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Accounting for Economic Growth in 20th Century Japan: From Hindsight to Foresight

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2008/77/EPS/TOM/ISIC

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Abstract

For much of the last century Japan experienced one of the fastest rates of economic growth worldwide. In this paper we argue that one of the main drivers of this growth was the successful introduction of new technologies which have significantly improved the efficiency with which energy has been converted into useful ‘energy services’ delivered to the economy. We describe an economy wide fuel exergy database which illustrates the transition in the structure of Japan’s energy supply, dominant energy conversion technologies and principal end-uses over the past century. We present a theory of growth that compliments the descriptive Rostow model of ‘staged development’ but extends it quantitatively enabling us to reproduce historical growth trends through consideration of the amount and way in which energy is used by society. From this complimentary perspective we summarise the role of resource scarcity as a major driver of technological progress in energy conversion technologies. We highlight the importance of dynamic and co-evolving government intervention to promote the development of increasingly resource productive and efficient systems of production and consumption.

Keywords: exergy, energy, efficiency, energy policy, economic growth, development theory.

1. Introduction

In an influential book, first published in 1960, W. W. Rostow presented his `stage' theory of economic development {{8612 Rostow,W.W. 1960; }}. He postulated five distinct stages of development, beginning with `traditional society', followed by the achievement of preconditions, then `take-off', `maturity' and finally `high mass consumption'. Preconditions comprise socio-political changes, such as freeing of serfs, elimination of feudal structures, rapid urbanization, and the growth of a commercial middle class. Rostow assigned great importance to the building of railways as a precondition for take-off, and acquisition of modern technologies and systems of production and consumption for post-war recovery. In a more recent publication Rostow identifies a stagnating population as the major challenge for Japan to address as it enters a fourth phase of development {{11346 Rostow,W.W. 2000; }}. In this paper we consider the economic development of Japan from the complimentary perspective of resource scarcity and technological progress – in particular energy supply, energy use, the development and deployment of increasingly efficient energy conversion technologies. From this perspective we identify a quite different set of challenges facing the political economy of Japan today and in the future.

We observe that Japan's transition from a largely feudal society to a highly industrialized urban economy has been accompanied by dramatic shifts in the quantity of energy consumed, the way in which energy is supplied and used and importantly the efficiency of use. We argue that Japan has been very successful in export led markets despite a scarcity of domestic natural resources because of the high efficiency with which raw materials and energy are combined to make products. We suggest that a focus on efficiency has enabled Japanese industry to overcome issues of domestic resource scarcity. Also that achievement of such levels of resource use efficiency has been made possible by long term and consistent government support of technology transfer, support for and protection of 'infant' industries and subsequent investment in domestic research and development.

In previous work we have developed an energy accounting methodology to provide inputs to an economic model that treats the US economy as a materials-processing system {{113 Anonymous 2003; }}. The model seeks to capture the transition in socio-economic metabolism from an economy largely dependent on energy provided by the sun to one dependent on fossil fuels and other alternative energy sources based on advanced technologies. The past century of economic activity in the US is explained surprisingly well by means of a three-factor production function {{1067 Ayres,R.U. 2005; }}. The first two factors are labor and capital, as is conventional. The third factor is an intermediate, namely `useful work', which is the output of a second sector, but can be treated as a third factor in a one-sector model if the combination of factors is the same in both sectors. Detailed explanation and justification are provided in the cited texts, so we do not recapitulate the prior work here. Suffice to say that an economic model that also explains Japanese growth throughout this past century of fluctuating fortunes must be of considerable interest. Such a model is presented in this paper.

The remainder of this paper is organized as follows: The complicated political-economic history of Japan is worth recapitulating in the context of energy and materials consumption and industry structure. We summarize the trends in natural resource inputs from fuel and other sources organized by major commercial fuels (coal, petroleum, gas, renewables and nuclear), intermediates (town gas, electric power). The most important energy-intensive industrial sector up to 1960, iron and steel, is discussed separately. The period since 1960 is considered in two parts, the MITI-dominated high growth period (1960-1980) and the subsequent period of much slower growth and the decade of stagnation after the collapse of the Tokyo stock market and real estate market in 1989. The last section pulls these threads together and presents the results of a quantitative model of economic growth. Finally we provide a set of conclusions drawn from this analysis.

2. Economic and socio-metabolic transitions

Japan was the first, and for several decades the only, non-western country to have achieved "take-off" in Rostow's sense. Some will note that the USSR, which was essentially a collection of traditional Central Asian societies colonized and administered by Russia since the late 19th century, also went through a very rapid growth process beginning (according to Rostow) in 1890.[1] But what makes the Japanese case especially interesting is the fact that Japan is almost

1. The Russian case is rather special, because of the catastrophic loss of confidence on the part of the Tsarist government after the defeat by Japan followed within a decade by the even more catastrophic defeat by Germany in WWI. These events created the window of opportunity for the extremist Marxist-Leninists to seize the reins of power in Russia (with considerable assistance from the German government). The government of Lenin, influenced by Marxist doctrine, imposed a rigid centralization of economic decision-making, including forced collectivization of agriculture accompanied by a domestic reign of terror under Lenin's successor, Josef Stalin. Nevertheless, the economy of the USSR also grew very rapidly both before and after WWII, as measured by

uniquely lacking in natural resources (in relation to population) and, consequently, the post WWII success of Japan's export-led strategy is all the more remarkable.

Prior to 1895 industrialization in Japan was slow and economic growth was stagnant. The Sino-Japanese war (1894-1895) changed that. It stimulated investments in capital intensive industries supplying the military {{11187 Yonekura,S. 1994; }}. At the same time, export trade increased encouraged by a drop in the exchange rate. The price of exports fell 40% during this period, despite the upward trend in domestic prices. In 1880 exports had accounted for 7% of GNP, by 1914 they accounted for 14-15%, mostly textiles[2]. This growing export trade acted as a stimulus to the government which, in 1896 enacted laws encouraging shipbuilding and navigation. The construction of a merchant navy required the development of many associated firms essential to this industry, including the machinery, motor, electrical and, most important, the iron and steel industries.

The subsequent history of Japan is, to say the least, the antithesis of smooth development. During the first half of the twentieth century Japan was a colonial power, controlling Taiwan, Korea, Manchuria (Manchukuo) and after 1937 much of China. In 1941 Japan initiated a broader war – probably triggered by the US oil embargo -- by attacking the United States at Pearl Harbor and capturing much of Southeast Asia, including French, British and Dutch colonies, as well as the Philippines. After the war ended in 1945, Japan was occupied by the US until 1950 when the Korean War broke out. This accelerated Japanese reconstruction and made Japan a staging area for US military intervention in Korea and an important global ally in the conflict with the communist bloc. Bi-lateral alliances with the 'free-world' permitted opened the door for unrestricted Japanese exports to US markets, accompanied by extraordinarily free technology transfer, and triggered an unprecedented growth trajectory (**Figure 1a**).

Figure 1a. *Historical growth of output and factors of production;* Figure 1b. *Factor productivities (GDP/Factor).*

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agricultural production, industrial output and military power.

2. The major exports, product of 'traditional industries' included (in order of importance in value) raw silk, cotton, tea, coal, copper, silk fabric, ceramics and glassware.

The historical time series of output, capital, labour, energy (exergy and useful work[3]) suggest, through breaks of slope, transitions roughly corresponding to Rostows' phases. However, it is evident that superimposed on these major 'phases' are other transitions (breaks of slope) occurring most noticeably in 1970 and 1990. The Rostow model does not explain their occurrence well. But we note that these transitions - major and minor - have been accompanied by dramatic shifts in the quantity of energy (exergy) consumed, the way in which energy is supplied and used, and the efficiency of energy use. For example in 1970 we witness for the first time an increase in the output productivity of useful work and in 1990, again for the first time, a decline in exergy productivity (**Figure 1b**). These transitions seem to have been driven by trends in resource prices and availability as well as changes to the patterns of production and consumption and consequently the way in which energy and materials are processed, largely driven by technological progress, increasing domestic wealth, and shifts in global markets.

The history of total energy (exergy) inputs to the Japanese economy is shown in absolute and relative terms in **Figures 2a,b**. The most interesting feature of these graphs is the early dominance of phytomass[4] (from land-based photosynthesis), including both wood and agricultural production – harvested and unharvested – but not even taking account of the importance of fishing. Phytomass accounted for over 75% of the total exergy consumption of Japan in 1900, declining to around 45% in the late 1930s, rising to a temporary post-war peak of 60% (c.1948), and declining subsequently to the present level of about 20%. This pattern reflects the transition from a rural (and still largely feudal) society to an urban society. Japan has certainly achieved an 'age of high mass consumption'.

