use of particular fuel types became linked to theories of social progress, politeness, and modernity. The pressure encouraged abandonment of the use of an abundant and relatively cheap resource—peat—and promoted the use of a scarcer and more expensive alternative—coal. Rapid expansion of the banking sector, access to capital for investment in mine engineering technology, and progressive enhancement of transport networks relieved those pressures and completed a transition to a marketization of the energy supply and a redeployment of labor from activities like fuel-winning to what were perceived as more economically productive tasks.

For most of the period under review in this paper, reliable quantitative data concerning population levels in Scotland is lacking. Estimates, however, suggest that around 1450 the majority of Scotland's urban centers had populations below 1,000. Probably only Aberdeen, Dundee, Perth, and Edinburgh had populations over 5,000 before 1500, with Edinburgh rising to about 12,000 in the later sixteenth century. These urban centers were classed as "royal burghs"—communities that had received royal charters bestowing exclusive economic privileges over aspects of trade and commerce and assigning exclusive rights over the natural resources of a defined hinterland. One key aspect of these privileges was the right to fuel resources, mainly specified as peat by the later Middle Ages.

Documentary records indicate that peat supplies were already under pressure in some burghs before 1300. However, legislation to control extraction dates mainly from the post-1500 period. With fuel supply having a large influence on the nature of craft and industrial activity as well as affecting domestic routines, local access to alternative energy resources determined winners and losers in urban economies and regional development. The natural distribution of accessible fuel resources imposed limits to development in certain regions. Late medieval Scotland had abundant fuel, especially peat, but most was concentrated in the "wrong" places. On the mainland, the main peat supplies by the fifteenth century were in upland blanket peat bogs, far from the main centers of population, or in coalfields that were accessible only on the fringes of the Lowlands. These geographical and geological factors meant that in the late medieval and early modern periods, Scotland was energy rich but economically poor.

Given that the majority of Scotland's population was rural and had access to the upland peat supplies that lay distant from the small urban centers, pressure to develop alternative sources or types of fuel was driven largely by the small urban population, mainly the mercantile and craft elites who dominated urban government. Intensification of extraction of bulk fuel supplies for urban domestic and industrial needs remained limited where easy access to peat sources still existed. It was further hampered by the prevalent use of personal ("free" or cheap labor) to "win" fuel for private, domestic use. There was, consequently, limited market pressure for developing alternative fuels.

Seasonal labor patterns up to the early nineteenth century also encouraged the use of personal labor for fuel-gathering activities. Until the era of rapid urbanization and industrialization in Scotland after about 1750, the bulk of the population satisfied domestic fuel needs through the use of their "free" labor to cut peat from common resources. Urban population growth, however, broke the link between personal labor and household fuel supply. Contemporary economic theorists, whose ideas gained wide currency amongst the political and economically-dominant classes, saw the "free" labor used in fuel-gathering as a subtraction from the notional labor pool. This wasted human energy and time, they argued, could be applied instead to market-oriented production. There followed an era of rapid expansion of the waged-labor sector, limiting the ability of a significant portion of the laboring population to involve themselves in direct production of their own food and fuel requirements and consequently stimulating demand for basic commodities on the market that could be purchased with wage income. One result was a stimulus to the commercial production of fuel on a large scale to meet that demand.

Greater demand, however, was being created by the industries in which many of this new waged laboring class were employed. Scotland's early industries had been small-scale and intensely localized, many lying in districts like the Carse of Stirling, where fuel had once been easily accessible in the formerly peat-covered carse (low-lying, fertile valley land). This was the center of medieval Scotland's principal "industry": the manufacture of salt through the sleeching and boiling of brine. As peat-sources became exhausted in the Middle Ages, salt-masters began to seek alternative fuels. Coal was being mined further east along the shores of the Firth of Forth before 1200, and salt production moved closer to this new fuel source. Mining expanded rapidly after 1400, perhaps partly in response to climatic deterioration in the "little ice age," when increased rainfall is recorded as affecting peat-cutting, supply, and use. The coal that was mined, however, was mainly consumed locally because the transport infrastructure remained rudimentary. Mine operations, too, were under-developed and non-commercial, most being mere seasonally exploited adjuncts of private landed estates, intended to supply their owners and their immediate dependents. Only mines close to major urban centers in the immediate vicinity of the workable seams, like Edinburgh and its satellites along the Fife and Lothian coasts, had increased output to supply burgh markets. Ironically, northern Scottish burghs were importing coal mainly from northeast England by the fourteenth century and continued to do so into the nineteenth century.

Apart from in the burghs closest to mines, coal remained principally a fuel used for industrial processes. It had largely replaced peat for boiling seawater in salt-pan operations around the Firth of Forth by the fifteenth century. It was improvements in mining technology, however, plus access to capital for investment in the eighteenth century, that boosted output and delivered cheaper coal to some markets. This availability of an abundant and reliable supply of fuel for industrial development finally removed any

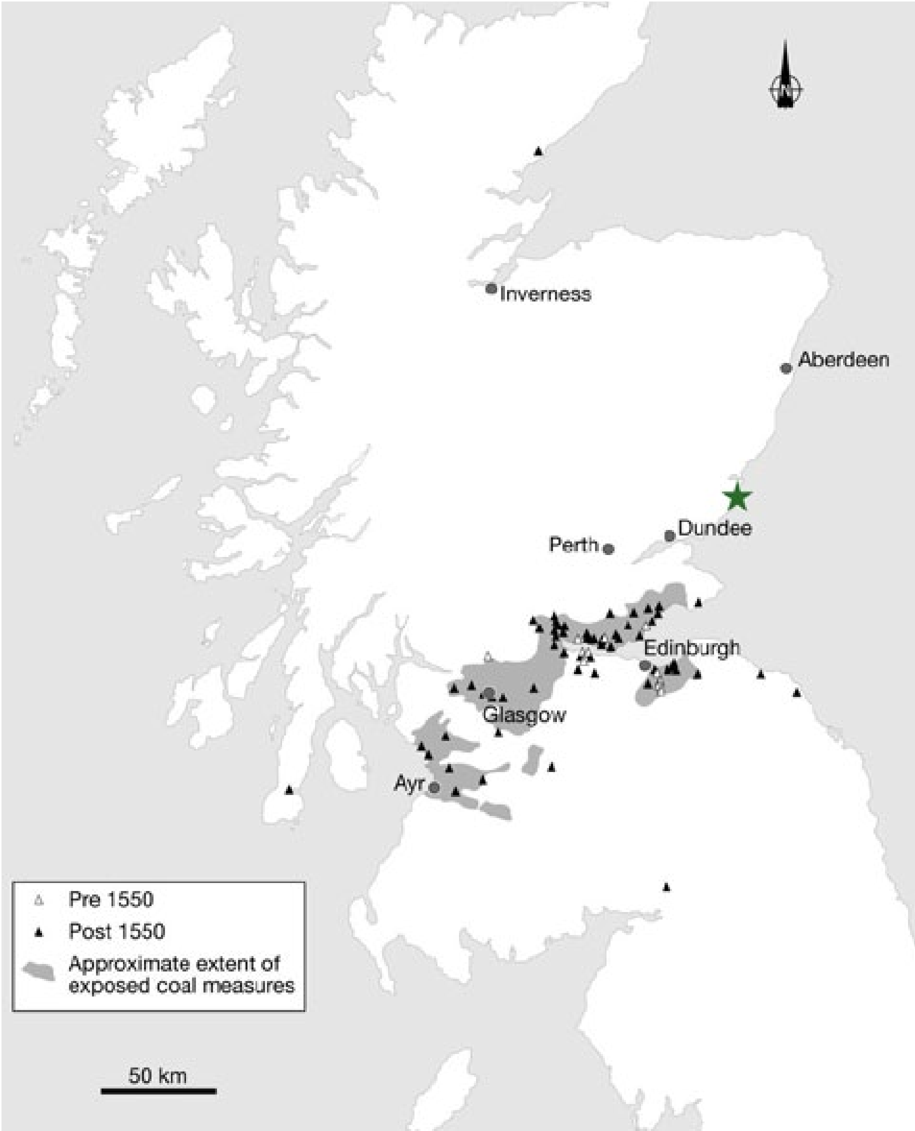

Figure 1: Scottish coalfields. The star marks the position of Red Head, the coastal headland north of which transportation of coal by sea was subject to punitive levels of duty.

lingering dependence on peat close to the coalfields. Taxes on long-distance transport of coal, however, continued to hinder the economic development of areas remote from mines.

Industrial demand led the way in stimulating the development of mining and an increase in output, but domestic use remained low as long as cheaper alternatives that could be obtained with personal labor remained accessible. There was also resistance to the new fuel. Knowledge of the different hearth technology necessary to burn coal and how to cook with it remained limited. Introduction of hearths that were designed for burning coal and that channeled the fumes out of domestic settings was limited due both to cost and to cultural conservatism. In some regions, an impetus towards adopting coal was provided by to the increasing scarcity of peat. From the 1760s, "improving" landlords (who capitalized their property and introduced "scientific" land management and agricultural methods to intensify and increase production) were stripping peat mosses to reach the alluvial clay below them, believing this to be good agricultural soil. At the Flanders and Blair Drummond mosses west of Stirling, for example, the owner of Home Drummond dumped tens of thousands of cubic meters of fuel-quality peat into the River Forth. Former users of this resource were then obliged to burn coal instead.

Further pressure for a move to coal came from fashion and the status of coal in elite society as an icon of modernity. In much Enlightenment-era literature, coal use was seen as a key indicator of an advanced, "modern," and "polite" society, with traditional fuels (especially peat) viewed as indicators of social, economic, and cultural backwardness. Edinburgh's New Town physically embodied the symbolic transition, with all new houses built there being designed and constructed with coal-fired hearths. Elsewhere, the social elite began to convert formerly wood- or peat-burning hearths for coal use, displaying their cultural advancement publicly and encouraging the rest of society to emulate them.

The argument over the merits of coal as opposed to peat and other traditional fuels was also being won on the grounds of thermal efficiency versus economic viability. As the table below shows, although peat was far from useless as a fuel for industrial processing, its lower calorific value per unit volume rendered it uneconomic to produce and store at the scales necessary to supply the needs of manufacturers who were operating at the new, industrialized levels. Extraction, processing, transportation, and storage were all cheaper and easier for coal. Greater labor expenditure and the greater volume required to produce equivalent thermal energy rendered peat impractical as a fuel for intensive industrial use within the limits of the available technology.

Substance	Megajoules/kilogram
Wood	17–20
Peat	20–23
Coal	28–33

Figure 2: Effective calorific value of dry substance. 1 megajoule = 239 kilocalories. Peat has thermal efficiency capable of smelting iron but significantly lower calorific value per unit volume—only 16 to 25 percent of that of coal.

Pressure from the "improving" landlords like the Scotts of Duninald in Angus, who wanted cheap coal to fuel the limekilns on their estates just north of Red Head, led in 1793 to the repeal of the punitive levels of duty on the shipment of coal by sea. Overnight, coal became cheaper in seaports and soon displaced peat, but in inland and non-industrialized areas it remained prohibitively expensive.

In 1800, coal mined at Dollar, east of Stirling (fig. 3), sold at four times its mine-head price 20 km to the north in Auchterarder and at six times its price only 16 km further in Crieff, rising to nine times in winter. It would take the nineteenth-century transport infrastructure revolution, constructed on the back of the rapid industrialization that occurred in the decades up to about 1840, to change that inequality. By the middle of the nineteenth century, coal was very much king and the use of older, "traditional" fuels was limited to the inhabitants of economically marginal or peripheral areas in Highland and Hebridean regions, where the local economy still functioned largely at a subsistence level.

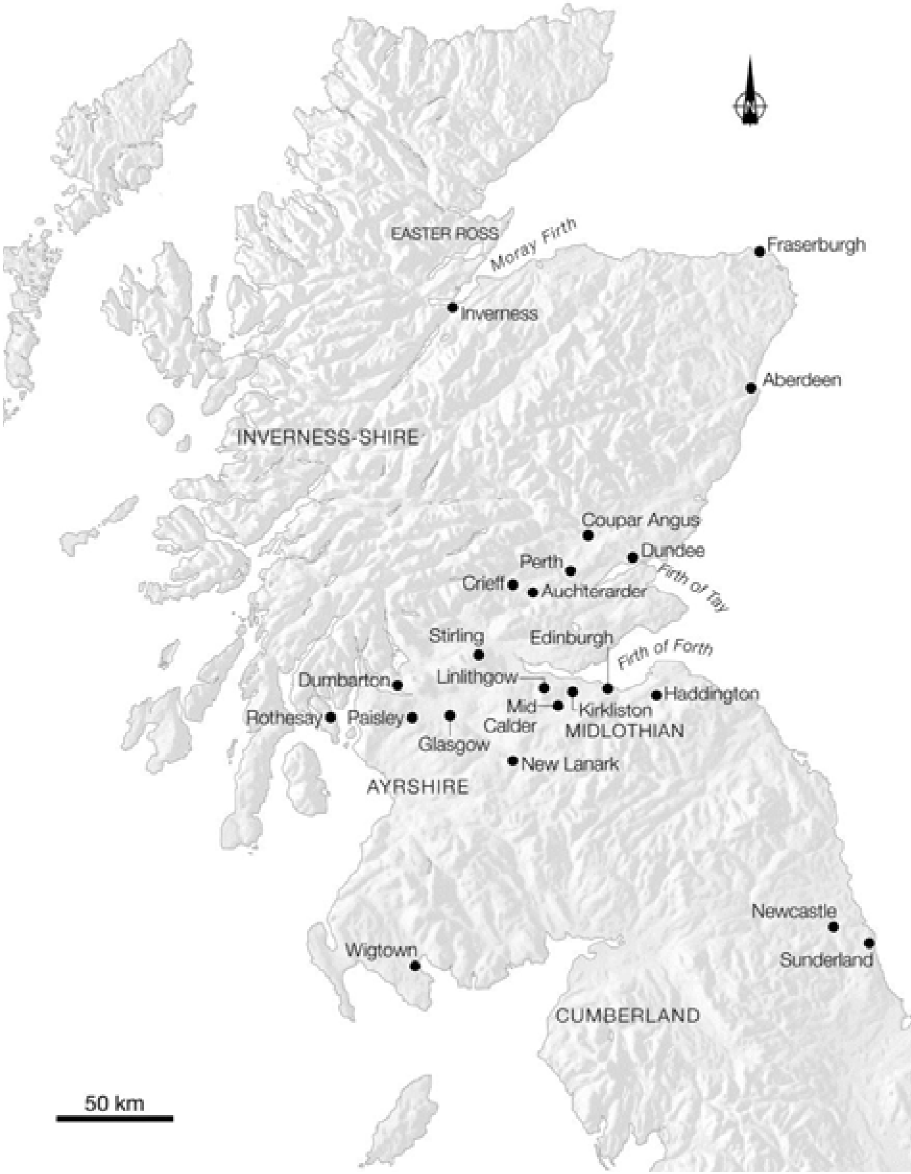

Figure 3:
Scottish towns and coal sources c. 1800

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Liam Kennedy

"The People's Fuel": Turf in Ireland in the Nineteenth and Twentieth Centuries

The role of turf or peat in Irish national development is, to say the least, controversial. Robert Kane, writing in the mid-nineteenth century, envisaged a major contribution to economic growth and welfare from this natural resource. More than a century and a half later an edition of Keven Myers' "Irishman's Diary" in the *Irish Times* consigned turf to the rubbish heap of national fantasies: "Once upon a time, we built a state around the concept of a Gaelic-speaking, peat-fired economy, and then stood on our quaysides bidding tearful farewells to our young people." Recent historical scholarship seems to concur, at least as far as the industrial exploitation of turf is concerned.