Other interesting features of the graph are, of course, the rise and decline of coal, which peaked in relative terms (about 40%) in about 1940, and the later importance of petroleum, which peaked (again in relative terms, at about 40%) in the mid 1970s. The rise of coal was accompanied by the development of a rail network (now all electrified), that of petroleum with the road infrastructure. The subsequent decline in dependence on imported oil is partly due to

3 Exergy is a measure of the ability of energy to perform work, defined as the maximum amount of work obtainable from a system as it reaches equilibrium with a reference environment. Exergy is what most people mean when they talk of energy. We will use energy and exergy interchangeably. Useful work can be divided into three main categories, muscle work, mechanical work, and heat. The ratio of the two defines energy (exergy) efficiency.

4 We consider only that fraction of phytomass that contributes to the provision of muscle work from human labourers and draught animals (the latter being very small in Japan). Details of all exergy estimates can be found in {{11484 Williams, Eric 2008; }}.

active intervention by the Japanese government, which has introduced many energy conservation measures, and the shift away from oil to gas for electric power generation, as well as promoting nuclear power for the same purpose. Japan has recently been a leader in promoting the use of wind power and photovoltaic power, although neither is yet significant on the national scale.

Figure 2a. "*Energy inputs by source*" and 2b. "*Energy inputs breakdown by source*".

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Clearly changes in the growth trend of total energy supply coincide, more or less, with Rostovian 'phase changes'. The first period (1900-1950) coincides with the latter half of Rostows' export led second phase; energy supply grows linearly with little change in the fuel mix. Japan was doing more of the same and achieving economies of scale. Post-1950 energy supply rises exponentially and with the acquisition of new technologies and wealth effects on the supply mix and patterns of consumption changes dramatically. Post-1990 a third phase is evident. It corresponds with the bursting of the Japanese "bubble economy" in 1989. Since then there has been a long period of stagnation (primarily due to credit contraction due to the government policy of preventing weak banks from failing) and accompanied by the slowdown in the rate of growth of energy inputs. The energy supply mix reveals a continued process of fuel substitution (oil to gas) and the development of nuclear power. In the following sections we attempt to provide meaningful interpretation of energy supply and use trends, in the light of evolving systems of production and consumption and government policy.

2.1 Managed decline: Coal

Japan, in contrast to England or the United States, was not blessed with large domestic supplies of high quality coal necessary to power an industrial revolution. Japanese coal is mostly of poor quality and supplies of coking coal for industry or anthracite for domestic purposes were insufficient. An American official during the occupation explained, "while the effort required for producing a given amount of coal is high, the cost for a given amount of heat is still higher", {{11347 Ackerman, E.A. 1953; }}. This limited the profitable expansion of Japan's coal production sector.

In the 1880's the Japanese government sold off the country's (nationalized) mines to several big firms (*zaibatsu*) such as Mitsubishi, Sumitomo and Mitsui, as a cost-cutting measure.

The new owners made only limited efforts to reduce extraction costs through mechanization. Indeed domestic coal mining activities remained at a low level of mechanization until the 1930s, while being extremely profitable because of price restrictions. The profits were not ploughed back into the mining industry, but went to finance the development and expansion of the *zaibatsu* activities into other fields. The importance of the coal industry (and by virtue government enforced price restrictions) in providing capital for investment elsewhere in the economy during the first half of the century should not be underestimated.

From the 1920s until the start of the China War in 1937, coal sales were poor, and the industry stagnated[5]. Efforts to increase productivity through mechanization stopped once the larger zaibatsu mines had captured market share. The big-coal companies, faced with a glut in supply and the possibility of falling prices (and profits), sought not to increase productivity but rather to restrain production, to ensure oligopolistic profits on domestic and colonial high-quality and special coals. From 1929 to 1932 rationalization and wage reductions were favored over capital investments to reduce production costs. A new source of labor (Koreans) further slowed the trend towards mechanization[6]. Indeed, Japan's mining industry has never competed on a level playing field with other world suppliers. The low production costs of the prewar period had been sustained through appalling labor conditions and poor practice (seeking only the best quality coals at the expense of long-term activities).

As the China war raged demand for coal increased after the long period of slack. In 1940 the coal industry was re-nationalized and the breaking of the monopoly controls resulted in increased coal production. Yet, by 1949 the coal industry was less profitable than it had been before the war. As the direct result of improved labor conditions and a 30% reduction in the numbers of hours worked per day over the period pit workers averaged only 176 hours per month (7.5 hrs per day over a 6 day week) and surface workers spent 193 hrs working each month, or 8 hrs each day for seven days. This was surprisingly low compared to equivalent workers elsewhere in the world. Consequently by 1955 labor costs had risen to 55.1% of all mining costs (from 34.3% in 1940), while labor efficiency (measured in man-hours per ton produced) had dropped to

5. In 1921 unsold coal stocks totalled 4 million tons and over 200 mines had closed due to the depression. By 1926, through rationalization, the 10 largest companies (zaibatsu mines) controlled 62% of Japan's coal reserves. This altered the pattern of coal supply. In 1922 small mines (<100,000 tons per annum) accounted for 27% of total output, large mines (>1 million tons per annum) only 6%. In 1936 this figure had grown to 27% {{4595 Hein, L.E. 1990; }}.
6. By 1945 the ratio of foreign 'slave' and contract labour to Japanese labour was 3 to 1, there being 150,000

50% of the 1935 level of 216 tons per year per miner {{4595 Hein,L.E. 1990; }}. However that decline undoubtedly was partly due to declining quality of the resource.

In 1950 coal still supplied more than 50% of Japan's total energy requirements. The government's rationalization plans of the 1950s sought to restructure a healthy domestic coal mining industry to underpin the Japanese economy. Finally Japan's coal industry underwent significant mechanization, involving considerable capital costs. Only the larger mines, producing high-quality coals, were capable of doing this. As a result, they were briefly able to maintain their control over domestic prices. Yet high prices, resource depletion, technological progress, constant industrial strife and low levels of investment by large coal operators meant that, despite windfall profits during the Korean War, Japan's efforts to modernize its coal production industry failed.

From 1960 on the focus of government induced programs turned from rationalization to `managed decline'. Efforts to reduce costs had not been successful. The additional costs of meeting higher standards of working conditions and increased extraction costs as reserves diminished in size (diminishing returns to capital, technology and energy), effectively meant that cheaper foreign imports of coal came to dominate the market. Yet, as it happens, the availability of alternative cheap fossil fuel supplies (oil and gas) meant that Japan was able to rebuild its economy at relatively low capital cost. Reliance on imported fuels came to represent an energy policy consistent with the *"production first" self-sufficiency policy* advocated by Prime Minister Nakayama Ichiro (1955).

2.2 Long term support despite an uncertain future: Iron and steel

When the American Commodore Matthew C. Perry arrived in Japan in 1867 steel production was small-scale and localized, based on the traditional Tatara technology using sand iron as a raw material and producing only a few hundred tons a year[7]. There were no blast furnaces or steel mills. The Meiji restoration saw the inauguration of the country's first state-owned iron works at Kamaishi (1881) producing 5000 tons of pig iron (compared to Great Britain's 8.3 million tons, and the US's 4.2 million tons.) This unprofitable venture was sold ten years later. Under the

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foreign miners in Japan.

7. The famous Samurai swords were, of course, steel (of extremely high quality) but made by an extremely labour-intensive method consisting of a hot forging by hammer in a charcoal flame to increase the surface area,

supervision of the Ministry of Agriculture and Commerce the first state-run iron and steel works was initiated in 1897.

The Yawata integrated iron and steel works (completed 1901) was a second attempt to ensure domestic supplies, as military tension with China increased in the 1890s. In 1905 Japan produced 125,000 tons of pig iron and 107,000 tons of crude steel. It was not until several years later (~1910) that efforts were made to recover the by-product blast furnace gases. The by-products were not considered economically useful. The inexperienced Japanese engineers feared that recovery of the gases would reduce the quality of the coke and therefore put at risk the quality of the iron/steel they manufactured. Indeed, the primary concern at Yawata in the early years was simply ensuring an adequate supply of high quality coke for the production of iron and steel. The fact that the Yawata works were government owned was initially a boon (ensuring business and support) but it was also a burden. Yawata was unable to achieve economies of scale through specialization, because the company was mandated to produce all of the country's steel requirements. Production reached 7.65 million tons in 1943. (Great Britain produced 80.6 million tons in the same year.)