The focus of this paper, however, is on turf as a source of heat and energy for households. Ireland was a largely agrarian society in the nineteenth century, and, with the notable exception of the northeast of the island, modern industrialization did not take root until the later twentieth century. Domestic fuel supply was the critical energy issue. Arthur Young was one of the earliest to observe how Irish cottiers benefited from easy access to home-produced fuel, as opposed to the English laborers shivering in their cottages and dependent on purchased coal. The subsistence crops of potatoes and turf constituted the mainstay of living over much of Ireland before the Famine, and were important for long afterwards. There are various impressionistic accounts of the quantity of turf used by rural households in the first half of the nineteenth century, though these are far from plentiful, and of course the quality of the turf varied within a particular bog and between bogs. Only one source, to my knowledge, gives hard evidence for the amounts saved. This is the *Turf Account Book* of 1859–60 from the Coolattin estate in County Wicklow and now in the National Library of Ireland, ms. 4987. A preliminary analysis of these account books suggests wide variation in the amounts of turf saved, with 40 kishes per annum being the median figure. There is the awkward issue of once popular but now obscure measures, based on volume rather than weight. No doubt there were kishes and kishes, depending on the part of the country. Wakefield suggested the dimensions of a kish were 4 x 2 x 3 feet, or 24 cubic feet. McEvoy's estimate was a little higher at a cubic yard (27 cubic feet), though this seems to refer to a heaped kish, so the two estimates may well be very close. Estyn

Evans provided photographic evidence for the size of a kish, with dimensions implying that a kish equaled 22 cubic feet. As archaic measures go, the range of values is reassuringly narrow. On balance, Wakefield's estimate may be the one to be preferred. On the basis of information supplied by Wakefield, it is possible to calculate that a kish weighed 444 lbs or almost exactly four hundred weights (of 112 lbs each). There is nothing that can be done in relation to the problem of variations in the quality of turf, in view of the absence of any price data for the estate.

Forty kishes would imply the production and consumption of eight tons of turf per household per annum, on the above assumptions. It might be reckoned that standards of firing, as with other items of consumption, were somewhat lower before the Famine. On the other hand, for most households the amount of turf available depended almost exclusively on two factors: weather conditions and household labor. Labor was more plentiful before the Famine. Still, the standard of housing, including the number of hearths, was higher around 1860 compared to some decades earlier, and housing on the Coolattin estate was probably better than in the western parts of the island. Much of the poorest housing on the estate had been pulled down during and after the Famine. An early-twentieth-century estimate puts the consumption of turf higher, however, as does incomplete experimental work by the author using modern hand-won turf on an open-hearth fire. For present purposes, eight tons per household per annum will serve as a crude approximation.

Similarly crude forms of estimation help to paint a picture of the output and consumption of turf on a countrywide basis. Turf was an almost pure subsistence good, even more so than potatoes, with most of the produce destined for home consumption or local markets. The high volume-to-value ratio made turf an unattractive commodity for sale in the context of the transport technology of nineteenth-century society. If roughly 90 percent of turf was for personal or highly localized consumption, as seems likely, then the principal determinant of turf production was a demographic factor, that is, the number of households in rural and village Ireland.

Most rural households used turf, as did many town dwellers in provincial Ireland. In view of the rich boglands stretching across the central plain of Ireland, it seems reasonable to conclude that turf was widely available in the towns of the Irish midlands, as well as, of course, in the countryside. The east-coast towns seem to have depended primarily on coal, most of it imported in view of the limited production from the Irish colleries at Castlecomer, Ballycastle, and Coalisland. In the 1840s the Grand Canal brought in approximately 30,000 to 40,000 tons of turf per annum to Ireland's capital, Dublin, but this would have covered only a fraction of Dublin's fuel needs. The table below contains a set of estimates of the production and consumption of turf in Ireland in the nineteenth century. Turf being a subsistence good, the two should be much the same. The steps in the argument are fairly self-evident. Consumption of turf is assumed to be eight tons per household. The number of households can be taken from the censuses of population. About two-thirds of households probably burned turf, though if anything the proportion may have been higher during the first half of the nineteenth century, when coal imports were limited.

	1801	1845	1851	1926
Population (thousands)	5,000	8,400	6,516	4,229
Mean household size	5.2	5.6	5.4	
No. of households (thousands)	962	1,500	1,207	
Proportion turf-using	68%	68%	65%	"half"
Turf-using households (thousands)	654	1,020	784	
Consumption (thousands of tons)	5,231	8,160	6,275	3,600*

* Official estimate of turf output in the Irish Free State (26 counties). There are no figures for the newly-created statelet of Northern Ireland (6 counties), following the partition of the island in 1921.

In the first half of the century, the trend in turf production and consumption was undoubtedly upwards, as the numbers of households multiplied. This must have also been true of the eighteenth century, especially during the period of vigorous household formation from the mid-1740s onwards. In round figures, the information in the table would suggest the production of some five million tons of turf about the time of the Act of Union (1800), a massive eight million tons on the eve of the Famine, then falling to six million tons by the end of the Famine at mid-century. The trend after 1846 was inexorably downwards as households and hearths were extinguished through death, migration, and emigration. The effect of demographic change was reinforced by economic forces. Coal was making inroads into urban Ireland and its hinterland. For example, markets not only for turf but also for coal appeared in turf-rich, inland areas such as Strabane and Omagh in the 1880s. The penetration of the countryside by coal imports is not known in any detail but was aided by developments in road, rail, and sea transport. Cost-reducing innovations in the coal-mining industry also meant that competitive pressures were unrelenting. It is likely that the decline in the production of turf was slowed by the demand caused by rising standards of comfort and the more extensive cooking of foodstuffs for animals, maize in particular, on the part of turf-burning householders.

Still, the remarkable aspect of turf is its resilience. When the Irish Free State produced estimates of turf production for the first time, for the year 1926–27, the aggregate output was 3.6 million tons. The inclusion of turf from Northern Ireland, for which no figures appear to be available, would edge this total up still further towards four million tons or so per annum. This suggests that output roughly halved between 1845 and 1926. This seems dramatic until one takes into consideration the fall in population in Ireland during this period. The decline in turf production turns out to be much the same as the decline in population, which for the island of Ireland was almost exactly 50 percent between 1845 and 1926. Over the same period, the number of households declined by just 37 percent, indicating that households were becoming smaller over time. Turf production and consumption fell by 49 percent. There was thus a shift in the direction of burning coal for domestic needs. Still, this hardly represents an easy victory for King Coal.

Output declined, as the numbers indicate. However, the decline was largely invisible. Landscape painting in Ireland, from Paul Henry to John Luke, gives not a hint of the gradual retreat of turf, while sentimental ballads from the "Old Bog Road" to Johnny Cash's "Forty Shades of Green" perpetuated the image of a turf-burning people. The paradox is easily resolved by distinguishing between aggregate production and production per household. The fact is that most rural households, and many in the villages, still used turf rather than coal or wood up to the early 1950s. The decline in turf production and consumption at the *household* level was a remarkably gentle one in the century after the Great Famine. Change was much more noticeable at the aggregate rather than the household level. This tendency was in fact reversed in the 1930s and the 1940s, though under rather special circumstances.

The output of turf of 3.6 million tons in 1926–27 may be compared with an import of 1.8 million tons of coal into the Irish Free State in 1926, valued at £3.4 million. The official valuation of turf production in 1926–27 was £3.3 million, a virtually identical value. As a significant proportion of the coal must have been destined for non-domestic use in industry, on the railways, and in public institutions, it follows that the dominant domestic fuel was still turf in the 1920s. This was true not only in terms of volume but also in terms of value. For some years during the Economic War (1932–38), when the Irish Free State sought to "burn everything English except its coal," to borrow a phrase from Jonathan Dean Swift, and much more importantly during World War II, the rising tide of coal imports was reversed. Because the major competing fuel was simply not available for domestic consumption during World War II, turf was virtually the only show in town as far as the domestic fuel market was concerned. It was also adapted, although with much less success, to power trains and small-scale industry. Wood made a minor contribution, but Ireland was one of the least forested countries in Europe. Taking the long view, the major retreat of turf as a domestic fuel did not come until the 1950s, when cheap supplies of coal and oil made heavy inroads into the Irish energy market.

Any conclusions must be tentative at this stage, but the following seem warranted, at least on the basis of the evidence and assumptions made so far. Turf remained the major fuel resource of Irish households from the seventeenth to the mid-twentieth century. The production of turf expanded vigorously, in step with population, through the eighteenth century and up to the eve of the Great Famine. There are no signs of problems of depletion approaching the Famine, so fuel poverty was not a significant factor in a rural society experiencing rapid population growth and pressure on land resources. On the contrary, it is clear that turf made a significant contribution to the welfare of the rural population in 1845.

Once the Famine struck, the output of turf went into decline. This decline was especially marked after 1950. However, in the century after the Great Famine, it is perhaps the resilience of turf production and consumption that is most striking. While overall turf production declined, as did rural population, production *per household* registered only a mild decline.

This is all the more remarkable given that there is little evidence of technical change since the seventeenth century in the "winning" of turf from the environment. The contrast here with coal, which enjoyed streams of cost-reducing innovations, is striking. Presumably the persistence of turf, and of other forms of subsistence production, was in large part a function of underemployment in the countryside and the low cost of family labor.

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Fridolin Krausmann

The Social Metabolism of European Industrialization: Changes in the Relation of Energy and Land Use from the Eighteenth to the Twentieth Century

In recent years, social (or, more narrowly, industrial) metabolism has become a prominent concept in sustainability science because many global sustainability problems are directly associated with humanity's growing demand for raw materials and their transformation into wastes and emissions after processing and use. Industrialization involves a fundamental transformation of society's metabolism and in particular of the energy system. In this essay, I will offer an historical sociometabolic perspective on the changing relationship between energy and land use during industrialization. This perspective will highlight the difficulties in substituting biomass for fossil fuels, a strategy that is currently being pursued and that is central to sustainable development.

Agrarian societies are fuelled by a solar-based energy system. They tap into available flows of solar energy to sustain their energy needs, rather than exploiting stocks of energy carriers. In contrast to hunter-gatherer societies, agrarian societies actively manage terrestrial ecosystems in order to increase the output of useful biomass. The land-use-based energy system they establish—a system where most of the primary energy comes from agricultural sources—can be termed a *controlled solar energy system*. In this energy regime, biomass is quantitatively the most important source of energy and amounts to more than 95 percent of primary energy supply. Although water and wind power had some socioeconomic importance, quantitatively they were only of regional significance. In general, wind and water accounted for at most a few percent of the primary energy supply.

In the agrarian sociometabolic regime, the availability of land, the productivity of the land, and the efficiency of biomass conversion methods determine the amount of available primary energy. The land use system, with its limited potential to supply certain types and amounts of primary energy, therefore constitutes a major limitation on the growth of population and physical wealth.

There are distinct energy limits in agrarian societies. Pre-industrial land use systems are low input systems and external energy or nutrient subsidies are practically absent.

Agriculture relies more or less exclusively on natural cycles and local socioeconomic resources for energy and plant nutrients. Typically, this entails a complex optimization of locally available resources. Soil fertility is managed using a combination of strategies such as the rotation of land use, nutrient transfers between different land cover types, reuse and recycling of materials and plant nutrients, and minimization of losses. Farm animals provide the muscle power needed for farming the land as well as being a source of fertilizer, additional food, and raw material; they make it possible to utilize non-edible crop by-products, food waste, and land that is unsuitable for crops. A land-use system optimized in such a way allows for the maintenance of soil fertility and yields, and also allows for the production of a certain amount of agricultural surplus. It further satisfies the condition that land use achieve a positive energy return—that is, that the amount of energy produced in the form of food and fuel exceed the energy invested in cultivation. This positive energy return is an essential feature of agriculture in any agrarian sociometabolic regime.

Energy production per unit of cultivated land is variable and can be enhanced by agricultural modernization strategies. Ultimately, however, it cannot exceed a certain figure. Assuming a mix of land use types, including a certain share of low productivity land and land not available for biomass production, it has been estimated that agricultural land use systems under temperate climatic conditions yield up to 20–40 Gigajoules/hectare on average in the long run.

The inherent limitations of the biomass-based energy system, namely low power density, lack of conversion technologies, reliance on animate power, and high energy costs of transport also shape patterns of material use. Biomass is the most important raw material and is not only used as food for humans, feed for animals, and heating, but also for construction purposes, clothes, tools, and furniture. Except for biomass, all materials are used in rather low quantities, both in terms of volumes per capita and per area. Reconstructions of the historical metabolism of agrarian Austria and the United Kingdom show that the yearly consumption of all materials ranged from five to six tons per person, of which biomass constituted 80–90 percent.

The impact of the agrarian sociometabolic regime on demographic and spatial patterns is evident. Agricultural surplus is limited and the large majority of people live on and from the land. Spatial differentiation and urban concentration is limited by the high energy cost of land transport, which permits the transport of energy carriers and bulk materials only across comparatively short distances.

Agrarian regimes significantly alter the natural environment, changing the composition of vegetation and animal species as well as the properties of soils and water cycles. They also create a great variety of new ecosystems. Because agrarian regimes are based primarily on the use of renewable resources, maintaining ecological sustainability is essential. However, there is no guarantee against severe fluctuations and sustainability crises, or even collapse. Growth can be achieved only within certain limits; it is based on increasing efficiency and optimizing land use. Usually, such efficiency gains bring the whole system closer to a threshold: There tends to be positive feedback between biophysical growth and population growth, and agrarian societies show an overall tendency to increase area productivity (biomass production per unit of land) at the expense of labor productivity (biomass production per unit of labor input).

Under these conditions, material and energy output per capita reach a limit or even start to decline. Thus, in general, agrarian societies face sustainability problems as a result of the limited availability of resources, the difficulty of maintaining soil fertility over the long term, and a tendency for population growth to outstrip food supply. Pollution problems occur only locally at mining sites or in urban agglomerations.

Industrialization is a transition process during which the growth-related sustainability problems of the agrarian sociometabolic regime can be overcome. Social and technological change based on the use of a new type of energy carrier, namely fossil fuels, extends the inherent growth limits by removing the negative feedback loops—that is, loops that reverse whatever change is imposed upon the system—operative in the agrarian regime. This triggers a transition that ultimately transforms most features of society. Gradually the problems of energy scarcity and the concomitant environmental burdens are resolved, to a certain extent at least. The industrial sociometabolic regime, however, creates new types of sustainability problems.

Such a transition process was experienced for the first time in England under a unique combination of institutional change, population growth, improvements in land use practices, and the increasing use of coal. Coal-based industrialization, while allowing for the introduction of the new industrial sociometabolic regime, was characterized by population growth, as increased industrial production led to a growing demand for human and animal labor. The rapidly growing population had to rely on the delivery of food from a largely pre-industrial low-input agricultural regime. The United Kingdom, as well as most of the rest of Europe, did not achieve a mature energy system based on fossil fuels until after the 1950s, when oil and electricity and the internal combustion engine replaced the older coal-based technologies, leading to the industrialization of agriculture as well as a gradual decoupling of industrial production and human labor.

The agricultural limitation on physical growth was not removed until the twentieth century. The transformation of agriculture based on fossil-fuel driven technologies began in the New World and took off in European countries only after World War II. Among the key processes that drove the industrialization of agriculture were the substitution of fossil-fuel driven machinery for human and animal labor, the removal of the nutrient limitation through the availability of inexpensive fertilizers and other agrochemicals, and road-based transport, which allowed inexpensive transfers of large quantities of inputs and agricultural products, facilitating large-scale specialization. In European countries, draft animals disappeared within just two decades, the agricultural labor force was reduced by more than 80 percent, and nitrogen availability increased by a factor of 10. Agriculture underwent a fundamental alteration. The traditional local combination of intensive (e.g. cropland) and extensive (e.g. pastures, woodland) land-use types and crop cultivation with livestock husbandry became obsolete. External inputs and energy subsidies abolished the strong dependence on natural regeneration rates and scarce internal resources. Large-scale differentiation and specialization of land use became possible and triggered transfers of large quantities of food, feed, and plant nutrients across increasing distances.

In the two decades after World War II, yields per unit of area tripled and the overall output of food products doubled. However, the increases in output were achieved through fossil-fuel-based inputs, and the surge in agricultural area and labor productivity came at the expense of energy efficiency. While Austrian agriculture produced 5–10 units of output per joule of invested energy in the nineteenth century, this ratio declined to less than one unit per joule in the 1970s. Agriculture changed from a low-input system to a throughput system with high inputs and high outputs.

The availability of an area-independent source of energy and the fossil-fuel-powered transformation of agriculture from an energy-providing activity to a drain on useful energy were the two main factors that allowed for a far-reaching decoupling of energy provision from land use and the control of territory. At the same time, the exploitation of large stocks of fossil fuels of high energy density by new technologies, such as the internal combustion engine and the electric motor, allowing conversion of primary energy into useful work, led to novel biophysical patterns of production and consumption, far-reaching structural change, a certain worldwide uniformity in social forms and institutions, and a surge in material and energy use per capita.

Even if "mature" industrial economies have left behind the strong momentum of biophysical growth, a high level of energy and material use is maintained. Material and energy use per capita exceeds the values typical for advanced agrarian regimes by a factor of three to five. At the same time, a surge in agricultural output permitted population densities 10 times higher than in most agricultural societies. As a result, the material and energy use per unit of area has multiplied by a factor of 10–30. The contribution of biomass to total primary energy and materials supply dropped to 10–30 percent yet the overall use of biomass increased: The substitution of fossil energy carriers for biomass allowed for new uses of biomass instead of reducing biomass consumption (e.g. reductions in the use of wood fuel were outweighed by the demand for paper and timber). In the industrial regime, the absolute amount of biomass used is thus higher than ever before. Due to tremendous increases in agricultural labor productivity, industrial regimes are characterized by a very low level of agricultural population, often lower than 5 percent. Urban population levels are high. Low transport costs support large scale spatial differentiation and concentration; they also support transfers of huge amounts of all kinds of bulk materials and energy carriers over long distances.

In agrarian regimes, scarcity, poverty, and an overexploitation of natural resources are always an imminent threat. In contrast, the dominant impression within mature industrial regimes is one of abundance, however unevenly distributed. Because of its enormous material and energy turnover, the industrial regime currently faces sustainability problems related to output. These problems stem from pressure on the regional and global absorptive capacity of natural ecosystems for wastes and emissions. Some of these problems, like acid rain, have been solved through technological advances, but other local and global environmental problems of the industrial socioecological regime develop or worsen. The list of severe sustainability problems experienced by the industrial socioecological regime includes climate change and global warming, biodiversity loss, and desertification. The relative freedom from scarcity, however, is likely to change. The industrial socioecological regime is based on the use of exhaustible key resources. The industrial metabolic regime, therefore, is a transitory rather than a stable regime.

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Silvana Bartoletto

Fossil Fuels Consumption and Economic Growth in Italy in the Last Two Centuries

During the last two centuries, both the size of the economy and the level of energy consumption have grown at a faster rate than the world's population. As a consequence, modern economies are able to produce goods and services on a scale inconceivable in pre-industrial economies. Even though energy has played an important role in the pattern of Italian economic development, it has only recently received the attention of historians of the Italian economy.

Energy was of central importance in the transition from the traditional to the modern economy. The introduction of new energy carriers and of engines able to transform energy into mechanical work was a necessary, although not unique, condition of modern growth in Europe and subsequently in the rest of the world. It is important, however, to consider differences between countries. While energy transition took place rapidly in northern Europe, especially in England and Wales, this was not the case in southern Europe. There, on the eve of the twentieth century, traditional energy carriers (firewood, water, wind power, fodder for animals, and food for humans) represented 70–80 percent of total energy consumed. In Italy, in particular, the contribution of traditional energy to total energy input didn't drop below 50 percent until just before World War II. Italy lacks domestic sources of fossil fuels and it is almost entirely dependent on external supplies. Energy dependence in 2009, for example, was about 84 percent.

Fossil fuels consumption in Italy had four main phases: the first, from 1861 to the eve of World War I, had a growth rate of slightly less than five percent per year; the second phase, corresponding to the Interwar period (1914–1945), had an overall growth rate of -1.34 percent; the third, from 1946 to 1973, had a growth rate of 17 percent per year; and the last phase, from 1974 to the present, had a growth rate lower than one percent per year.

The scarcity of energy resources has seriously affected the process of industrialization in Italy. Industrialization has followed a different path from countries like England, where the Industrial Revolution occurred much earlier. In fact, Italy has specialized

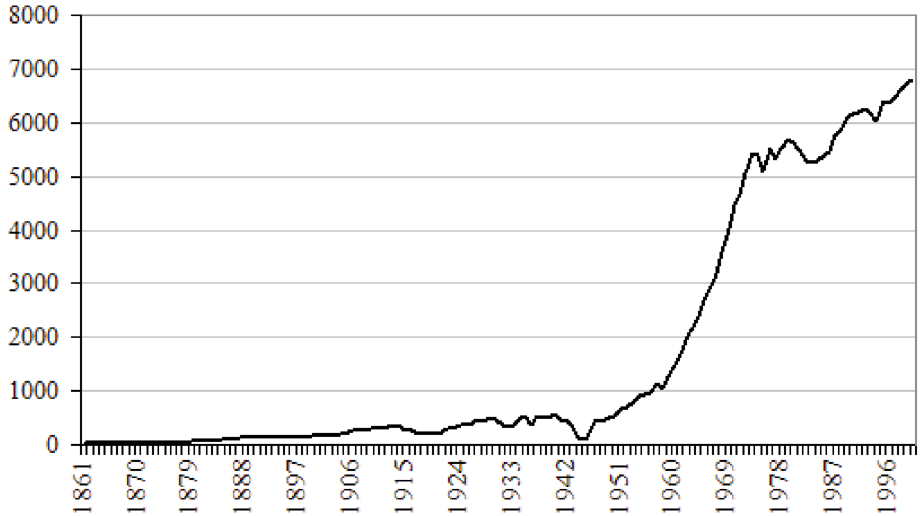

Figure 1: Fossil fuels consumption in Italy, 1861-2000 (Petajoules)

in industries with a high intensity of labor, which has been relatively abundant, and a low intensity of energy, which has been scarce relative to countries in northern Europe and North America. In 1910, the United Kingdom produced about 270,000 tons of coal per year, Germany 150,000, and Italy only 3,000. A census report for 1911 stated that about 58 percent of the total horsepower of Italian industries (1,603,836 hp) came from water power, while only 29 percent came from steam. Coal was imported from England at the beginning of the nineteenth century, or even earlier. At the time of Italian unification, coal imports, especially through Genoa, were increasing. The country's scarcity of fossil fuels resulted in fuel costs three to five times higher than in competing western European economies. Much of Italy's industrial growth from the 1880s to 1913 depended on the introduction of hydroelectricity, which expanded rapidly. On the eve of World War I, Italy was producing even more hydroelectricity than France. Until the 1960s, hydroelectricity in Italy was more important than electricity generated in thermal plants. Today, Italy is still the third largest producer of hydroelectricity in Europe, after France and Norway.

Italian oil imports started in 1864. Oil remained of secondary importance until the 1950s, when it surpassed coal as a source of energy. Use increased rapidly until 1973 and slowly declined thereafter. Natural gas was already used at the end of the nineteenth century but did not become important until the 1950s, surpassing coal in the 1970s. In 1973, fossil fuels represented about 88 percent of total energy consumption. The oil price shocks of the 1970s had a significant impact on the Italian economy, causing a slowdown in the growth of energy consumption per capita. This was, however, only temporary, because oil consumption soon picked up speed, albeit at a lower growth rate than before. By the eve of the energy crisis of the 1970s, oil was the most important source of energy. In 1973, oil accounted for 82 percent of total consumption, coal for 6 percent, and natural gas for 11 percent. The contribution of oil later fell to 54 percent in 2000 while natural gas rose to 37 percent.

Nevertheless, modern energy consumption in Italy is still lower than in other European countries, and lower than the European average. The differences evident in Italy's pattern of growth have led historians to emphasize the elements of weakness and backwardness it presents, rather than those of originality and strength. While this pattern of low energy consumption distinguishes Italy from the northern and central European countries, it resembles that of other Mediterranean countries such as Spain.

The passage from an economy based on traditional energy sources to one based on fossil fuels had significant environmental consequences. The rise in fossil fuel consumption has led to an immense increase in carbon dioxide emissions, producing one of the most serious environmental problems of our time: global warming. Changes in the composition of the energy basket have an important effect on CO_2 emissions, because different energy carriers emit different amounts of CO_2. The historical transitions from firewood to coal, oil, and gas in the primary energy supply can be summarized as a gradual transition from fuels with low hydrogen/carbon ratios to fuels with high hydrogen/carbon ratios. The more hydrogen relative to carbon, the more energy is obtainable with fewer emissions. For traditional energy carriers such as firewood, this ratio (H/C) is 0.1:1; for coal, it is 0.5:1 to 1:1 (depending on the type of coal); for oil, 2:1; for natural gas, 4:1.

Carbon dioxide emissions from fossil fuels consumption rose from three million tons in 1870 to 444 million tons in 2000 (fig. 2). The increase in emissions was particularly stark after the Italian takeoff of the 1950s. Between 1950 and 1973 emissions rose from 46 million tons to about 400 million tons, with an average growth rate of 11 percent.

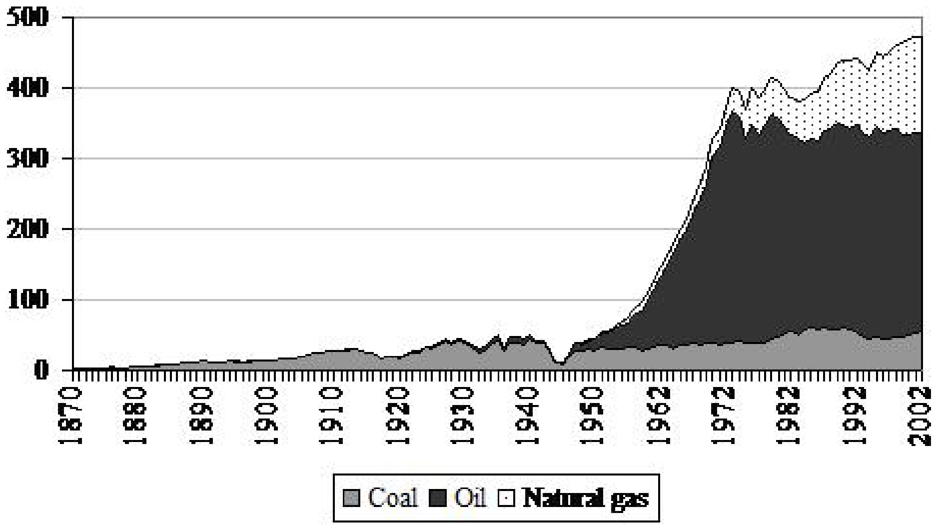

Figure 2: Total CO_2 emissions in Italy 1870–2000 (million tons)

Recent estimates indicate that proven reserves of fossil fuels are likely to be inadequate to sustain the potential growth of the world economy to the end of the present century. Moreover, in Italy the role of renewable energy sources, including wood and geothermal energy, is still marginal. In 2009, renewable energy sources accounted for about eight percent of total primary energy consumption. The transition to fossil fuels, which was the basis of modern growth during the last century, now risks triggering a new Malthusian trap if there is not a reduction in dependence on fossil fuels and encouragement for the development and consumption of alternative energy sources.

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Verena Winiwarter

The View from Below: On Energy in Soils (and Food)

Pre-modern agriculture is commonly described as suffering from a paucity of nutrients. The paucity in nutrients is a consequence of energy scarcity. Energy scarcity was a standard feature of pre-modern agricultural operations, so using one's energy well was critical. Some energy had to be spent tilling and improving the soil, work for which return on investment came only after several growing seasons. Agricultural manuals make a case for such work, as they regard effort targeted at soil ecosystems below the surface, as yet unseen and largely unknown, to be of the utmost importance.

Photosynthesis, likewise unknown as a concept in pre-modern agriculture, provides the basis of all agricultural operations. To keep plants growing, their energy-creating machinery has to be kept running; for that, plant nutrients are necessary. Energy investment in manuring, fertilizing, plowing, harrowing, marling, and other operations with the soil was and is necessary to obtain food.

Charles Darwin considered his 1881 book *The Formation of Vegetable Mould through the Action of Worms with Observations on their Habits* as more important than his evolutionary work. The origins of the book go back to his paper "On the Formation of Mould," read 1 November 1837 and published in the following year in the *Proceedings of the Geological Society of London.* Darwin had investigated a phenomenon nowadays called "bioturbation," the mixing of soil by the action of soil organisms. Considerable energy is spent by those organisms, whose metabolic output as they digest earth is central to mold formation. Worms are very important farm workers.