The basic principle for steel producers in Japan has always been to produce as much iron and steel using as little coal as possible. The high prices of coal throughout the first half of the 20th century caused the Japanese to put much effort into increasing the yield from coke production and secondly to conserve and recycle materials and energy. Having started at the end of the 18th century at least 100 years behind the Europeans, by 1933 the Kuroda Coke Oven at the Yawata Works was almost as efficient as those in Germany. The coke ovens energy recycling system improved yields and by-product processing, reusing the gas generated in the coke oven and blast furnaces. Coal consumption per ton of steel produced fell from 3.7 kg in 1924 to 1.58 kg in 1933 {{11187 Yonekura,S. 1994; }}.

The Korean War (1950-52), and resulting shortages (and access to US markets negotiated in exchange for Japanese support for the US war effort) was a welcome boon to Japanese industry. For example, a tripling of the price of steel in 1950 stimulated capital investments, which provided the world's first ore-to-steel continuous casting plant in 1953, the Chiba Bay factory. In this way, the experiences of rationalizing the coal industry served as the basis for

followed by folding and quenching, repeated many times.

similar but more rapid and arguably more successful efforts in the iron and steel and petrochemical industries. Efforts in this direction culminated in 1962 with Japan being the first to adopt the Basic Oxygen Furnace (BOF) from Austria and the Waste Gas Cooling and Clearing System (WGCCS). Further innovations in ore preparation technologies and the use of very large blast furnaces provided the Japanese iron and steel industry with considerable competitive advantage by the late 1960s.

After 1950 Japan's share of the global market increased from 6.5% in 1960 to 28.6% in 1973. This success was attributable to several important features of the industry in the post WWII period were (1) high labor productivity (compared to US), (2) large, timely and continuous investments in leading edge technology such as the basic oxygen furnace (BOF) and continuous casting, developed outside Japan and (3) rapid capacity expansion to achieve economies of scale {{6432 Lynn,L.H. 1982; }}. These innovations, in turn, allowed still greater economies of scale.

A more complete explanation of Japan's success (with regards steelmaking) would emphasize, "highly effective raw material acquisition and logistic systems, and productivity gains which overcome rapidly rising labor wages and lowered actual unit labor cost over the 1960s"{{10453 Van Dresser Jr., J. 1972; }}. Other authors emphasize (1) protection of the domestic steel industry through exclusion of foreign importers, (2) controlling overcapacity and competitive price cutting, (3) allocating the right to increase capacity based on each company's demonstrated capacity {{11348 McGraw,T.K 1986; }}. Other contributory factors included the Iron and Steel Institute of Japan; which was effectively a technological network.

Despite underestimating the difficulties of assimilating Western technology and overestimating domestic iron ore reserves, there is strong, albeit qualitative, evidence that long term state intervention did much to support the development of this industry through protectionism during it's infancy {{11349 Elbaum,B. 2007; }}. In turn, this key industry has spawned many spillovers that helped in the development of other industrial sectors in Japan.

2.3 Rational use of liquid fuels: Petroleum

Japan has virtually no domestic petroleum production. Before the second war, petroleum accounted for only 7% of domestic energy supply, almost all of it (93%) imported. The primary source (80%) of imports up to 1941 was the US (California), and the remaining 10% came from the then Dutch East Indies Company. Petroleum usage before the war was mostly reserved for the military, with a small amount for transportation (trucks and buses) and kerosene for domestic lighting.

Up to the early 1930s', 60% of the Japanese market was served by two companies, Rising Sun (a Royal Dutch Shell affiliate) and Standard Vacuum (a merger of ESSO and Socony-Vacuum (later Mobil) operations in the Far East. The rest was divided among 30 Japanese companies. In 1934 the Japanese government passed a law forcing foreign companies to maintain a six months stockpile of crude oil, and otherwise favoring domestic firms. In 1937, on the occasion of the start of war against China, a Synthetic Oil Industry Law was passed, with the objective of supplying half of Japan's 1937 consumption from coal by 1943. (This law was obviously inspired by German developments in the field of coal liquefaction. However it was beyond Japanese capabilities at the time.) Increasing military needs for the war economy, on the one hand, together with increasing US public disapproval of the Japanese invasion of China, resulting in an embargo of US exports, on the other hand, resulted in extreme supply scarcity. Indeed, in the late 1930s the Japanese fishing fleet - source of much of Japans' food supply - was ordered to rely on wind power.

The war years essentially removed petroleum from the domestic supply, and in the last year of the war, domestic refinery capacity was destroyed. Buses in Tokyo and other cities were running on wood or charcoal. Oil imports resumed in 1948. The US occupation authorities permitted refinery reconstruction in 1949, at first only by the same western companies that had originally dominated the domestic market, plus Gulf. The Korean War and the end of the occupation opened the door to rapid expansion of domestic refinery companies.

In 1962 the Ministry of International Trade and Industry (MITI) obtained the authority to grant import permits and allocate sales, mainly to domestic firms. In the late 1960s the Japanese economy was growing at 11% per year, and oil consumption was increasing at an 18% rate. By 1972 Japanese consumption had reached 4.4 million barrels/day, an increase of 137 times the 1948 level, and oil accounted for 70% of Japanese energy consumption – compared to 7% less than a quarter century earlier.

Part of this tremendous increase in consumption was due to the spread of motor vehicles. In 1955 a mere 69,000 cars were produced in Japan. By 1968 output had increased to 4.1 million vehicles. While a significant number was exported, 85% were sold and used within Japan at the time. This resulted in a huge increase in domestic demand for gasoline. The enormous increase in car exports (mainly to the US) began later, primarily as a consequence of a sharp increase in demand for small cars after the so-called oil embargo in 1972-73. Japan was perfectly positioned to benefit from the ‘global scarcity’ having developed its domestic car industry under similar conditions[8].

2.4 Electrification

Technological progress has permitted significant evolution of the systems of production and consumption. Arguably the most important technological advance of the last century, generating many spillovers, was the widespread adoption of electrification. Japan’s first electric power utility, a coal-burning steam plant owned by Tokyo Electric Light Co., began production in 1883 {{4595 Hein,L.E. 1990; }}. Concurrently a nascent hydroelectric industry harnessing run-off river water was developing. By 1896 thirty-three electric-power companies were competing (mostly coal powered). Prices declined as a result. New thermal power plant technology was introduced, and new hydroelectric capacity was developed. Prices continued to fall. Over the 1920s high rates for electric lighting were used to subsidize lower rates for industrial uses of electricity (especially the railways), placing electricity in direct competition with coal for that market.

Figure 4. “Energy inputs to electricity generation”

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From 1935 to 1943 the Japanese government took control of electric power supplies, which were considered as munitions after 1943. During the war, electric utilities were poorly supplied with spares and replacement parts. Some transmission lines were also pulled down, and the copper was used for munitions. This caused a sharp decline in electricity consumption during the war yeasrs. Thanks to fuel shortages, hydroelectric plants had to supply all final consumer demand immediately following the end of war, in 1945. However, as demand increased power shortages

8. Similarly Brazils’ ethanol bio-fuel industry has seen rapid growth.

became common.

Thanks to its mountainous topography Japan has considerable potential for the generation of hydroelectric power. By 1950 over 50% of all electric power came from falling water. Japan began electrification and railway construction in the 1890s. As in the US, street railways and trams were early users of electric power, but thanks to the availability and low cost of hydroelectric power in most parts of the country, railway electrification was much more widespread in Japan than the US. Steam powered locomotives were phased out entirely by 1970 and unlike the US diesel fuel was never used for railways. Today the entire Japanese railway system is electrified. Electricity came to dominate household energy consumption faster than elsewhere in the World. In fact, by 1955 an estimated 98% of all Japanese homes had electric lights {{11350 Wit,D. 1956; }}.

Demand for electricity in post-war Japan rapidly started to outstrip potential supplies. In August 1946, with post-war shortages of fuel, the government restricted household and industry consumption of electricity. The Korean War, beginning in 1950 placed even greater demands on supply. Industry was denied access to electricity for 2 days of each week for a couple of years. A lively debate on both sides of the Pacific ensued. How could demand be met? In 1956 hydroelectric power was less than half the cost of thermal power generation, but cheap domestic river-based capacity was exhausted. Significant increases in supply were not possible without considerable investments in reservoirs and dams (also relocation and compensation costs). Thermal power was cheaper on paper, but domestic coal production was increasingly costly and of low quality, while domestic supplies of petroleum or gas were tiny. Atomic power seemed to offer an alternative[9]. Should the US provide the technological expertise necessary to develop Japanese domestic nuclear power generation[10]? Japan's Atomic Energy Commission asserted that atomic power could compete with fossil powered plants on costs. Given adequate time, Japan was in a position to develop the technical expertise, however with US technology transfer this process could be speeded up (and American dominance in the region could be maintained). The final decision was to develop all potential supplies of electricity, and ensure a degree of energy security through diversity.

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9. The International Bank Survey estimated the Okuizumi dam project would cost $464 per kW, while the thermal power plant at Meiko would cost $179 per kW. Nuclear power plant capital costs were estimated at $210 to $450 kW {{11350 Wit,D. 1956; }}.
10. Concerns in the US were that economic instability brought on by energy shortages may push Japan to join

Consequently, in the mid-1950s a huge expansion program for electric power generation was initiated, first in hydroelectricity then in thermal power and subsequently in nuclear power. In 1956 the Basic Law for Atomic Energy went into effect. Other legislation was introduced to help promotion of nuclear research and development for non-military purposes. Electric power companies also started internal research. Competition between ventures with commercial potential caused continuous development and rationalization. This investment stimulated demand in other industries (such as engineering) supply machinery and technical services to the electricity generating industries. Investment at first was for new foreign technologies. But as replacements were needed after several years the electric utilities shifted to Japanese suppliers, thereby stimulating domestic engineering and technology industries.

2.5 Leadership, vision, coordination and negotiation: MITI

The period of fastest growth of the Japanese economy was from 1960 through 1980. Annual growth averaged over 9% per annum, largely driven by export sales, especially to the US. During that period, and especially the 70s, the Japanese economy was competing directly with the US economy for market share in industry after industry. The US balance of merchandise trade was comfortably positive in the 1950s, but fell to negative $20 billion in 1980. (This trend has since accelerated dramatically.) The US share of export markets for high technology products had been 35.5% in 1954. It was under 20% by 1980 {{780 Ayres,R.U. 1984; }}. Most noticeable was the loss of whole industries, from the US to Japan, including consumer electronics (radios, TVs), watches, cameras, sewing machines, bicycles, motorcycles and machine tools. A few of these industries (motorcycles and bicycles) have staged partial recoveries in the US, but most of the losses seem to be permanent.

Popular explanations of Japan's remarkable post-war growth included the suggestion that government intervention by the Ministry of International Trade and Industry (MITI) played a major role, especially in the development of the steel, shipbuilding, electric power, petroleum refining and electronics sectors. MITI's `indicative planning' function may have been exaggerated, as conventional wisdom now claims. But it was MITI that acted on behalf of `Japan Inc.' when centralized negotiating authority was advantageous. MITI coordinated the acquisition of huge numbers of important US and European patents, starting with the crucial steel industry

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the Communist world {{11350 Wit, D. 1956; }}.

patents already mentioned. Japan later acquired the integrated circuit patents, for very modest royalties – as compared to what firms in other countries later paid. It did this by forcing IBM, Texas Instruments and Fairchild to license most of their key semiconductor technologies to competing Japanese firms, in exchange for permission to create Japanese subsidiaries, in order to gain access to the growing Japanese market {{1624 Boretsky,M. 1973; }}.

The production history of the dynamic random access memory (D-RAM) chip is especially interesting, in this regard. The first 1K RAM chip was manufactured by Intel and marketed in 1970. It was produced for 5 years, entirely by Intel and US licensees. But when the 4K RAM was introduced in 1975 Japanese producers captured 12 % of a much larger market. The 16K RAM appeared in 1978, and the Japanese share rose to 40% of a still larger market. When the 64K RAM appeared in 1981, Japanese firms had become the dominant producers, with 70% of the market {{780 Ayres,R.U. 1984; }}.

MITI reached the zenith of its influence in the ICT domain with the famous “fifth generation” computer systems (FGCS) project, initiated in 1981 with a projected budget of $500 million over ten years. The goals set forth for the FGCS were incredibly ambitious. Achievement of the objectives were expected to make Japan the world leader in computer technology. This did not happen, partly because FGCS was too much focused on super-computers and partly because Intel learned its lesson and kept control of the micro-processor market it also initiated in 1980, and because Japan was slow in developing office applications of PC’s. MITI has consequently lost much of the prestige it formerly enjoyed, just as Japan also encountered new competition in many of its key industries (including steel, ship-building and semiconductor manufacturing) from South Korea, Taiwan and Southeast Asia.

Needless to say, despite the relative decline in status, MITIs efforts to assist the acquisition of and promote innovation of computer and telecommunications (ICT) technologies gave Japan a considerable global presence in this sector. The effects of the expansion of this sector on patterns of energy consumption and economic growth are hard to ascertain. However it is widely understood that ICT is less energy intensive than traditional industrial and manufacturing sectors, typically generating more value-added (output) per unit energy consumed. Moreover, the application of ICT in other sectors is likely to have increased energy efficiency[11].

11. The debate as to the net effect of ICT on emissions and energy efficiency is wide-open. Information

The shift from heavy industry to service industries represents an important strategy to 'decouple' – subject to constraints – energy consumption from economic growth. Indeed this concept of substituting technology for energy is central to perhaps the most important initiatives from MITI, the Sunshine and Moonlight Projects.

2.6 Efficiency and technology substitution: The fifth and sixth fuels.

MITI was responsible for perhaps the most persistent and long-term push by a government agency to conserve energy, increase energy efficiency and develop alternative (low-carbon, renewable) energy supplies. Over a 30 year period over $50 billion was spent on R&D through two national projects called "Sunshine" and "Moonlight"[12]. These projects were backed by government subsidies and regulations to incentivize the diffusion of alternative energy supplies (for example solar, wind and biomass technologies.)

These projects were not primarily, as may be thought, aimed at improving Japan's environmental footprint, though of course this objective was and is increasingly of significant importance. Rather, Japans historical experiences of resource scarcity had taught them the importance of improving the productivity of scarce resources (capital, labour), and in particular energy. This can be achieved through technological substitution which generate efficiency gains, and alter the 'optimal' mix of factor inputs. To this effect the government initiated R&D consortia to link fundamental research in universities with more applied, industrial research in energy technologies.

Evidence suggests that the catalytic role of MITI had more widespread effects on the Japanese economy through unintended spillovers. By increasing R&D expenditure for fundamental research and linking this to a broad range of industries across many sectors, technology spillovers and inter-technology substitutions were encouraged. For example the discovery of high-temperature superconductive materials has generated many applications for energy, but also in electronics and for measurement technologies. Similarly the elucidation of certain biological mechanisms led to the development of a first generation of neuro-computers and superconducting generators.

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communication technologies have the potential to enable, enhance and transform many energy related activities, but as the sector grows it is possible that gains are outstripped by a rebound effect, as total consumption /emissions grow.

12. The Sunshine Project involved R&D on new energy technology, while the Moonlight Project focused on

By engaging business and the private sector in the quest for improved technological capabilities both projects stimulated the creation of new market spaces, and in the energy domain, lead markets in so-called cleantech industries {{11449 Fan,Peilei 2006; }}. The Sunshine Project has had the most conspicuous success. Between 1980 and 1990 PV industry R&D grew from approximately 10,000 million Yen to over 120,000 million Yen, in line with but exceeding the growth in MITI Sunshine project R&D funding (**Watanabe 2003**). Today, Japan boasts four companies in the top 15 of global PV cells[13], and they share 45% of the world PV market. Their growth has been supported by a 'virtuous cycle' of successive cost / price reductions driven by cumulative R&D and production experience {{11356 Shum,Kwok L. 2007; }}.

The concept of a virtuous cycle driving down costs has resonance at the level of an individual technology but also at the sectoral and macro-level of analysis. In the next section we present a theory of growth that compliments the descriptive Rostow model but extends it quantitatively enabling us to reproduce historical growth trends by focusing on the amount and way in which energy is used by society.

3. Virtuous cycles driving economic growth

The previous discussion qualitatively describes certain aspects of the dynamics of energy supply, use and technological change. It is now time to re-consider the aggregate effects of these dynamics, reflect on their relative importance and attempt to explain quantitatively their role in driving the empirical rates of economic growth. We start from the principle that growth cannot be explained simply by either capital accumulation or labour productivity in isolation. We argue that it is not helpful to attribute growth to an undefined and exogenous technological progress. Rather we insist that specific consideration of the role of energy in relation to the other factors (capital, labour and technology) is appropriate. Capital, labour, energy and technology cannot be considered independent of one another; they compliment and substitute for each other in varying degrees, constrained by the dominant technology.