Earthworms and other soil biota create, by means of their metabolism, the niche in which they thrive—the humus-rich, loose soil with lots of nutrient minerals that agriculturalists find the most productive for rearing plants. Therefore, niche construction should be incorporated into an understanding of agriculture. One can describe agriculture as a human effort of cultural niche creation, but it can also be seen as worms domesticating humans to co-create their niche. In their 2003 overview of the biological principle of niche construction, biologists Odling-Smee, Laland, and Feldman use earthworms as an example of their concept. The worms burrow, drag organic material into the soil, mix it up with inorganic material, and cast the digested material; all of this serves as the basis for microbial activity. Earthworms dramatically change the structure and chemistry of the soils they live in, creating niches. In temperate grasslands earthworms can consume up to 90 tons of soil per hectare per year. Earthworms also contribute to soil genesis, to the stability of soil aggregates, to soil porosity, to soil aeration, and to soil drainage. Because their casts contain more organic carbon, nitrogen, and polysaccharides than the soil they ingest, earthworms affect plant growth by ensuring the rapid recycling of many plant nutrients. In return, the earthworms probably benefit from the extra plant growth they induce by gaining an enhanced supply of plant litter. All of these effects typically depend on multiple generations of earthworm niche construction, leading only gradually to cumulative improvements in the soil.

Manure has important consequences for earthworm habitat. It increases the amount of soil organic matter (SOM) as well as raising the pH of the soil, which makes biological activity shift from slow, fungi-dominated processes to faster, bacteria-dominated processes. Under the predominance of bacteria, the rate of mineralization caused by microbial decomposition of organic matter is increased. The water-holding capacity of the soil is increased, as are its hydraulic conductivity and infiltration rate. Nitrogen, phosphorus, and potassium are added while the bulk density is decreased. Recalcitrant components of manure form a reserve pool of nutrients for mineralization. In short, most of the characteristics of soil are profoundly changed by manuring, providing a different habitat for the subterranean workforce.

Applying Laland, Odling-Smee, and Feldman's work to soil ecosystems, we can say that earthworms create the ecological niche that humans consider man-made, an agro-ecological niche. But life on the farm is best understood in an even more dialectical way. From the niche-construction perspective, evolution is based on cycles of causation and feedback. Organisms drive environmental change and organism-modified environments subsequently select organisms. Nest-building generates selection for nest elaboration, defense, and regulation. Niche construction is not just an end product of evolution, but a cause of evolutionary change.

To explain this, Odling-Smee introduced the notion of ecological heritage in 1988. Biology has long turned away from the idea of a habitat as a fixed set of environmental parameters, and has come to understand niches, the places of a population in an environment, as the product of interactions among the organisms forming the niche. The niche of an animal reflects its role in a community: eating its prey, being eaten by its hunters, occupying a place in a habitat. When ecologists talk of a "niche" they talk about the animal's role rather than "where" the animal can be found. A species' characteristic ways of living can include making lasting changes made to their environments. Such changes have effects beyond the lifespan of the generation responsible for the changes. An ecological inheritance is the result. Niche construction is a very common phenomenon, with dens and burrows being good examples of the heritable parts of a niche. Such constructed niches can be quite permanent structures, used (and changed) by several generations of inhabitants. This means that the purposive intervention of the species leads to a change in the local environment, which then acts as a selective force for future generations. Not only the environmental conditions as such but also the ecological inheritance, for example the burrow, are a means of natural selection. Humans construct their ecological niche by building their type of dens (houses) and by altering natural systems through colonizing interventions. The lasting changes they make act as means of natural selection on them. One such example is provided by zoonoses, diseases which crossed from animal hosts to humans as a result of the close contact between humans and their domesticated animals.

Another such example is provided by agricultural soils. Agriculture usually takes place on soils left by one generation of humans for the next. The ecological inheritance in this process is not small. Soils bear a lasting, discernible mark of previous cultivation, leaving a particular ecological inheritance. Some amendments are particularly long-lasting. The most common of these is marl.

The use of this mixture of clay and calcium carbonate is recorded as early as the ninth century, and evidence for continued reliance on marl to improve soil fertility runs in the nineteenth century. Various sources, such as farmers' diaries and recommendations to farmers from experts, indicate widespread knowledge of the benefits of using marl.

Gathering, storing, hauling, and spreading manure was part of the huge internal material flows on the farm necessary to keep it productive. These material flows matter. Manpower is crucial to the maintenance of soil fertility. The use of marl is an obvious example. As effects cannot always be noticed quickly, with yields varying from year to year, the more immediate needs determine where farm work is allocated. That meant that in some cases farmers ignored the need for marling and did not enjoy the benefits. Nineteenth-century agronomists were often enthusiastic about the fertilizing properties of marl. Government officials chimed in with recommendations for improving soil fertility through the addition of marl.

The history of marl use and the strong support for its application illustrates the need for a history that considers energy and coevolution. The concept of an ideal farm as laid out by Arthur Young in 1770 helps to illustrate the implications of the distribution of farm labor and manuring for human history. Young suggested that the farm should be "proportioned" so that all labor and soil fertility maintenance needs could be met. This was to be achieved at considerable expense, mainly because it entailed keeping farm animals and keeping them at work.

Labor expenditure for maintaining the subterranean niche went beyond hauling. Young criticized the practice of using unprepared manure and described the work entailed in preparing it. Valuable ditch-earth was also left unused, Young noted. Similarly, he was concerned with the failure of agriculturalists to exploit the potential contribution of the night soil of the townspeople to soil fertility. He was convinced that a small farm could not be as profitable as his model farm, an important reason being the neglect of niche construction work by farmers busy with their short-term work.

The model farm would run into a dilemma, or, to put it more in economists' terms, into a problem of optimization. Feeding the animals whose excrement is needed to feed the soil biota is expensive. As Young's account is detailed, it is easy to assess, through his listings and calculations, the overall labor investment that an ideally proportioned farm would have had to make in soil-habitat management. Hauling marl and manure were crucial to success. But that in turn entailed keeping carts and teams of oxen or horses, digging marl pits, and making a big investment in infrastructure. Cattle, for example, would have to be kept in stables, which needed to be cleaned regularly.

We can calculate that 18 percent of the labor cost on the model farm came from manuring. 12–25 percent of feed for draft animals went into manuring. Additional expenses were incurred in buying and hauling straw, stubble, night soil, and so on. A rough estimate would be that 20 percent of all operations on Young's model farm were directly related to manuring.

This means that nutrient management was under severe labor constraints in pre-modern agriculture. While the manuals make clear that farm operators understood that they should invest in manuring, it was costly to do so. And as poorer farmers did not have the means to buy enough cattle even to convert their own straw into manure, there was also a capital limitation on soil biota management, with potential long-term effects on soil quality. The soil quality would eventually decline on such farms that were too small and poor to allow them to sustain it, bringing the smallholders into a downward spiral of declining yields. That not all smallholders were doomed has been pointed out by Robert McC. Netting, but the sustainable systems he describes are labor-intensive, almost horticultural in their nature. They develop ingenious methods, such as using fish ponds as nutrient pools, but they can easily be disturbed and brought to ruin, as their niche construction is fragile.

The energy investment in soil fertility is considerable. It might be as high as a quarter of the labor cost of a farm and its capital ramifications are significant. The energy investment goes into the provision of nutrients and into habitat improvement for the subterranean workforce of earthworms on which agriculture depends. It is a matter of perspective whether humans are providing a niche for those soil biota that produce plant nutrients as their excreta, or whether earthworms are providing humans with a niche in return for feeding them. Earthworms could argue that they domesticated humans to feed them. Nutrients and energy are closely intertwined and should be seen as two sides of the same coin rather than as two different constraints of agricultural success.

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The Twentieth Century and Beyond

Nina Möllers

Telling by Showing: Early Twentieth Century Exhibitions as Advocates in Energy Transition Processes

Popular perceptions of energy regime changes often suggest that transitions happen rather abruptly and result in complete substitutions of older, traditional energy carriers with more efficient, comfortable, and inexpensive ones. A closer look at the history of energy, however, shows that energy transitions, particularly when it comes to private households, are often characterized by a slow fade-out of older energy forms as they are increasingly replaced by newer, supposedly more modern energy carriers. The reasons for energy transitions and for the speed with which they occur are manifold. Scholarly literature has primarily focused on the technological, economic, and political circumstances in which they take place. Psychological, social, and cultural aspects have been underexposed. This has led to an incomplete, at times even biased understanding of energy history. The neglect of these issues is particularly grave for private households, where recent studies have demonstrated how both users and mediators (organizations positioned between producers and consumers) can significantly affect energy choices and practices.

As agents of knowledge and appropriators of technology, exhibitions (and most notably museum exhibitions) have played an important role in the early twentieth century, when gas and electricity, the quintessential modern energy sources, aimed to oust wood, coal, and peat while simultaneously competing intensely with each other. Exhibitions are multimedia, synesthetic arenas of cognition and experience where the dichotomy between producers and consumers of energy is overcome. On the exhibition floor, producers' expectations and interpretations, translated by the exhibits' curators and designers, meet with the hopes and fears of the consumers. Exhibitions can never depict their content neutrally. Displaying and arranging objects, texts, and images are acts of interpretation. In this way, exhibitions and the stakeholders in them exercise a mediating influence in the process of energy transition. On a fundamental level, exhibitions formulate and convey knowledge about specific technologies, appliances, and their energy needs. Beyond that, they communicate ideas about modernity, gender roles, political ideologies, and consumption styles. They also serve as translators between different, at times opposing stakeholders in the economic, political, and cultural worlds. By decoding the language of exhibitions and uncovering inscribed discourses on energy, a fuller understanding of energy transitions, their delays, their circumstances, and their consequences will result.

Convincing German consumers of the need for a private energy transition from wood, peat, and coal to gas and electricity was not as simple as it may seem in hindsight. Despite giving the impression of a rather predetermined, linear success story, electrification proved to be a contested field in the early twentieth century in Germany. Consumers were reluctant to abandon their traditional energy consumption practices, which were determined by the energy carrier that was used, for the sake of new energy forms that often required very different handling and carried the danger of unreliability, excessive costs, and even potential harm to the body. Therefore, gas and electricity networks, appliance manufacturers, and reform-oriented social activists, architects, designers, and educators worked towards a fast and complete transition from older (and, in their eyes, obsolete) energy carriers like wood, peat, and even coal to gas and electricity by educating the users about the advantages of these new energy forms in customer centers. Because exhibitions are ideally suited for conveying messages to the masses, they became an increasingly important medium for advocates of the new energy regime in the early twentieth century. Almost all of them used consumer-oriented settings to promote comparisons with traditional sources. The strong competition between gas and electricity as modern, network-dependent energy carriers influenced the exhibition world tremendously. Both energy forms competed for sales to private households, which promised to grow into a large and, compared to industry, stable market. At first, gas started from a better position. Its supply network had already been established in the late nineteenth century and was thus ready to grow. The relatively low price of gas in comparison to electricity also meant that even the middle and lower classes could benefit from the conveniences of gas lighting and connected appliances such as irons, small cooking plates, coffee-pots, and gas heating. After World War I, however, with the expansion of the electrical grid, electricity quickly gained ground. Faced with this competitive situation, both the gas and the electricity industries developed elaborate marketing campaigns and established central institutions for the promotion of gas and electricity as readily available, cheap, and easy-to-use energy sources.

Records of discussions by the Munich government about a proposed exhibition on gas scheduled for 1914 show that the industry felt increasingly threatened by electricity. In the face of wide-reaching and emotionally effective promotion campaigns for the Promethean technology of electricity, stakeholders lamented the lack of publicity for gas and policymakers' lack of awareness of the potentials of gas. What bothered the gas industry in particular was its rival's campaign to present electricity as the cleaner, easier, safer, and more versatile form of energy. For smaller appliances such as irons, coffee-pots, and cigar lighters, gas had a hard time proving its equality with electricity. Technical requirements played a significant role in this, too, as electrical plugs were easy to handle, despite lacking security standards, compared to gas lines and valves, which were prone to leaking, leading to gas poisoning, fire, and occasionally even death.

Figure 1: Title page of the exhibition catalog "Gas: Its Production and Its Municipal, Private and Industrial Usage, Munich 1914."

In both the general and trade literature, the growing competition between gas and electricity became a hot topic over the course of the 1910s. In 1911, the director of the *Zentrale für Gasverwertung* (Center for Gas Usage) emphasized the affordability of gas for working-class households and explicitly criticized electricity for keeping households from modernization. Since electrical lighting kept gas out of the homes of many middle- and lower-class families while electricity remained too expensive for cooking, these families were forced to stick with outmoded and inefficient coal stoves. Beyond these differences, the gas and electricity industries shared the impression that it was mainly the reluctant German housewife who stood between them and enormous profits. In the December 1911 edition of the *Journal für Gasbeleuchtung und Wasserversorgung (Journal for Gas Lighting and Water Supply)*, the travelling promoter of gas usage in the home, "Fräulein Josepha Wirth," claimed that "our housewives are, when it comes to the question of the home, particularly the kitchen, endlessly con-

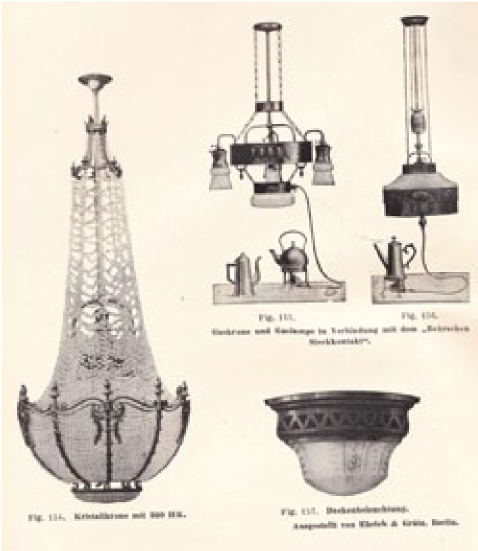

Figure 2: In reaction to the rising competition with electricity, gas suppliers and appliance manufacturers promoted gas lighting devices equipped with connecting valves for the operation of irons or coffee pots. Source: exhibition catalog "Gas: Its Production and Its Municipal, Private and Industrial Usage, Munich 1914."

servative. They cling to traditional customs until they have seen convincing evidence that just 'good' is not good enough."

The Munich Gas Exhibition in 1914 that was organized by the municipal gas company and the *Zentrale für Gasverwertung* under the patronage of the Bavarian King Ludwig III aimed at informing both the general public and municipal, regional, and national political stakeholders about the versatility of gas. The sections of the exhibition covered everything from the technologies of extraction, refinement, and distribution to the use of gas in industry, trade, and the private household. In their exhibition booths, household gas appliance manufacturers listed the same advantages as they did for their electrical appliances: cleanliness, comfort, time saving, and affordability. Gas appliances also shared some problems with electrical appliances. Since many homes lacked central heating systems, cooking with gas was not an option year-round. Gas cookers did not heat up the room as cooking with coal stoves had done and, secondly, steam that came with the burning of gas would cover the cold walls, furniture, and dishes. "Combination" was therefore the buzzword on the exhibition floor. Several companies displayed their new inventions, ranging from gas stoves that could also be used as coal-heating systems in the winter to stoves with integrated storage heaters in the fashion of familiar fuel-saving cooking boxes. Steering the right course between the technical needs arising from the use of gas as fuel and the expectations and usage patterns of housewives was a challenge that engineers of gas and electric stoves shared.

Many manufacturers, such as the long-standing family business F. Küppersbusch & Söhne, were in fact reluctant to stake everything on one card and continued to produce both coal- and gas-fired appliances while also developing electrical models. In general, the gas exhibition in Munich focused less on the competition with electricity and instead featured gas in relation to earlier energy sources, particularly coal. By curating the exhibition in this way, the gas industry succeeded in presenting gas as the newer energy form that connoted modernity, despite the fact that coal was still being used by many people for quite good reasons. Yet the fact that gas was quickly losing out to electricity became absurdly obvious. The exhibition halls where the gas industry displayed its refined technology had already been electrified a few years earlier. In order to provide the infrastructure for the exhibition's demonstrations of gas usage, gas pipes had to be re-installed and electrical lighting fittings remodeled. Those electrical lamps that could not be remodeled for gas were kept inoperative for the duration of the exhibition.

Figure 3: Exhibition stand of F. Küppersbusch & Söhne at the Munich Gas Exhibition, 1914 showing both gas and coal kitchen appliances. Source: exhibition catalog "Gas: Its Production and Its Municipal, Private and Industrial Usage, Munich 1914."

Even though the course was already set, the gas industry managed to keep its product in the game during the 1930s and 1940s. Despite widespread electrification of more and more urban households during the 1920s and 1930s, gas remained an alternative for many already connected to the gas grid. However, unlike the even more traditional coal, gas made inroads only in those areas where governments and private investors were willing to provide the necessary financial and bureaucratic support for gas companies and their building of a gas network. As municipal governments had to choose either electricity or gas, with the former winning in more and more cases, gas was able to maintain its position as the primary energy source for domestic heating and cooking only in scattered urban "gas pockets" in German-speaking areas such as Vienna or (in the post-World War II period) Bielefeld in West Germany.

Even more surprising, however, is the steadfast presence of coal as an energy alternative for private cooking, bathing, and heating. Due to a fear of energy shortages, many households were not willing to commit themselves to a network-dependent energy source over which they exercised even less control than they did with coal. In the 1950s, the so-called "economic miracle" brought German households a long-wished-for share in the booming consumer society, including modern electrified living spaces. Germany's development towards a mass consumer society during these postwar decades would eventually deliver the final deathblow to traditional household energy forms like peat, petroleum, wood, and coal. While coal continued to be an important energy source, its usage moved outside of the home into the arena of electricity production. At the same time, however, coal and, to some extent, wood played a significant role in the history of private energy consumption until the 1970s. At least in the psyche of German consumers, coal still figured prominently as a reliable energy source, as high sales figures of combination stoves that used both electricity and coal demonstrate. The psychological imprint of energy shortages during World War II and rationing in the immediate postwar years left its mark well into the years of decreasing energy prices and all-encompassing household electrification. During the late 1940s and early 1950s, it was difficult to get coal, but at least people felt that their private energy supply was ultimately in their power rather than in the hands of gas or electricity networks detached from their daily lives. At the same time, coal, wood, and peat made their users' hands dirty and the air smelly—vivid evidence of the process of energy transformation. With the all-electrical household that became a reality for most German households in the 1960s and 1970s, the sensory experience of energy usage was reduced to plugging appliances into wall sockets. The electrification of the private household was also a transition from an energy-conscious lifestyle to energy oblivion, in which users were detached from the primary energy sources behind their comfort—be it coal, oil, or uranium.

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Karin Zachmann

Energy Regimes, Foodways, and the Efficiency of the Human Engine

This essay explores connections between energy regime changes and nutrition, as well as the impact of such changes on nutritional knowledge and food policies in the nineteenth and twentieth centuries. At the core of this second part is the thermodynamic revolution, which led to a new conception of the human body and thus a new paradigm of nutritional physiology. Whereas nutrients had previously been viewed in a hierarchy, with some more important than others, the new paradigm considered them interchangeable based on the first law of thermodynamics (heat and energy are equivalent and neither lost nor gained within a system). In the latter part of the twentieth century, with the advent of the information age, a new concept of nutrition emerged, with information instead of energy being seen as critical for understanding the physiology of nutrition. While these concepts shaped food policies, they did not necessarily change production policies; practice did not align with theory. Instead, since the mid-nineteenth century, the hierarchy of nutrients concept (with protein at the top) has been enthroned while the development of industrialized livestock production has decisively reoriented Western foodways towards a diet centered on animal calories. This misalignment of theory and practice indicates how energy regimes, the state of food and nutrition, and strategies of production and consumption in food and agriculture are interconnected in manifold but not always straightforward ways.

Food is the most important fuel for the human body. In traditional energy regimes it is the main source of power. Humans can use their energy output to master other forms of energy. The more successfully they do so, the more they control their environment and achieve goals not strictly related to animal existence.

For most of human history, humans relied on wild plants and on animals that had converted solar energy into carbohydrates, lipids, and proteins, and thus into chemical energy that served as fuel for the human body. The range of human activity was limited by the resources that happened to be available in nature. They could live only where their needs did not surpass nature's reproductive capacity. To overcome this, humans had to learn how to control and increase the supply of plants and animals or had to discover new sources of energy. These two problems were solved by the Agricultural and the Industrial Revolutions respectively.

The Agricultural Revolution was the process whereby humans learned to control, increase, and improve the supply of plants and animals at their disposal. Paradoxically, with the transition from the hunter-gatherer society to an agrarian society, the nutritional condition of humans deteriorated, as revealed in decreased body heights (Sieferle 1997, 73–4). As humans developed greater control over their food supply, the population density increased because a given area of land could provide food for more people. At the same time, however, the quality of the food deteriorated. There was a decrease in meat, in the percentage of fresh foods over stored, preserved, and processed foods, and in variety. There were also frequent shortages of proteins, vitamins, and minerals. However, a return to the nutritionally richer hunter-gatherer society was impossible, because agrarian society led to population growth.

Part of the development of societies was the establishment of foodways. The term was coined by anthropologists, who define foodways as "a culture's primary form of nutritional sustenance. … Each foodway relies upon one particular food source as the foundation for one's meal. For the Japanese it is rice, for the Mexicans it is maize, for large parts of Africa it is yam, for the Masai of East Africa it is blood drained from the vein of cattle and for the Americans it is meat" (Willard 2002, 116). For Europeans it was grain.

The cultural dimension of foodways becomes obvious in local cuisines. Through the selection, preparation, and cooking of food, a cuisine transforms nutritional raw materials from a natural to a cultural state. Food chains, foodways, and cuisines are closely connected. For centuries, food chains were organized on a predominantly regional basis so that the geographical and climatic context in which people lived as well as their regional culture determined their foodways. Imported food products, such as spices, sugar cane, coffee, or cocoa, remained luxury goods until the eve of the Industrial Revolution and thus did not challenge the regional determination of foodways—as long as the foreign products did not become domestic products.

Despite their efficiency in producing food, agrarian societies remained societies of scarcity as their energy supply depended on the fiercely contested availability and usage of space. Space was necessary to create food energy from fields, to grow fodder for the draft animals that provided mechanical energy, and to grow forests for thermal energy. Intensifying the usage of space was the main way to increase the supply of energy. Fostering innovations in agriculture and forestry was a central concern for early modern states. That their success remained limited is obvious, since our early modern ancestors experienced famines several times within the course of their lives.

The Industrial Revolution went hand in hand with the transition to the fossil fuel energy regime. The new energy regime gave rise to new technologies that enabled mankind to harness energy sources that had been unattainable before. The great transformation in social and economic organization, however, was not accompanied by equally significant improvements in living conditions. On the contrary, economic historians observed common people's declining biological standard of living in both Europe and North America. In the century of the great transition Robert Fogel observed "decades of sharp decline in height and life expectancy, some of which occurred during eras of undeniably vigorous economic growth" (Fogel 2004, 29).

Thus, early industrialization was characterized by a restricted food supply. The lowest strata of society had been too weak for work. "At the end of the eighteenth century British agriculture, even when supplemented by imports, was simply not productive enough to provide more than 80 percent of the potential labor force with enough calories to sustain regular manual labour. . . . Begging and homelessness were reduced to exceedingly low levels, by nineteenth century standards, only when the bottom fifth of the population acquired enough calories to permit regular work" (Fogel 2004, 42).

It is in this stage of transition, when the availability of new power sources suddenly increased the scope of human activities but potential manpower suffered from an insufficient energy input, that national food supplies and the efficiency of diets became subjects of scientific concern.

With the spread of steam engines, the shackles of the traditional energy regime loosened. The diffusion of steam power evoked hopes of an age of unlimited growth and progress. The observation that it was heat that enabled the working of machines transformed the steam engine into a model for everything. Using the steam engine as an analogy of the universe meant advancing the principles of thermodynamics as the basic framework to understand the workings of the natural as well as the man-made world. An important breakthrough toward this goal was fostered by the simultaneous yet independent measuring of the mechanical equivalent of heat (Joule's equivalent) by the German doctor Robert Mayer and the British brewer and gentleman of science

James Prescott Joule. This measure allowed a quantitative understanding of the relations between natural forces. Concretely, this equivalence made it possible to compare energy transformations in machines as well as in organic and inorganic nature (Neswald 2006, 133). Nutritional physiologists' preoccupations became closely connected to the world of engineers.

Robert Mayer's main interest was in explaining the metabolism of animals. Equipped with the mechanical equivalent of heat and with the law of conservation of energy, Mayer was the first to replace the chemical concept of metabolism with a thermodynamic one. The chemical theory of metabolism explained the motion of muscles as the combustion of muscle material. Thus, every motion of the muscles destroyed their own substance, which then had to be regenerated by vital forces. Robert Mayer argued against this idea as early as 1845, stating that, like steam engines, muscles obtain their fuel from the outside. Thus both the muscle and the steam engine were perceived as machines that transform chemical energy into heat and mechanical energy—that is, into work (Neswald 2006, 133–43).

The concept of metabolism as a transformation of forms of energy did not gain ground until the last third of the nineteenth century. Until then, a chemical understanding of metabolism prevailed, based on a biochemical concept of food as a compound of three nutrients: carbohydrates, lipids, and proteins. The German chemist Justus Liebig was one of the most famous advocates of a chemical understanding of metabolism. Based on his explorations of meat, Liebig determined a hierarchy of nutrients with proteins at the top. His student Pettenkofer, together with an entrepreneurial engineer, put the concept into practice, establishing the Liebig Meat Extract Company in Uruguay. The hierarchically framed nutrient paradigm, however, threatened political stability because it required increasing the percentage of meat in working class diets. Since meat was the most expensive foodstuff, championing the chemical paradigm as the foundation of food politics would have aggravated the already tense and conflict-ridden social situation in the early to mid-nineteenth century (Tanner 1999, 89-120).

In contrast to the chemical concept (which was partly replaced rather than abandoned), the thermodynamic interpretation of metabolism provided ideas for the improvement of diets without challenging the social system. According to the thermodynamic paradigm, it was not the nutritional but the caloric content of foods that determined the quality of diets. Thus, food improvement was achieved by balancing calories and costs within available budgets. To reach this conclusion, nutritional physiologists had further refined the comparison of the human body to the steam engine. In the 1860s, this equation was already common knowledge in physiology. Adolf Fick, a German physiologist, actually spelled out the equation in his *Compendium der Physiologie des Menschen mit Einschluss der Entwicklungsgeschichte* (1860). He argued that it made perfect sense to compare the energy principles of the body with those of the steam engine (Neswald 2006, 363).

Displaying a similar mindset to that of the engineers who strove to improve the efficiency of the steam engine, physiologists tackled the task of how to increase the efficiency of the human engine. Two fields of physiology emerged: ergonomics dealt with the output of human engines and thus with the capacity of bodies to do work, as well as with the most appropriate or efficient application, while nutritional sciences studied the input of the human engine in order to determine the caloric content and the combustion efficiency of food.

To determine the efficiency of the human engine, physiologists had to consider how much food/fuel the human engine required for work and for its basal metabolic rate. And they had to find out what kind of food provided the best combustion economy. This was meant to increase a nation's work capacity—and therefore economic growth—as well as to diminish an entropic waste of energy in food. Both were crucial aspects at the end of the nineteenth century, since the law of entropy fuelled nations' fears that they would struggle to survive within the increasingly fierce competition among imperial powers. In parallel, serious conflicts were triggered by the question of how to distribute the wealth of societies more fairly. Thus, the provision of food and improvement of diet ranked high on the political agenda in Germany.

Fully aware of the increasing importance of food and nutrition politically and socially, the influential nutritional scientist Max Rubner positioned and advanced the science of nutritional physiology (*Volksernährungslehre*) as part of social hygiene. He rooted nutritional physiology in the thermodynamic paradigm. The core aim of his nutrition program was to determine the relative caloric value or the specific dynamic effect of various foods. Just as the power and efficiency of the steam engine depended on the quality of the coal burned, physiologists assumed that there was an optimal fuel for the human engine. Rubner conducted experiments to explore the effect of staple foods on the production of heat. High-protein food produced the most heat, which Rubner interpreted as the result of digestion. Therefore, the chemical caloric value did not correspond to the organism's energetic use value because bodies need to invest various amounts of energy to digest different foods. As the effort linked to protein digestion was especially high, Rubner concluded that meat was not an especially efficient food. Meat could be useful to stimulate the unstable digestion of intellectuals but the optimal fuel for manual workers was the potato. Therefore, Rubner categorically fought against the "meat cult" that was prominent at the turn of the twentieth century (Neswald 2006, 373f).