We regard the Japanese economy as an evolutionary energy and materials processing system. The system consists of processing stages, starting with resource extraction, conversion, production of finished goods and services, final consumption (and disposal of wastes). We

R&D on energy conservation technologies. By 1980 over 60% of MITI's budget was for energy related R&D.
13. Sharp 363 MW, Kyocera 207 MW, Sanyo 165 MW, Mitsubishi 121 MW. These companies are sometimes

observe a general transition from poor quality[14] energy carriers (biomass, charcoal, coal) to higher quality resources, oil, gas, nuclear, PV and wind. At the same time technological progress has restructured the way in which energy is used. Arguably, it is productivity of those individual tasks (or energy services) that energy enables us to perform that determines the productive role of energy in society. Figure 4a and 4b show the history of energy use in Japan, developed by the authors in a previous study{{11484 Williams, Eric 2008; }}.

Figure 4a *Useful work inputs by type,* Figure 4b *Useful work inputs breakdown by type*

<<INSERT NEAR HERE>>

These reveal several important trends which we shall only summarise here: (i) the decline in importance of muscle work, (ii) the increase in industrial use of high and medium temperature heat, but subsequent decline as a fraction of total energy use, (iii) growth in demand of energy for residential and commercial space and water heating / cooling, (iv) the dramatic increase in demand for mechanical drive (for transport), and (v) the increasing importance of electricity as an energy carrier.[15] These trends are concordant with the shift from a feudal to a highly industrialised manufacturing and increasingly service dominated socio-economic metabolism of high mass consumption.

Figure 5a. *Efficiency of energy conversion for different types of useful work.*

Figure 5b. *Cumulative consumption vs. fuel specific conversion efficiency.*

Figure 5c. *Aggregate exergy to work conversion efficiency.*

<<INSERT NEAR HERE>>

From these estimates, and applying thermodynamic principles, it is possible to estimate approximately the time trend of efficiency for each end use group or for each fuel and through aggregation and simple division of total work by total energy input we estimate the aggregate energy efficiency for the national economy{{11484 Williams, Eric 2008; }}. The efficiency of delivery of each energy service has increased monotonically (Figure 5a). The five-fold improvement in aggregate efficiency from 1900 to 1980 is dramatic (Figure 5c). The most rapid

major polysilicon suppliers (Mitsubishi) or are involved in installation and distribution (Kyocera and Sharp).

14. Here quality refers to the calorific heat content of the fuel per unit mass.

15. Note that electricity is pure work and is used to provide all other forms of work. Figures 4a and 4b show only the fraction of primary fuels used for electricity generation and not the subsequent breakdown of electricity use for other forms of work. This conversion step is considered in the aggregate efficiency estimate however.

change coincides with the post-war period of technology transfer and capital investment described earlier. Nevertheless, the efficiency of use of each of the major fuels (coal, oil and gas) has stagnated after rapid improvements[16] (Figure 5b). And worryingly, aggregate efficiency improvements also show signs of stagnation since 1980[17], despite the significant efforts of MITI.

Figure 6a. *Empirical and estimated GDP using the LINEX function.*

Figure 6b. *Time trends of output elasticities of factors of production*.

We argue that the dramatic efficiency improvements and technological substitutions observed up to 1980 are intimately related to the growth of the Japanese economy over the same period. To qualify this assertion we performed two tests. The first involves testing the ability of our model to reproduce historical growth trends18. When efficiency improvements, resulting largely from technological substitutions, are factored in to a three-factor production function to explain economic growth, it is possible to reproduce historically observed rates (**Figure 6a**) without any exogenous assumptions of technological progress[19] {{5827 Kuemmel,R. 1985; }}. As **Figure 6b** shows the output elasticity of useful work is considerably greater than its cost share in the national accounts. Similar results were found for the US, the UK and Austria and Germany in similar studies {{1067 Ayres,R.U. 2005;5834 Kuemmel,R. 2000; }}.

The second test elucidates the presence or absence of statistical 'causality' relationships between the input factors and output[20]. The test is required to indicate whether increased demand

16. Experience gained in coal-based energy technologies clearly fed into oil and gas based energy technologies, as their efficiency of use increases at a faster rate with cumulative experience, evidence of a cumulative knowledge effect.
17. This phenomenon of increasing efficiency of individual services contrasting with stagnating efficiency of aggregate measures has been described as 'efficiency dilution' and can be explained by two processes (Williams et al 2008). The first process results from the scarcity of efficient energy sources, such as hydroelectricity (average 80% efficiency of conversion) for less efficient sources (oil and gas – 40 to 60% efficiency, nuclear 33% efficiency) in the face of ever increasing demand (Figure 3). The second is a rebound effect, the result of developing wealth and the increasing dominance of less efficient energy services (transport, space heating, diverse electrical appliances) in the energy service demand mix (Figure 4b).
18. A model that is capable of reproducing the past without unreasonable assumption or over-parameterisation may serve as a useful means of evaluating alternative future energy-technology-economy scenarios.
19. We use the LINEX production function {{5827 Kuemmel,R. 1985; }}. It is common practice to include a 'technology multiplier' in the production function. Given that useful work = exergy input times efficiency, our model effectively factors in technological progress generating efficiency improvements With useful work as the factor of production representing energy services it is possible to remove the abstract and undefined technology multiplier. In this model it is no longer abstract technological progress that drives growth, rather efficiency improvements.
20. Granger causality describes the situation where one time series is useful for forecasting another{{4170 Granger,C.W.J. 1969; }}. We tested for Granger causality within the multivariate cointegration analysis framework of Johansen {{5217 Johansen,S. 1991; }}. We tested for short-run or "weak" Granger causality indicating that lagged values of the change in useful work consumption provide statistically significant

for useful work occurs as a consequence of output growth, acts to increase output growth or whether the relationship between output and useful work is bi-directional. The results are presented in **Figure 7**. They reveal that there is both short and long-term granger causality between useful work and GDP. The implications are two-fold. Firstly, if useful work stimulates output growth, then any reduction in energy supply without a proportionate increase in energy efficiency may act to constrain output growth. Secondly if increases in useful work supply stimulate output then for a fixed energy supply any increase in the efficiency of energy use serves to drive output growth.

Figure 7. *Granger causality relations between output and factors of production.*

These results imply that efficiency improvements are at the heart of a virtuous cycle, the principle engine of economic growth throughout the majority of the 20th Century. The cycle works as follows: knowledge, driven by R&D (embodied in energy conversion technologies), generates technological substitutions for capital and energy. Product and process improvements ensue. Product improvement generates increased demand for final goods and services, generating increased revenues. Process improvement lowers limits to the costs of production, as does increased demand through economies of scale. At the same time technological progress reduces the costs of energy inputs (as more useful work can be delivered by unit of exergy consumed) which further lowers the limits to the costs of production, enabling substitution of a cheap energy-capital complements for scarce and expensive labour. This virtuous cycle generated growth throughout the export-led and mass production and consumption phases defined by Rostow.

4. Conclusions: Lessons from the past and recommendations for the future

In this paper we have sought to add a dimension to Rostow's theory of staged development by considering the historical dynamics of socio-economic metabolism. This enabled us to reflect on the role of resource scarcity, technological progress and government intervention to promote the development of increasingly resource productive and efficient systems of production and consumption.

information on future values of the change in GDP. We also tested for long-run or "strong" Granger causality

Two clear lessons have been learnt: firstly, when resources are constrained rational and efficient use should be promoted; secondly possibilities for substitution of technology for scarce resources should be incentivised and supported. In short, resource scarcity must drive innovation if it is not to lead to slow growth or worse stagnation. The lessons learnt from Japan indicate that evolving government intervention has done much to promote the efficiency-technology substitution process.

Evidently the form of government intervention has changed over time reflecting the changing socio-economic paradigm. Earlier 'hard' policy interventions focussed on direct financing, price fixing, controlling competition, market entry and exits. Later 'soft' interventions are less intrusive and focus on stimulating industry R&D expenditure, providing administrative guidance, maximising spillovers by fostering synergistic networks, and more recently through attempts to encourage social innovation through 'non-codified and extra-legal guidelines'[21]. We argue that despite inevitable failures, each period of intervention, having its' own character provides an important lesson. We summarise them here:

- Protect nascent domestic industries;
- Manage industry decline where no competitive advantage can be achieved;
- Support proven competences and capacities;
- Rationalise production and define clear strategic priorities;
- Seek bi-lateral agreements for technology transfer;
- Stimulate domestic industry R&D expenditure;
- Promote the creation of lead markets with large potential spillovers.

The importance of these activities for economic development is revealed through their impact on the long-run trends of energy use efficiency. We suggest that with declining relative labour inputs (number of hours worked) it has proved possible to achieve sustained growth in Japan through efficient use of energy and capital. Labour productivity, is gained through innovation in productive capital-energy combinations.