This "meat cult" was not just a cultural attitude; it corresponded to changed consumption patterns. Industrial meat production took off in the second half of the nineteenth century when fossil-fuelled transport systems began to restructure the world food market. New methods of livestock production and highly mechanized slaughterhouses changed the systems of meat provision and led to a gradual but noticeable increase in meat consumption. This increase was interrupted by both world wars but meat consumption accelerated after each war and resulted in a new foodway during the second half of the twentieth century. This foodway was and is characterized by a dominance of animal calories and processed food. As was already the case at the turn of the last century, meat consumption is criticized today. Now, though, the argument is different. Today, industrial livestock production is perceived as the second biggest cause of climate change (surpassed only by the energy consumption of buildings) because of its low land use efficiency and the high emission of greenhouse gases. At the turn of the last century, however, the polemic against meat was not concerned with the overall energy efficiency of meat production but with the efficiency of its digestion in the human engine. The thermodynamic school of nutrition criticized meat as an inefficient and even dangerous food but could not stop meat producers from conquering a food market based on the transition towards a high-energy agriculture. The meat producers in turn could justify their activities by appealing to the long lasting belief in the hierarchy of nutrients.

Although the thermodynamic paradigm of nutrition did not replace the nutrients or chemical paradigm entirely, the energetic concept dominated food issues well into the second half of the twentieth century. This concept was based on the first law of thermodynamics: the conservation and transformation of energy. The idea reduced the value of food to caloric content and asserted the material interchangeability of foodstuffs. The energetic concept was also informed by the second thermodynamic principle of entropy, which increased popular awareness of energy loss in the process of digestion. As the thermodynamic paradigm aimed at the efficiency of the human engine, it was most appropriate for economies of scarcity.

The war economies of the twentieth century fostered the application of the human engine concept with regard to food rationing. National Socialism took a pioneering role when it established a rationing system that defined caloric needs with regard to bodily work requirements, gender, and age. The League of Nations distinguished this "German-Type-Rationing" from an "Anglo-American Type," which based wartime food rationing on social criteria.

Nazi Germany not only based its wartime food rationing system on the concept of the human engine but also used it as an instrument of the racist policy of annihilation through hunger. Nutritional physiologists contributed to this policy with large-scale experiments that sought to determine the minimal rations needed to keep the concentration camp inmates and forced-labor workforce deployable (Heim 2003).

From the 1950s, in all developed countries, material conditions and scientific concepts of nutrition changed. The food sector rapidly expanded after the years of scarcity during the war and the transition to an era of mass consumption started with a widespread desire for overeating. The new regime was called the gluttony or binge wave. Agriculture boosted these new eating habits as it experienced a tremendous productivity increase. In Germany, the number of people one farmer could feed increased from 10 in 1949 to 133 in 2006. According to Vaclav Smil, the average energy inputs per cultivated hectare increased more than eighty-fold between 1900 and 1990, with the most dramatic increase taking place in the second half of the twentieth century (Smil 1994, image 191). Simultaneous with the increase in food supply due to enormous productivity gains, the food needs in rich countries changed due to a restructuring of work requirements. As machines took on more of the physically demanding work, calorie requirements for laborers decreased. The most pressing nutritional problems thus became overeating or unbalanced diets. In this context, the thermodynamic paradigm of nutrition, which was based on the concept of the human engine, became obsolete. It was replaced by a cybernetic body concept that focused not on the energetic content of nutrients but on the effects of active ingredients in food such as vitamins, trace elements, and special acids or enzymes. Like information effect feedback and adaption in systems, micronutrients influence the processing of food in the human body. The effects of micronutrients become visible when they are lacking, as in the case of scurvy, pellagra, or rickets. The gradual replacement of the thermodynamic concept of nutrition was a product of new knowledge of genetics and reproduction. The new understanding of vitamins as so-called micronutrients fostered the spread of the cybernetic body concept in nutritional physiology.

The demise of the thermodynamic concept of nutrition at the beginning of the second half of the twentieth century thus reveals the complex relationship between energy regimes, foodways, and concepts of food and nutrition. With the suddenly rising supply of crude oil and natural gas and new, politically-motivated consumption regimes, energy consumption took a remarkable leap. Pfister (1996) described it as the "1950s syndrome." This change was also felt in agriculture and the provision of food, with rising energy inputs in food production and, in its wake, a growing supply of high-energy food, especially animal protein. In this context, the foodways of the Western world changed, as meat gradually became the new staple food. With an abundant energy supply at hand for physiological needs, however, nutritionists initially lost interest in the energy content of foods. The consequences of these developments can be observed in rising body height and increased longevity but also in the remarkable growth of the body mass index of Western populations.

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Hybridization of Electric Utility Regimes: The Case of Wind Power in Denmark, 1973–1990

Historian of technology Thomas P. Hughes has argued that as technological systems mature they become difficult to transform. The process of maturation involves an expansion of organizational as well as technical networks. Mature systems, therefore, are analogous to heavy bodies, "obeying" the law of inertia. The "mass" of technological systems consists of rules and regulations, decision-making routines, technical expertise, educational programs, private and public policies, enterprises, funds, and technological artifacts. Hughes refers to this as "technological momentum": eventually the systems appear autonomous, each following its own path of technological development.

In virtually all modern industrialized societies, electric power systems have developed a technological momentum of their own: centralized power production that benefits from economies of scale; extended networks of high-voltage transmission lines; big electric utilities and their networks of suppliers; and highly diversified consumption units, from private homes, through small and medium-sized businesses, to large-scale, year-round manufacturing plants. Consequently, shifting the technological path of electric power systems can be very difficult. In the course of the twentieth century, the electric utility system became an energy regime in its own right, replacing traditional forms of energy production.

Since the 1970s, however, the electric utility system has been subject to significant changes. Technological limits and economic crises ended the "golden years" of electricity production typified by high annual growth rates. Furthermore, from the early 1980s onwards a traditional source of energy, initially promoted by energy activists and environmental movements, began to penetrate the electric utility regimes in an increasing number of countries. Wind power use involved a radical shift from centralized to decentralized electricity production and from utility-owned to privately-owned electricity production. While the share of wind power use appeared marginal initially, it quickly rose in subsequent decades, accounting in 2010 for approximately 22 percent of Danish, 16 percent of Spanish, 9.5 percent of German, and 2.3 percent of US electricity production. The question is whether the system has in fact changed radically or whether the changes are ultimately insignificant to the system as a whole.

Based on our research into the contemporary history of wind power in Denmark, we want to argue for a third way: the hybridization of electric utility regimes by means of innovative adaptation of wind power. Today, wind power accounts for a significant amount of Danish electricity production, and the current national energy policy projects up to 50 percent wind power penetration by 2020, defined as the fraction of energy produced by wind compared with the total available generation capacity. Around 5,200 wind turbines, including offshore wind power plants, are currently installed, with a total capacity of 3.8 Gigawatts (GW). In order to reach the 50 percent goal, the government in power as of November 2012 will be inviting new tenders for 1.2 GW of offshore and 1.8 GW of land-based wind power.

The development of wind turbine manufacturing and wind power penetration in Denmark has engaged many diverse actors:

- Small-scale manufacturers of farm equipment, who took up wind turbine manufacturing during a crisis in Danish agriculture in the 1970s and created the world's leading wind turbine industry.

- Wind engineers at the former Test Station for Windmills at Risø, who not only managed the system approval scheme that began in 1991 but also assisted manufacturers in their research and development (today, wind turbine approval is managed by the Danish Energy Agency and the Department of Wind Energy at the Technical University of Denmark).

- Meteorologists at the National Atomic Research Facility in Risø, where the Test Station was located, who developed the Wind Atlas methodology on a contract from the national energy research program that began in 1976. This methodology facilitated relatively easy and reliable projections of local wind energy resources for wind turbine owners and wind park developers.

- The Danish Association for Wind Turbine Owners, which began collecting statistics in 1979 for all wind turbines erected in Denmark, including information on ownership, manufacture, and monthly production. These statistics enabled a high degree of market transparency from an early stage.

- A relatively strong energy movement, which combined opposition to nuclear power with many grass roots initiatives within renewable energy, the most visible of which was the 2 MW Tvind Mill, completed in 1978.

- Energy planners and policy-makers, who integrated wind power along with other renewable energy sources in Danish energy policy as early as 1976, and who have since expanded the portfolio of Danish wind power policies.

The role of the utilities in Danish wind power development has been ambiguous. Many utility managers during the 1970s, 1980s, and 1990s opposed wind power, at times even working against the integration of wind turbines into the power grid. On the other hand, the research departments of the Danish utilities companies were engaged in wind turbine development, and many utility companies (although sometimes more or less forced to by government) have erected wind power plants.

Moreover, when wind power development took off in the early 1980s, the utilities helped to establish voluntary purchase agreements, perhaps the single most critical requirement of a successful wind turbine project. The voluntary agreements lasted until 1992, when the government had to intervene in a conflict between the utilities and the Association of Wind Turbine Owners. At the time, it surprised most people that the government followed the advice of the wind turbine owners, fixing the wind power tariff at 85 percent of normal residential electricity prices. In 2000, the fixed wind power tariff was abandoned as a result of electricity liberalization. Today, wind electricity is sold on the open electricity market, but wind turbine owners still receive an additional payment from the government based on when they were connected to the grid and the number of kilowatt hours supplied to the grid.

A high degree of local support for wind power is one of the characteristics of wind power development in Denmark. Although there is a National Society of Windmill Neighbors resisting the erection of land-based wind turbines and arguing that the support of the Danish wind industry is bad for the economy, this type of resistance is not widespread. In addition to the high degree of environmental consciousness in Denmark, wind power receives widespread support because of ownership structures that empower individuals and communities. As of 2001, when compulsory registration of ownership was discontinued, more than half of the installed wind capacity was owned by private individuals. Wind turbine cooperatives owned about 20 percent, while the remaining 10–15 percent was controlled by the utilities. The Danish government has tried to restrict ownership to people living close to their own wind turbine, based on the idea that wind turbines should benefit the local communities where the wind turbines are erected, and not local or foreign investors.

The ability of a traditional energy source such as wind power, which has been used to produce local power for many centuries, to find its way into the modern electric utility regime based on large-scale central power production and a widely dispersed grid of power consumers, is surprising. The consequences for the grid are equally unexpected.

We maintain that the increasing penetration of wind power into the utility regime has depended on, and will depend on, three types of innovation:

- Technical innovations enabling more efficient transformation of wind power into electricity, the gradual scaling-up of wind turbine designs, and the management of decentralized and unstable sources of energy.

- Organizational innovations facilitating the public support of wind power and the continuing adjustment between new industrial and organizational forces on the one hand, and existing technological systems on the other.

- Market innovations that make it possible to assess the real price of wind electricity.

As a result of such innovations, wind power has become a hybrid energy source that integrates traditional and modern features. It is based on a traditional mode of energy conversion that uses rotating blades turned by the wind, and it continues to feature traditional characteristics like decentralized energy production and distributed ownership. At the same time, today's wind turbine technology has very little in common with the windmills of previous centuries. It is fully adapted to a highly complex electric utility regime, it responds to technical and economic system needs, and it contributes to system momentum, for example by rapid scaling-up of turbine power that exploits economies of scale.

At the same time, the electric utility regime has been subject to hybridization. In the late 1960s, the Danish electric power system depended more or less exclusively on imported fossil fuels, and the dominant organizational structure was the medium-scale, consumer-owned utility company. The 1970s energy crises, and to some extent what historian of technology Richard F. Hirsh has called the technological stasis in the development of steam power plants, provided the incentive to experiment with renewable energy technologies. For a number of reasons, and with the mediation of many different actors, wind power in Denmark proved to be a viable addition to the power system. Not only wind technology had to be adapted. The electric power system had to be adjusted to accommodate small-scale, decentralized power production units with variable power output, mostly in private ownership. The inclusion of wind power in the Danish electric utility regime did not radically transform the system, nor did it leave the system unchanged. Today, and in the foreseeable future, wind power and the electric utility regime merge to form hybrid energy systems.

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José R. Martí

The AC Electrical Grid: Transitions into the Twenty-First Century

The electric power system infrastructure is at a crossroads in the twenty-first century. After one hundred years of development of Tesla and Westinghouse's synchronous alternating current (AC) generation and transportation systems, the grid has evolved into a complex system-of-systems upon which a nation's critical infrastructures heavily rely. Canada, for example, identifies 10 critical infrastructures: energy, communications, food, health, manufacturing, finance, water, transportation, safety, and government. Disruptions in this system, such as power blackouts, can have extensive and highly negative consequences.

Despite the complexity of the electrical grid, electricity has become ubiquitous to the point that, in modern societies, it is taken for granted. Prices have been reasonable, availability has not been a concern for the general population, service continuity has been excellent despite behind-the-scenes wars, and environmental effects have been largely ignored. Monopolistic ownership and technical prowess have made the grid "invisible" to the user.

In the twenty-first century this will be different. It will no longer be possible to ignore cost and environmental impact, and the continued availability of affordable electricity will no longer be a given. The twenty-first century will be defined by a higher level of public awareness, and the grid will become "one more concern." The traditional paternalistic grid will be broken down not by regulation, but by the need to use local energy resources, such as solar, wind, and other renewable resources. Distributed ownership of power generators, along with user awareness of consumption, will become the norm.

In this essay, then, I will discuss the history of the AC electrical grid, before examining possible changes to this system in the twenty-first century. I hope to show that, alongside and as a result of the changes mentioned above, Direct Current (DC) power generation and distribution can make a comeback, leading to a safer, more reliable, and more efficient electrical system.

Before we address the future, though, we should consider the past. How has the AC electrical grid come to occupy such a dominant position in our societies?

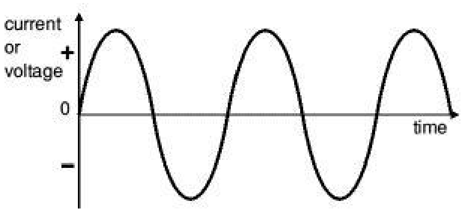

Figure 1: Alternating current (AC), where voltage, or current, is a sinusoidal value where waves oscillate.

Two characteristics of the AC grid of the twentieth century have been responsible for its rise and its ills. The alternating nature of AC waves makes it easy to change voltage levels using relatively inexpensive coupled-coil power transformers: this is the grid's major strength. Generating AC voltages using synchronous generators is straightforward. Doing so, however, leads to the requirement of synchronicity, which is the grid's major weakness.

To understand these two concepts, we need to understand the behavior of alternating current. In AC systems, voltages and currents are a sinusoidal wave (fig. 1), oscillating in North America at 60 Hertz (Hz) and in Europe at 50 Hz. In an AC grid, many oscillating waves must move synchronously in order for the grid to transmit electricity.

This oscillating nature of AC voltages and currents allows for the voltage levels to be changed; this in turn makes it easy to transport electricity over long distances from large generation centers to the consumer's location. Since power equals voltage times current, transforming the voltage to a high value decreases the value of the current and the size of the wire required to transport the electrical energy. In high-voltage systems, electrical power can therefore be transmitted efficiently over long distances using relatively thin wires. (This is not possible with DC electricity since coupled-coil transformers cannot change the DC voltage level.) After the energy is transmitted, the electricity can be brought down to low voltages for safe industrial and consumer use.