Our resource based perspective does not deny that such innovations are driven by knowledge accumulation, and as such our model does not contradict the underlying framework of Rostow. Rather, we perceive efficiency improvements as being a realisable metric to ascertain the

indicating how fast deviations from the long-run equilibrium are eliminated following changes in each variable.

cumulative productivity enhancing effects of knowledge accumulation on systems of production and consumption. As such there is a clear need to maintain year on year improvements in energy efficiency. However, as we have shown this is proving increasingly difficult to achieve.

There are two principle underlying reasons for the observed slowdown and stagnation of efficiency improvement, providing indications where Japan and similar societies need to act. Firstly, the dominant technologies that are strongly embedded into current systems of production and consumption are reaching technology asymptotes. Secondly, the incremental improvements in existing systems of production and consumption are negated by wealth or ‘rebound’ effects that have meant that some efficiency gains are outstripped by increased consumption of less efficient energy services (such as space heating, transport, or parasitic losses[22]).

Both problems need to be addressed by repeating that which Japan has proved itself capable of in the past, namely radical and disruptive innovation. This is not to say that incremental improvements are ineffective, rather that the dramatic improvements in energy efficiency that gave rise to unprecedented rates of growth in the past cannot be achieved only by doing more of the same better. Indeed, the need for radical change is exacerbated by requirements to reduce greenhouse gas emissions. Certainly it is necessary first to take advantage of the low and negative-cost energy efficiency solutions. As a recent report indicates there are many such opportunities in production and consumption practices {{11483 Enkvist, Per-Anders 2007; }}. Historically, the largest efficiency improvements have occurred in industrial energy use. Commercial and residential energy use efficiency has in contrast been much slower. And indeed, as their importance in the energy service demand mix increases so economy-wide efficiency improvements have slowed. We conclude that it is not sufficient to encourage innovation in systems of production in isolation. Rather it is necessary to reflect on the industrial ecology of current systems and to stimulate a process of ecological modernization of existing ‘wasteful’ systems of production and consumption.

21 *www.6cp.net/downloads/BigProject%20Japan-%20Y.Harayama%5B1%5D.ppt*
22. Parasitic losses include ‘standby mode’ on electric appliances as just one example.

Figure 1a. Historical growth of factors of production

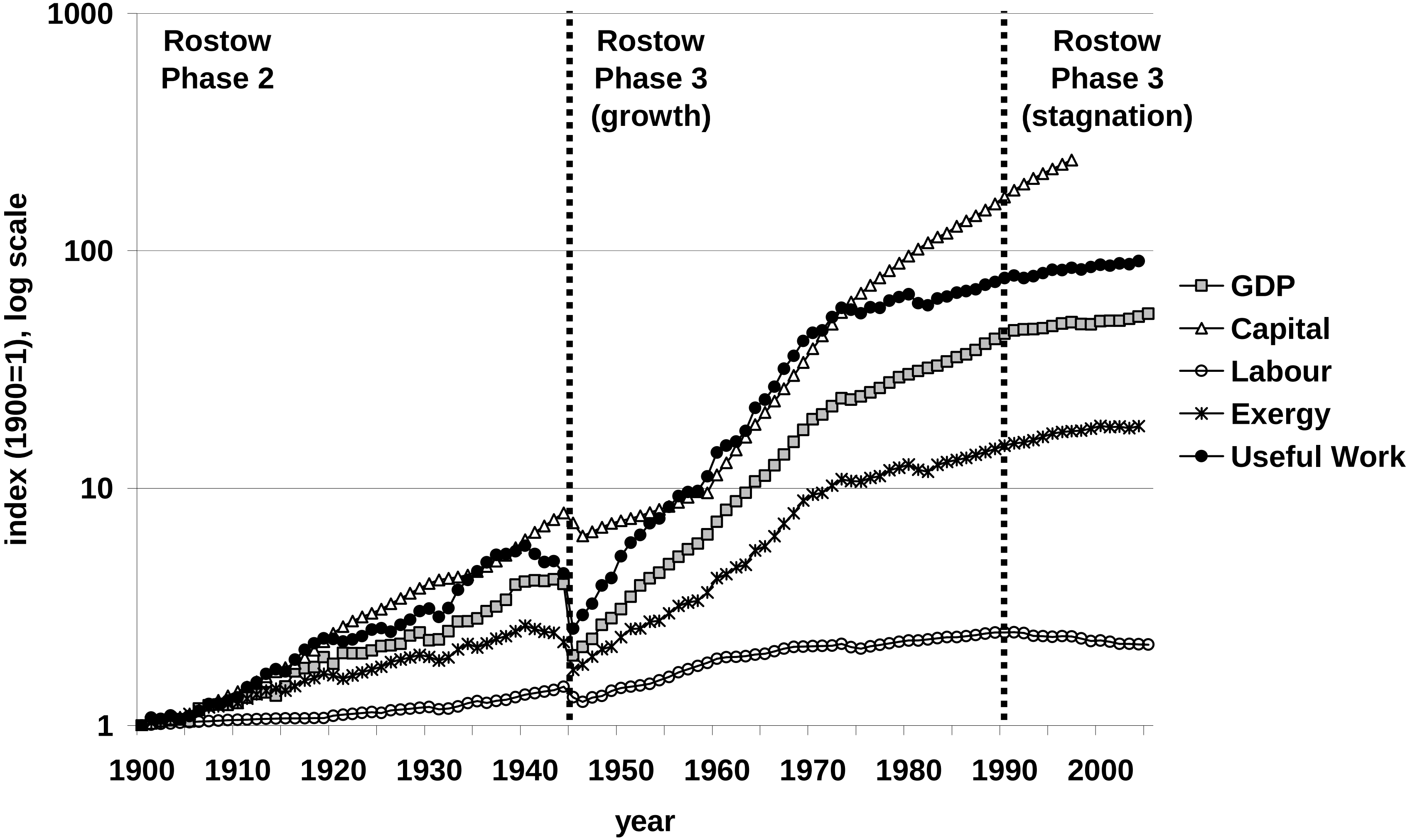


Figure 1b. Factor productivities (GDP / Factor)

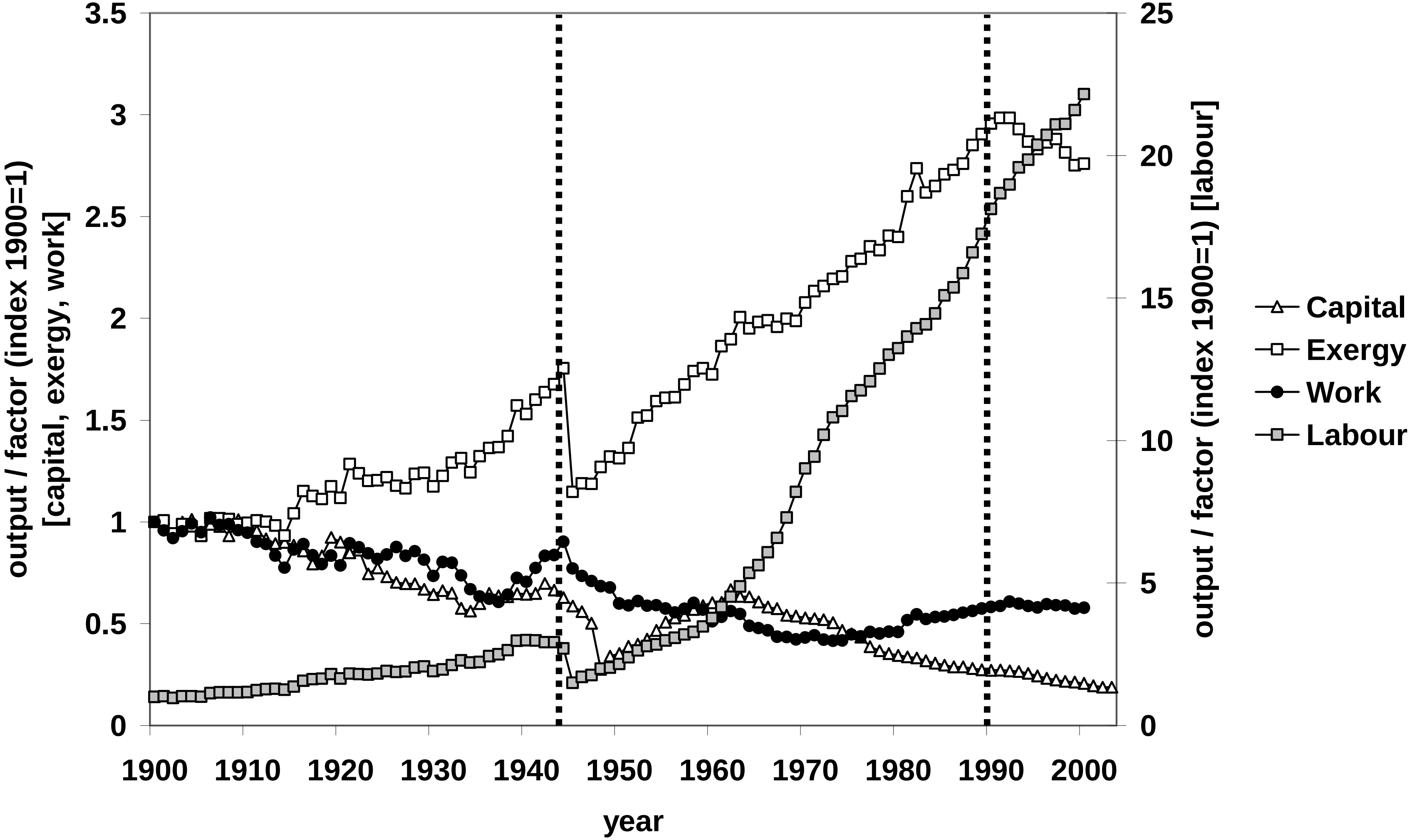


Figure 2a. Energy inputs by source, 1900-2005

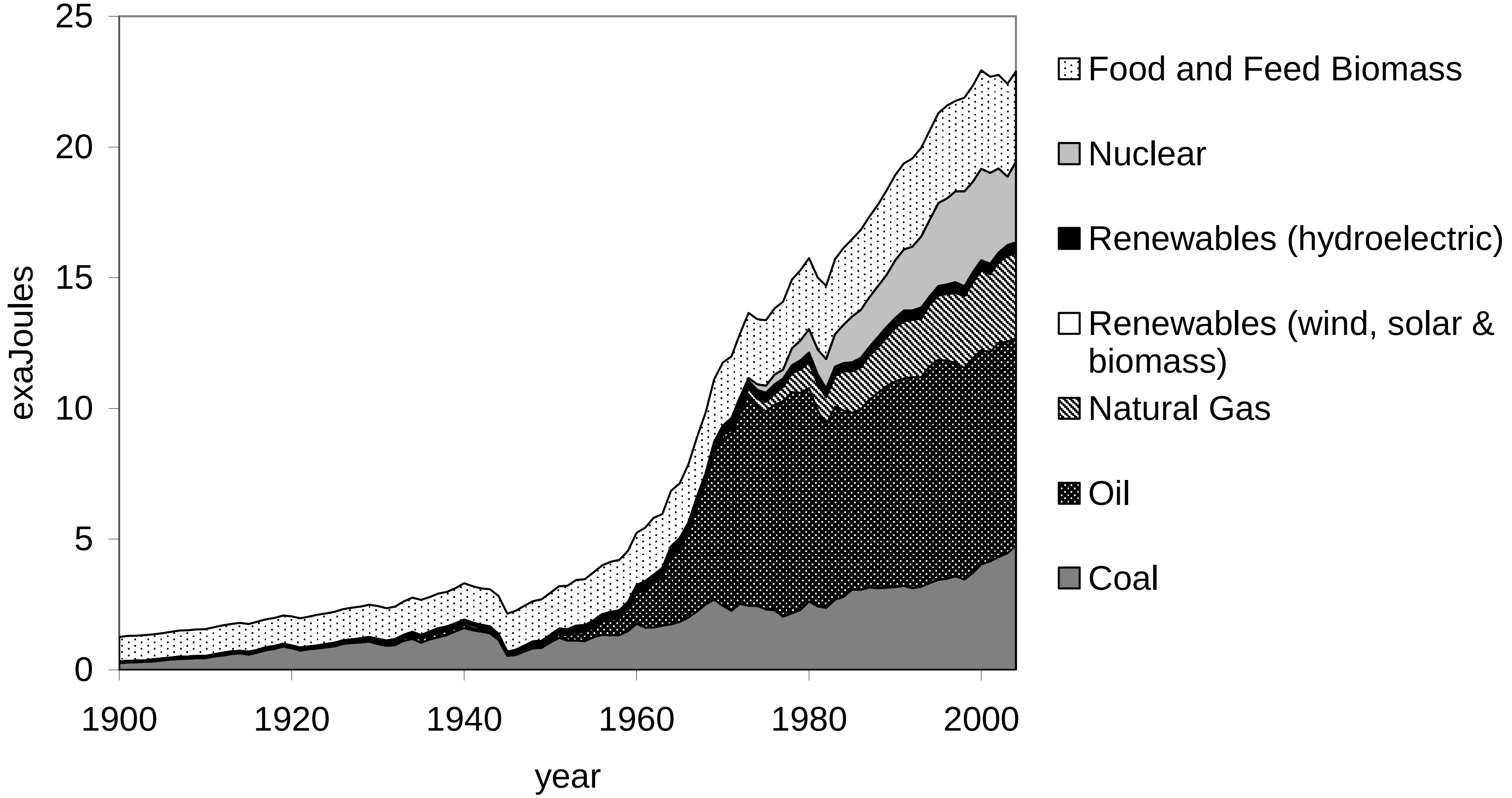


Figure 2b. Energy inputs breakdown by source, 1900-2005

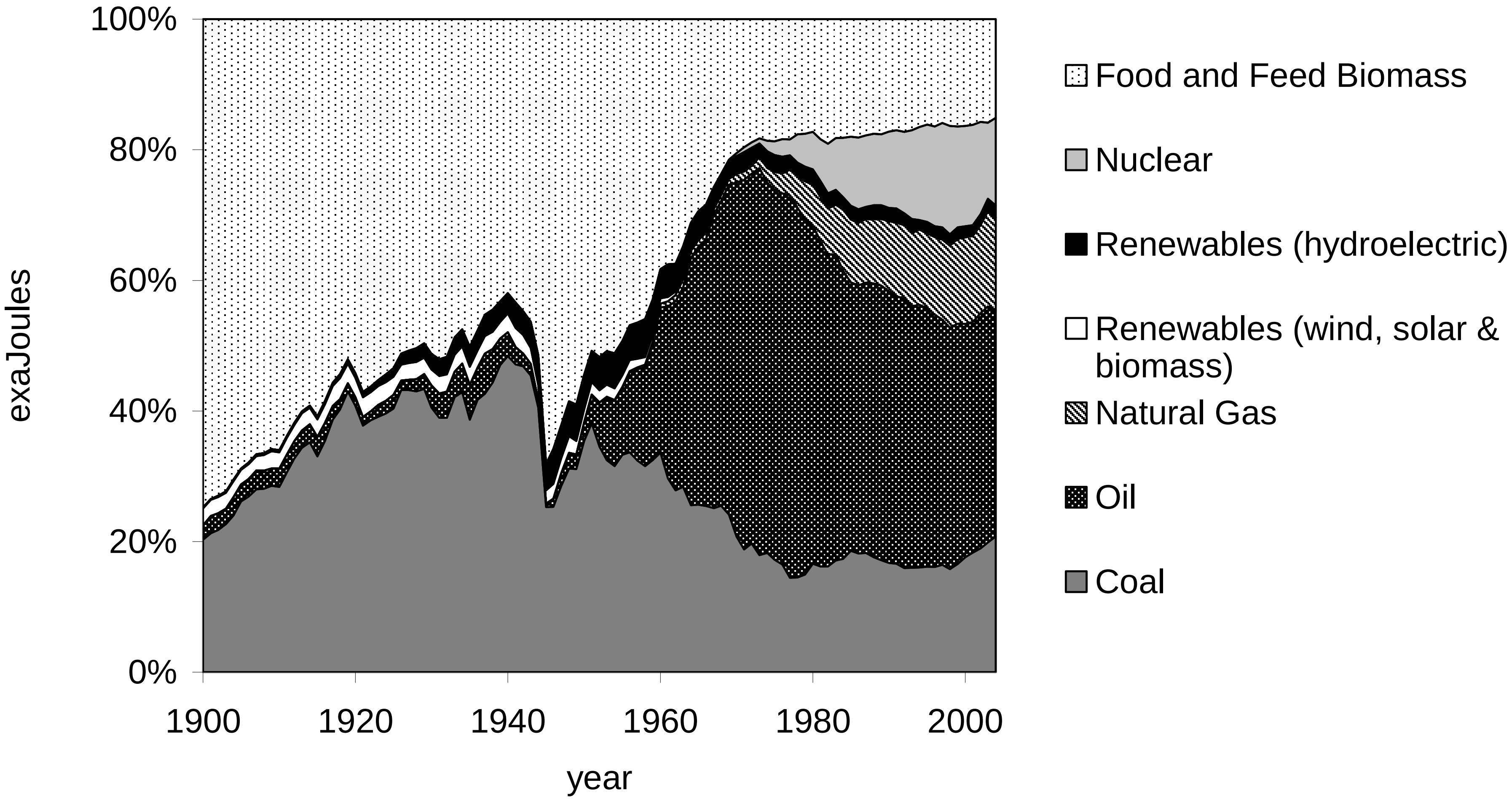