Nicola Tesla's concept of synchronous AC generators and William Stanley's power transformers were the disruptive technologies of the nineteenth century that boosted the development of long-distance electric power generation and distribution systems. The synchronous AC electrical system, with its capacity to transmit power over hundreds of kilometers, dominated Thomas Edison's DC electrical systems, which could transmit power over only a few kilometers.

While synchronous oscillation proved hugely beneficial, though, it meant that the electrical system was inherently fragile. In an AC electrical grid, the rotor angles of all major power generators must turn at the same speed. When, due to some disturbance, one AC generator speeds up or slows down too much with respect to the others, the associated part of the grid is cut off. Unless immediate remedial action is taken, the entire system may collapse.

Two factors hastened the expansion of the AC power grid throughout the twentieth century: economies of scale and a high demand for electricity.

Economies of scale allowed for the construction of large central generating stations. These generating stations yielded a high efficiency of transmission, higher profits for utility companies, and lower costs for consumers. By the 1930s, it had become economically advantageous to interconnect multiple generating plants over wide geographical regions to reduce the transmission requirements, share spinning reserves (the extra generating capacity that comes from increasing the power output of generators that are already connected to the power system), and improve system reliability. Today, the North American electrical grid is the largest in the world, with a capacity of about 830 Gigawatts (GW) and total assets of $1 trillion. The next largest grids are those of Europe (781 GW), China (391 GW), Japan (243 GW), Russia (216 GW), and India (131 GW). The North American grid comprises three major extensive interconnected areas: the Eastern, Western, and Texas systems. The Eastern and Western systems include Eastern and Western Canada, while the Western grid also includes the northern part of Mexico. Interconnected power grids constitute some of the most complex systems ever created. A generator in Alberta, for example, has to run in sync with a motor in Arizona.

The expansion of the electric grid in the twentieth century was accompanied by a steady increase in consumer demand for electricity. In 1905 only five percent of urban homes in the United States had electric lighting; by 1930 that number had increased to more than 90 percent (Nye, 2010). Abundant and affordable electricity shaped consumers' habits and expectations, with consumers expecting new products and improvements over older ones. From 1900 to 1970, consumers' demand for electricity in industrialized countries doubled approximately every 10 years. Electricity improved the quality of life for the population with its conveniences, such as electric lighting, heating, refrigeration, air conditioning, household appliances, and electronic devices. Despite its achievements, the electric power grid has been showing significant signs of aging for the last decade and may be approaching its limit in meeting the electricity needs of the twenty-first century. Heavy investments by utility companies have focused on supplying consumers' energy demands with little incentive to upgrade the grid's infrastructure. The result is an aging electric grid that is being operated closer to its limits and is increasingly unstable. One consequence has been the rising number of large-scale blackouts. As indicated, due to the synchronous nature of the grid, problems that develop in one region spread in a cascading manner to the rest of the interconnected grid unless the area that has the problem is isolated.

The 11 most severe, large-scale blackouts in history have occurred since 1998, with the most recent one in India in July 2012. The Indian blackout was the largest in history and affected over 620 million people for two days. In North America, the Northeast Blackout of 2003 lasted four days and affected 50 million people in the Northeastern and Midwestern United States and Ontario, Canada, with economic losses of about $6 billion.

Due to the strong dependence of critical national infrastructures on the power grid, when a blackout occurs, the other infrastructures can shut down within seconds. The impact of a major blackout of even a few hours is enormous and can result in disruptions in communication and transportation systems, heating, water supply, and other utilities.

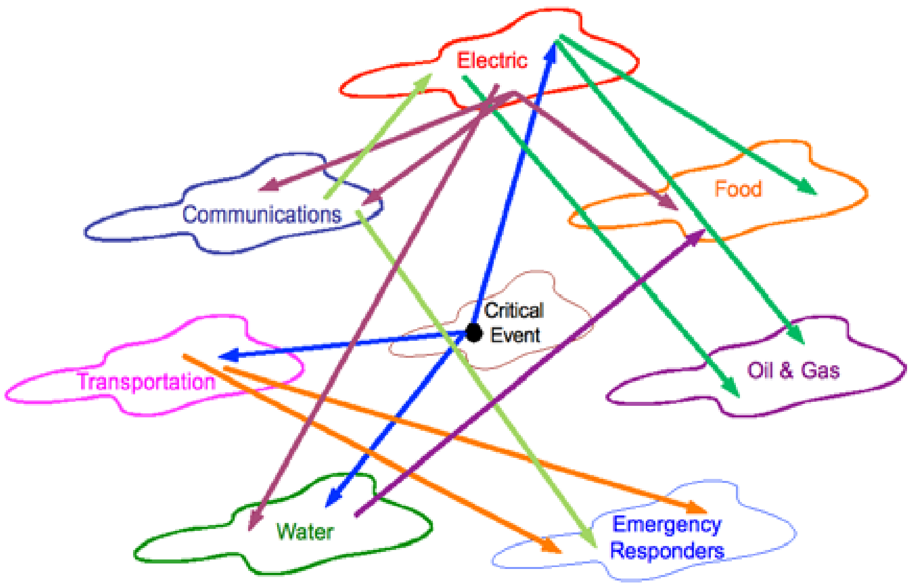

Figure 2: Critical Infrastructure Interdependencies

These, in turn, can affect emergency services and hospitals. The disruptive effects can ripple into everyday necessities, such as obtaining cash from ATMs or financial institutions and food supplies from supermarkets, to personal and social services, such as telephones and internet services. Where the interconnected power grid crosses national borders, more than one nation is affected. Since power supply systems are potential military targets, such as from terrorist groups, the power supply industry itself is a critical infrastructure.

The power industry has undergone two major changes in the past decades that increased the grid's risk of blackouts: deregulation and the emergence of independent power producers, including those generating renewable energy.

The deregulation of the electric power industry, in North America and most other industrialized countries, has contributed to an increase in power blackouts due to the lack of incentives to maintain a robust grid. Prior to deregulation, the power supply industry operated as a vertically-integrated monopoly that was responsible for all operations of the grid. Deregulation resulted in the separation of the system's tasks of generation, transmission, and distribution into individual economic entities, and, in the process, introduced new participants, such as independent power providers (IPPs), transmission companies (TRANSCOs), retailers, integrated energy companies (combining IPPs and retailers), and independent system operators (ISOs). After deregulation, there were few incentives to invest in a reliable and robust system, despite the large increase in electricity demand. For example, between 1990 and 2004 in the US, transmission transactions increased 400 percent, but the high-voltage transmission system expanded by only 2.8 percent. When utility companies stopped being monopolies after deregulation, independent system operators (ISOs) were given the task of overseeing the synchronized operation of the grid as a whole system. However, these ISOs could not directly control the operation of the internal systems of the individual companies.

The US Energy Information Administration projects a 53 percent increase in the global demand for energy between 2008 and 2035, accompanied by a projected CO_2 emissions increase of 35 percent. Electricity will be in very high demand in the future, particularly since information and communications technologies are highly dependent on it, and new technologies aimed at reducing fossil fuel consumption, such as electric vehicles, are based on electrical energy.

Unless the growth of alternative sources (solar, wind, biomass, etc.) is accelerated, traditional sources such as coal, natural gas, hydro, and nuclear power will remain the main drivers for large electricity generating plants in the next half-century, at least to maintain the existing base load. Coal and natural gas produce high amounts of greenhouse gas (GHG) emissions, of the order of 500 to 1,000 grams poer kilowatt hour (kWh) of electricity produced. This level of GHG emissions will continue to contribute significantly to extreme climate changes, which, in turn, threaten ecology and place human welfare at risk. Hydro energy is clean but can have a considerable impact on the surrounding eco-system. Nuclear energy does not contribute to GHG emissions, but presents serious safety concerns, such as the problem of nuclear waste.

Renewable energy sources, such as solar, wind, biomass, tidal, and geothermal, constitute valid alternatives to effectively reduce GHG emissions as well as political and economic dependence on fossil fuel supplies. However, the intermittence of renewable energy sources like wind or solar makes the supply less reliable.

Huge investments in power supply infrastructure will be needed in the near future to create smarter grids that can handle the technical challenges of volatile renewable energy sources. The technical problem of interfacing with the AC grid can be solved with power electronics, and the problem of dispatching electricity in the right quantities on demand can be solved with storage strategies. However, the existing aging grid is reaching its limits very rapidly, and these efforts may be insufficient.

The existing paradigm, based on a mostly AC system, consists of large generating stations located hundreds of kilometers away from the many small loads that are served. The new paradigm, based on distributed renewable energy sources, will consist of many small generators connected to the main grid through DC to AC power electronic interfaces.

Since about 80 percent of home loads can be more efficiently fed with direct current, DC grids will emerge that will connect local DC renewable generation to load districts. Considerable energy savings can be achieved by distributing DC current to homes. For example, electronic devices, such as computers, televisions, and mobile phones use DC for their internal operation. Currently, a power supply that converts AC to DC is used inside personal computers, with an energy loss in the conversion process of 20–40 percent. These losses would be avoided with DC distribution systems, in addition to the savings in the cost of providing AC to DC interfaces for each of the DC devices.

After a century of AC-dominated power generation and transmission, pioneered by Tesla and Westinghouse, DC power generation and distribution, pioneered by Edison, will make a comeback. Since local small generation facilities will have multiple owners, the new energy self-sufficiency paradigm will result in a more democratic energy infrastructure. During this much-needed move towards renewable energy sources, the existing AC grid will continue to play an important role in facilitating the transition towards new technologies. Where the main grid is accessible, it will also be used for storage and backup functions.

Abundant energy is not on the decline. The sun, wind, tides, waves, and heat in the interior of the earth will last for as long as the planet lasts. In 2010, the world population was 7 billion. Despite a century of investment in electric power systems, there are still 1.6 billion people without access to electricity. Rural electrification in scarcely populated towns is very expensive, with centralized generation great distances away. Local, autonomous DC systems that utilize local renewable energy sources can enable the growth of such rural communities.

In terms of sustainable economic development, the new paradigm of locally generated renewable energy can be the first step towards creating prosperous communities that use locally available energy resources to create local economies. Perhaps this change of paradigm in the way electricity is produced—small-scale and locally versus large-scale and centrally—can also lead to a shift from large concentrated population centers with highly wasteful and inefficient use of resources, to self-sufficient local communities that integrate energy and other resources with ecological, economic, and human variables, as well as to the sustainability of the planet and improved quality of life.

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Ben Gales

A Dutch Revolution: Natural Gas in the Netherlands

The classical story of the gas revolution in the Netherlands is a simple one. In 1959, explorers unexpectedly struck huge quantities of natural gas in the north of the country. Policy-makers were flabbergasted. Still, the Shell and Esso corporations, which were partners in exploration, and the Ministry of Economic Affairs, seconded by the Dutch State Mines as an expert in energy matters, worked out the "Master Plan," as it was soon labeled. That plan sketched what a gas society had to look like. Once agreed upon, the plan was implemented rigorously. A national network of pipelines was constructed and virtually all households were connected. The planned and swift adaptation of cooking ranges in kitchens to the new gas was one symbol of this top-down revolution. A second one consisted of debris: the piles of appliances removed from private homes. The US intervention in the "Master Plan" was the dramatic element in the story. Had it not been for Esso and its experience with natural gas in the United States, the Dutch would never have considered using natural gas for the comfort of its citizens. The Dutch were focused upon industry and, if not converted by US evangelists, would have given priority to industrial use of gas.

That story is not subtle, to say the least. The discussion about natural gas started immediately after World War II, though the topic was a very small part of the larger debate about the optimal institutional design of the gas industry. Should the supply of the fuel be organized like the electric industry or remain a local public utility? Frequently, suspicions arose that this debate slowed down exploration; that finding gas was not a priority for Shell, which had a monopoly but collaborated internationally with Esso. The preference for industrial use and the neglect of individual households are also themes that were addressed regularly from the 1940s onwards. Finally, the stress upon not knowing in this story is odd. Shell was a company operating worldwide and exploitation of natural gas deposits had been a rapidly increasing business in colonial Indonesia, Shell's birthplace. Furthermore, policy makers and other Dutch citizens not employed by Shell were aware of what had happened in the United States and France.

The gas revolution was revolutionary due to arrested development within the Netherlands. To illustrate the domestic roots of revolutionary change, I will focus on gas use in households. For most of the twentieth century, governments tried to guide the evolution of welfare. Dutch élites were particularly ambitious. Choices of households were managed: people should not enjoy maximal warmth at home, but socially expedient warmth. Change could be slowed down and could be arrested temporarily. In this model, shocks might be necessary to hold back change.

The traditional narrative about the history of energy in Dutch households runs approximately as follows: In 1900 the Netherlands was a kingdom of slums and blind alleys until suddenly a vanguard of reformers successfully changed the course of events. Better houses became the norm and life inside was more comfortable. This story is misleading, however. Misery, stench, and cold are good for making a book a prize winner some hundred years later, but today's myopia ignores to what extent a house with mainly cold rooms was a modern phenomenon.

Surveys of international organizations show that, by 1960, Dutch houses had many rooms. There were both more rooms and more occupants than anywhere else in Western Europe. One might consider this a positive feature. However, it was striking how rare showers or baths were, given the near universal provision of piped water. Heating that water was apparently a problem. Furthermore, the overall size of the dwellings was small despite the number of the rooms. Homes were smaller than they could have been, if we take into consideration that the Dutch were wealthy by international standards. The major factor in keeping size down was the "luxury" problem of heated space.

We can identify two phases of energy development before the natural gas revolution of 1959: a progressive nineteenth century, followed by stagnation in the twentieth century. Progress in space heating in the Netherlands was substantial before 1900 but came to a halt thereafter. Direct measurements of temperature inside the homes are scarce and measurements providing information about temperatures in all rooms are even scarcer. We have to rely on indirect indicators of progress: the chimneys of houses, the stoves inside the houses, or the number of openings for firesides and hearths in the rooms.

During the nineteenth century, the number of chimneys increased more rapidly than national income, but towards the end of the century the growth rate declined substantially below the earlier level. Tax-systems changed around 1900 and therefore complicate a comparison of the twentieth with the nineteenth century.

Household consumption of town gas, generated from burning coal, might help us fill that gap in the data. The household use of town gas increased by more than seven percent per capita each year between 1880 and 1910. Annual growth in town gas usage was only 0.5 percent between 1910 and 1950. There was substantial increase in consumption during the 1950s, but this only brought growth back to one percent annually. Growth flattens when industries mature and gasworks were an established industry, but something else is more important in the present context. Consumption of town gas is not a good indicator for heating. It could heat rooms, but town gas was not supposed to be used for that purpose. Up to the late 1950s, the norm was to burn gas for cooking or for boiling water. Authorities always worried that (poor) households might use kitchen ranges to heat their homes. Complex modeling revealed in 1950 that illicit use of town gas for heating was rare, even in undisciplined Amsterdam.

The size of dwellings is the best sign of a pattern of arrested progress during the twentieth century, though it is another indirect indicator that is difficult to interpret. Up to the First World War, the standard house became progressively roomier. The average size of houses probably started to decline by the end of World War I. That was certainly the case after 1945. The average size of a standard home began to increase once again just before 1960.

The evolution of house size suggests that housing conditions were Spartan. That was true for heating, which I consider an indicator of the quality of these conditions. People in the twentieth century followed the older norm that a decent house required only one heating point (or perhaps one-and-a-half, as cooking appliances complicate the issue). Access to chimneys suggests that there was not much positive change during the twentieth century. Of the houses built before 1914, 71 percent had two or more openings for stoves. This figure rose to 75 percent for those constructed during the interwar years, but declined to 51 percent after 1945. Over time fewer and fewer houses had an opening for heating the kitchen, a very sensitive issue and one of the most prominent desires of women. Furthermore, the infrastructure was often unsuitable. In many kitchens with an opening, there simply was not enough space to install a stove.

The diffusion of central heating was delayed in the Netherlands. Though an old technology, it first became an option, albeit a costly one, around World War I. Offices acquired central heating during the interwar years. Around 1960, experts stated that central heating was "normal" in Belgium, yet only five percent of Dutch houses had central heating. The Belgian censuses give a more nuanced view, but there was undeniably a central-heating issue. This issue was very much indicative of the mind-set at the time. The introduction of "social central heating" in the Netherlands initially meant that just one element was installed in a flat, in accordance with the existing norm. It became known as "social" heating around World War II, when the architect, a social democrat, designed the radiator a bit larger than was required, so that other rooms could be heated indirectly. Journalists were convinced that central heating was forbidden until well after 1960. There never was such a law, but there were arrangements and expectations that obstructed the diffusion of central heating.

After 1945, the Dutch state and a group of employers and trade-union officials collaborated closely to manage economic life in detail, in the belief that a managed wage policy was imperative. The Dutch also lived with a "managed stove policy." This was part of the social housing policy, which originated at the beginning of the century. Decent housing was a social right, but it had to be simple housing. The "managed stove policy," because it was above all a set of norms, was not intimately linked to state intervention. Norms were still adhered to when the state withdrew. Austerity was also part of a wider ideology to which architects and financiers adhered, and frugal use of scarce energy was received wisdom. After 1945, regulation became intense. At all levels, choice was severely curtailed. At the same time, existing habits and views were strengthened by external phenomena, such as the widespread feeling in the 1950s that an energy crisis was imminent. This explains why coldness remained the norm for a long time and why cold space was not contentious for such a long time.

Before 1940, the differences between other countries in Europe and the Netherlands were not that great. A major gap developed after 1945, because heating was part of the housing policy and housing was an essential ingredient of the managed wage policy. Rents were kept low—and energy became relatively expensive—in order to stimulate low wages and boost industrialization. Experts and policy makers were aware that it was easier to cement norms, for example by normalizing houses and their infrastructure, than to influence behavior directly.

The controlled wage policy was gradually undermined from the bottom up. This, however, did not happen with the "managed stove policy." Surveys of public opinion show that people resented the cold kitchen; the lack of space was an issue too. However, houses mainly consisting of cold space were not perceived as a major nuisance. There was an interesting split between public conviction and private experience. The post-war housing shortage was the most sensitive issue in the public debate. Gradually it came to stand for a miserable quality of life in general. For the average citizen, however, the housing shortage became more of a political priority and less of a personal experience. Cold rooms were an acceptable personal experience. Bikes, stereos, and cars were more sought-after objects of consumption than warmth. Of course, there was some friction between the public at large and policy makers. Experts labeled particular lifestyles as good for the common family. The objects of their expert opinions had other views on how they wanted to live. Families in flats started to change their living rooms into parental bedrooms, to the dismay of planners, who believed that living rooms should not be repurposed. Those changes, though, were minor infringements and were nothing compared to the family-living-in-the-kitchen problem (also seen as the problem of the family not using the available living room). This issue became popular among housing experts during the early twentieth century. It remained hotly debated until 1960, though the problem was being gradually solved. Since the First World War, new kitchens were usually made small, to prevent families from using them as a social space. An unforeseen consequence of this policy was that housewives worked in a cold environment.

The "Master Plan" conceived after the landmark findings at Slochteren put households center stage. Initially, Dutch officials were predisposed to earmark natural gas for use in new chemical plants or in energy-intensive hothouses, where tomatoes and flowers for export would grow. Esso, on the other hand, stressed the importance of households. Their view prevailed, because US consumerism fed into a debate about the negative aspects of Dutch heating culture and of Dutch accommodation policies.

Housing professionals had been discussing and researching these issues for some time and their reputation was on the rise. Some specialists questioned the priorities that had emerged after the Second World War. They identified the willingness to adapt to conditions in homes as a major barrier to overdue change. Others stressed that newly built accommodation would have no future value if the prevalent designs did not change. The value of a heated toilet for public health emerged as one of the "hot" issues, which, unsurprisingly, was easily ridiculed by outsiders. In the context of this article, the technocratic attitude is more important than the plans that were concocted. The housing professionals did not accept that there was a problem because sociological surveys showed an amazingly content population. The right course of action, then, was not to be determined by popular attitudes.

The discovery of gas in 1959 had revolutionary consequences. The share of natural gas in total energy consumption expanded more rapidly than expected. In the early 1960s, a 50 percent share was projected for 1975 but 70 percent was realized. The estimates for central heating were closer to the reality: a share in space heating of 35 percent in 1975 compared to estimates of 30 percent. The revolution started in the kitchen. Natural gas was the easiest substitute for town gas and, within the homes, town gas was primarily used for cooking and the provision of hot water. It is not surprising that the heating of space lagged, particularly given that it required extra investment. Installing central heating involved more than replacing an old hearth with a new type. Furthermore, most houses were old and were not amenable to new, "big" systems.

Nonetheless, there was a revolutionary change in the heating of homes—the truly revolutionary aspect of the Slochteren discovery. Central heating was integrated most rapidly into new social housing. The diffusion here was from more to less regulated sectors of the housing sector. The adoption rate in less-regulated subsidized housing outstripped the rate in non-subsidized new housing. The benefits of gas heating thus trickled upwards. This was the best indication that policy might work and that new conditions could be engineered.

Society changed even though most people did not see many reasons to change. And many distrusted the changes. The contrast between public and private frames of mind was an interesting aspect of public opinion. Polls unearthed a "class struggle sentiment" among ordinary people well before the riot of the building workers in Amsterdam of 1966, usually seen as the beginning of the turbulent 1960s. Many Dutch were convinced that De Gaulle and the French would profit more from Dutch gas than the common man in their own country. They were not wrong insofar as exports were an important part of the "Master Plan." The nationality of the consumers was, however, of only secondary importance: Large consumers' receiving the best deals fed the sentiment of distrust. The abundance of Dutch gas and expectations of a nuclear future stimulated exports and, more generally, encouraged the producers and the state to plan a lavish use of gas while it could still fetch a good price. The "Master Plan" had opted for a gas price linked to other energy carriers;

this made gas economic, but price discrimination actively invited consumers to use energy in large quantities. The resource needed to last only a short while.

The public uneasiness of the man in the street did not match his private sentiment. Most people were satisfied with the heating they had, whatever energy carrier was used and whatever the heating system was. People with coal hearths were not eager to change to gas in the middle of the gas revolution, as the price incentive for small users was not strong. The costs of the changes in the houses outweighed the energy savings. Furthermore, the price incentive would work only if behavior at home truly changed.

Private decisions were responsible for the switch to gas. The share of centrally heated homes in the total housing stock (thus in both old and new homes) only passed the 50 percent mark in 1980. Rising income and a shift towards durable consumption were the major factors. During the 1970s, consumption as a percentage of national income increased in most western European societies and in the Netherlands more than elsewhere. In the total housing stock, central heating trickled downwards. Richer households were the first to improve the quality of existing houses. The shift to natural gas was revolutionary but it took place mostly in state-controlled sectors like social housing. Revolutionary changes were, in fact, an aspect of control.

The changes were important, mainly because they made the Netherlands similar to other countries. The market share of central heating in the Netherlands in the mid-1970s had been reached in Switzerland and Denmark in the mid-1950s. Comparative data show that per capita household consumption of energy for heating went up considerably from the mid-1960s and continued to rise during the 1970s, in contrast to countries such as Germany. The position of the Netherlands changed from a relatively low to a relatively high level of household energy consumption. The insulation campaigns that emerged after the energy crises of the 1970s provide us with another perspective on Dutch revolutions. If the Gas Revolution was a shock that increased consumption, then insulation of houses was equally "revolutionary" in decreasing energy use from the late 1970s onwards. The drop was as remarkable as the previous increase. One should acknowledge, though, that the switch came a bit late.

What was revolutionary about the introduction of both natural gas and better insulation? These changes were oriented by government policy and, with respect to houses, sought to design a lifestyle. The Dutch preference for compromise and collective innovation led to markedly uneven processes: Dutch revolutions. Inertia and slow change occasionally end in sudden transformation.

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Matthew Evenden

World War as a Factor in Energy Transitions: The Case of Canadian Hydroelectricity

Energy transitions generally occur over long time periods in geographically uneven patterns. Multiple drivers lie in the background and diverse consequences in the foreground. Although the word transition suggests a neat from-to story, it is best modified with adjectives like jagged and episodic to provide proper perspective.

Of the many factors that shaped energy transitions in the twentieth century, the World Wars are rarely considered. Yet the dramatic effects of war mobilization on energy systems and the restructuring of supply lines through new geographies of military action and alliance suggest the importance of war as an external shock or crisis with the power to reshape the political economy of energy systems profoundly. Hydroelectricity in Canada during World War II provides one example of this process.

In the early twentieth century, Canada became one of the most active hydro developers in the world. Well-endowed with swift flowing rivers and uneven topography, with good access to capital markets and technology transfers, the country hosted a boom in dam building and transmission-line construction. Despite slow growth during the 1930s, by 1939 hydroelectricity accounted for 98 percent of all electric power generated. When measured per capita, Canada's generating capacity was second in output only to the United States. Within the country, the vast majority of this hydropower was concentrated in the central provinces of Québec and Ontario, and in a second tier of western development in Manitoba and British Columbia.

Hydroelectricity provided a ready energy resource for Canada at the outbreak of the conflict in 1939, but demand quickly outstripped capacity and led to a six-year development drive. By 1945, hydroelectric generating capacity had expanded over pre-war figures by 40 percent. New dams had been raised, transmission lines built, and diversions completed to meet the increased needs of wartime production. Most of the activity occurred in Québec and Ontario, though new dams were also built in Alberta and British Columbia. War did not initiate a transition to hydroelectricity, but it certainly consolidated it and propelled it further.

States respond to wars in part by redesigning institutions and constitutional arrangements. Although the division of powers in Canadian federalism makes the regulation of hydroelectricity primarily a provincial matter, during the Second World War the federal government assumed authority over the power supply through its Department of Munitions and Supplies. Herbert Symington, a Montreal lawyer with expertise in power matters, was appointed as the power controller with authority to regulate power in the interests of Canada's wartime strategy. Although Symington sought to negotiate with provincial governments and corporate interests, there is no doubt that this novel centralization of authority facilitated a rapid shift towards development in targeted regions linked to war production. Barriers to development were frequently overcome by Symington's intervention, delivered over the phone from his corporate office in Montreal. Wartime control entailed a shift from pre-war provincial regulatory asymmetry to wartime centralization and focused national strategy.

Power control policy developed around several principal considerations. First, available power and plausible sites of expansion were located in the central provinces, as were the majority of industries on military contracts. The focus of power control policy thus had to be Ontario and Québec; other regions were dealt with on a case-by-case basis as problems arose. Second, Ontario faced a looming crisis because of sharply rising electricity demands owing to war production. Third, the importance of the air war, and the shortage of aluminum in the UK and the US, placed political pressure on Canada and the Aluminum Company of Canada (Alcan) to increase output massively, a task that would require diverting electricity from other industrial centers in southern Québec and expanding hydroelectric facilities, particularly within the Saguenay basin. These factors led Symington to prioritize hydro for aluminum in Quebec while seeking to shore up Ontario's power supply by increasing water diversions in the Great Lakes and imposing demand control power conservation policies. Generating capacity soared as a result, but wartime industrial demand absorbed it just as rapidly. Until 1945, conservation policies limited commercial and domestic energy consumption and shut down some high-use manufacturing facilities, particularly pulp and paper mills. By the end of the war, the calls for conservation had worn thin, and consumers and manufacturers looked forward to having cheaply available electricity in the future.

Increasing Canada's hydro-generating capacity was one significant shift in these years, but the changes were also political, institutional, and social. By 1944, the federal state had begun to unwind its controls, and provinces had reassumed their jurisdictional primacy. The model of wartime control and the capacity of state planning helped to influence the creation of new provincial hydro agencies to intervene and drive development with a view to extending electrification across society. In Québec, the provincial government nationalized the Montreal Light, Heat and Power Company as Hydro-Québec, and in British Columbia the province created a new commission to oversee hydro expansion outside of urban regions. Beyond wartime dam construction, therefore, there was also a reorientation of the role of the state in hydroelectric development across Canada that set the stage for a new phase of post-war expansion.

Although the war drove hydro development in Canada, did it contribute to an energy transition? With such a short time frame in focus, the answer must be qualified. Although the dominance of hydroelectricity in Canada was hugely reinforced and advanced because of wartime development, this applied only to core hydro regions. Outside of central Canada, hydro expansion stalled. If regions were not significant sites of wartime production, they held no strategic priority for hydro development. Projects were therefore delayed and cancelled. But the war did restructure the country's economic geography in significant ways, building, for example, a massive aluminum smelting business that accounted for roughly 90 percent of British and commonwealth wartime supply and that relied on cheap hydroelectricity to operate effectively. In this fashion, the war propelled economic activity that could benefit from and build the foundations for a new hydroelectric regime. This was not, however, a simple or linear transition. As aluminum smelters drove up their demands for hydro, pulp and paper mills purchased coal boilers to offset conservation controls. As electric systems interconnected and built larger and larger regional systems, consumers reverted to wood fuel and sawdust to meet the frequent calls to modify their electricity demands. Behind a general story of growth, expansion, and transition, therefore, lay jagged subplots.

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Over the last two centuries, human beings have come to rely on ever-increasing quantities of energy to fuel their rising numbers and improving standards of living. On the one hand, this growing demand has led to marked transitions in patterns of energy production and consumption; on the other hand, the simplest forms of energy production remain essential to our societies. The coexistence of varied energy carriers and the resurgence, in a few cases, of older forms, have many explanations. In this volume of *RCC Perspectives,* scholars from around the world consider how our relationship to energy has changed, why it has changed, and how it may change in the years to come.

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