Figure 3a. Useful work inputs by type

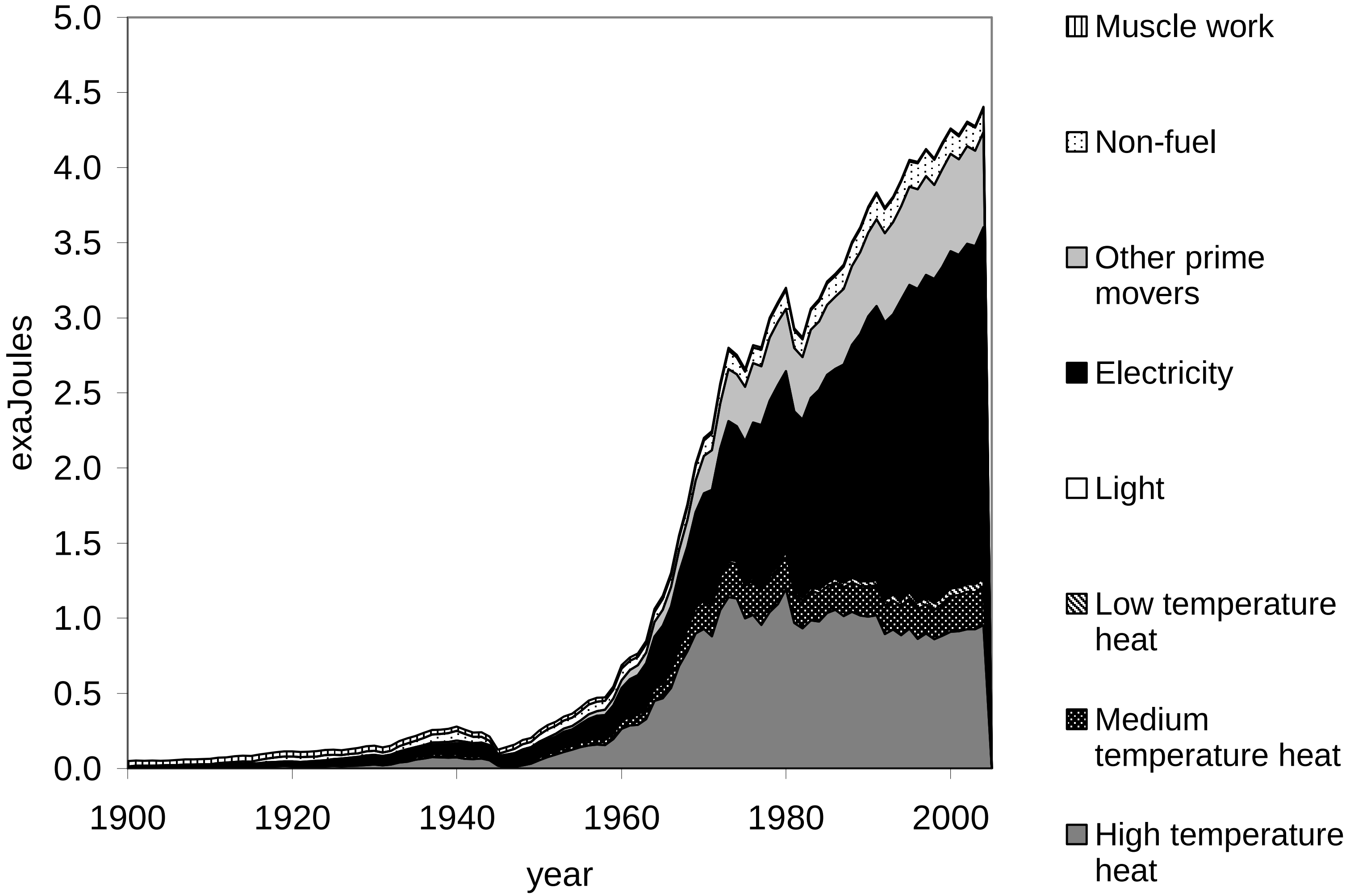


Figure 3b. Useful work inputs breakdown by type

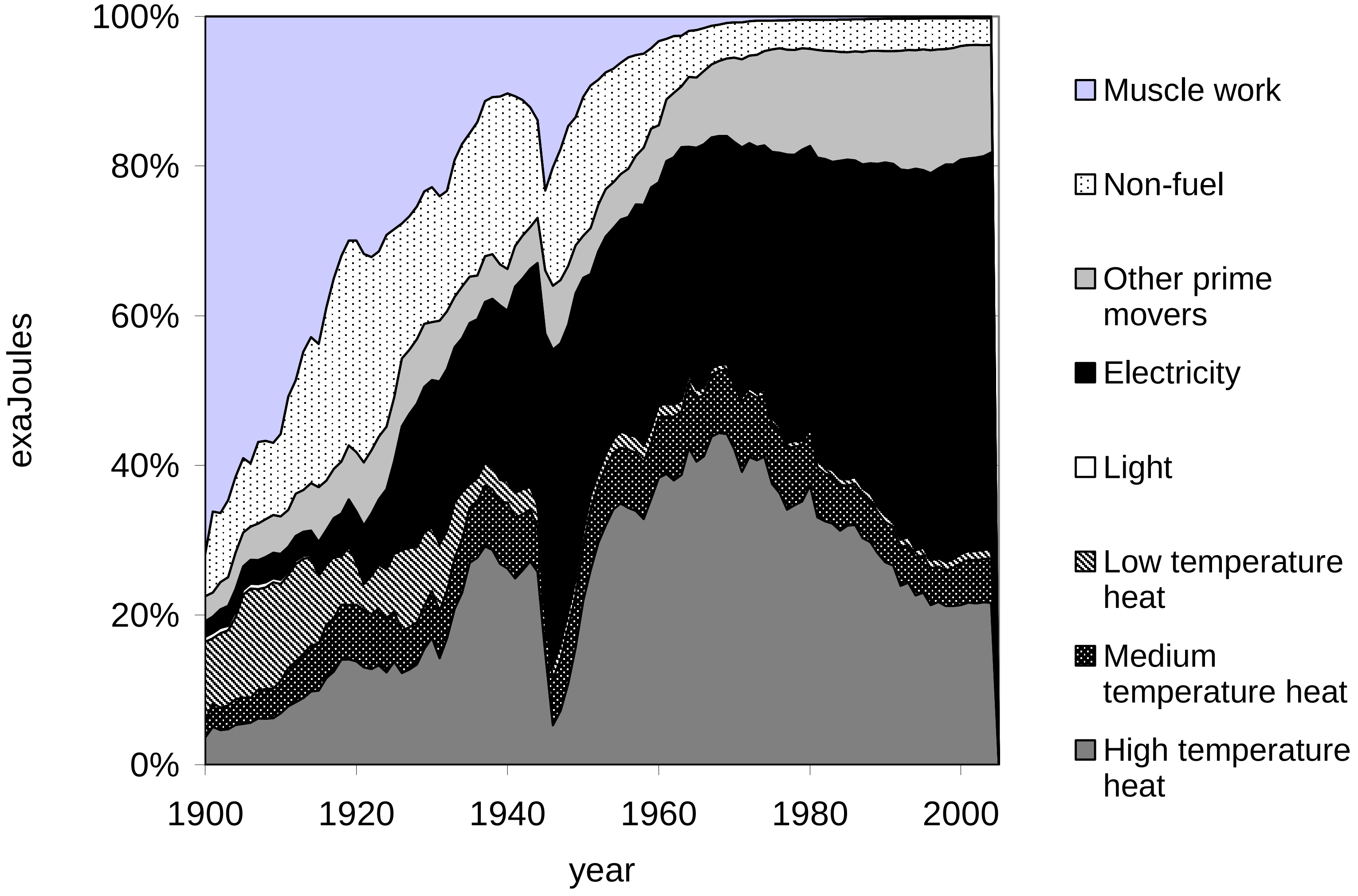


Figure 4. Exergy inputs for electricity generation by source

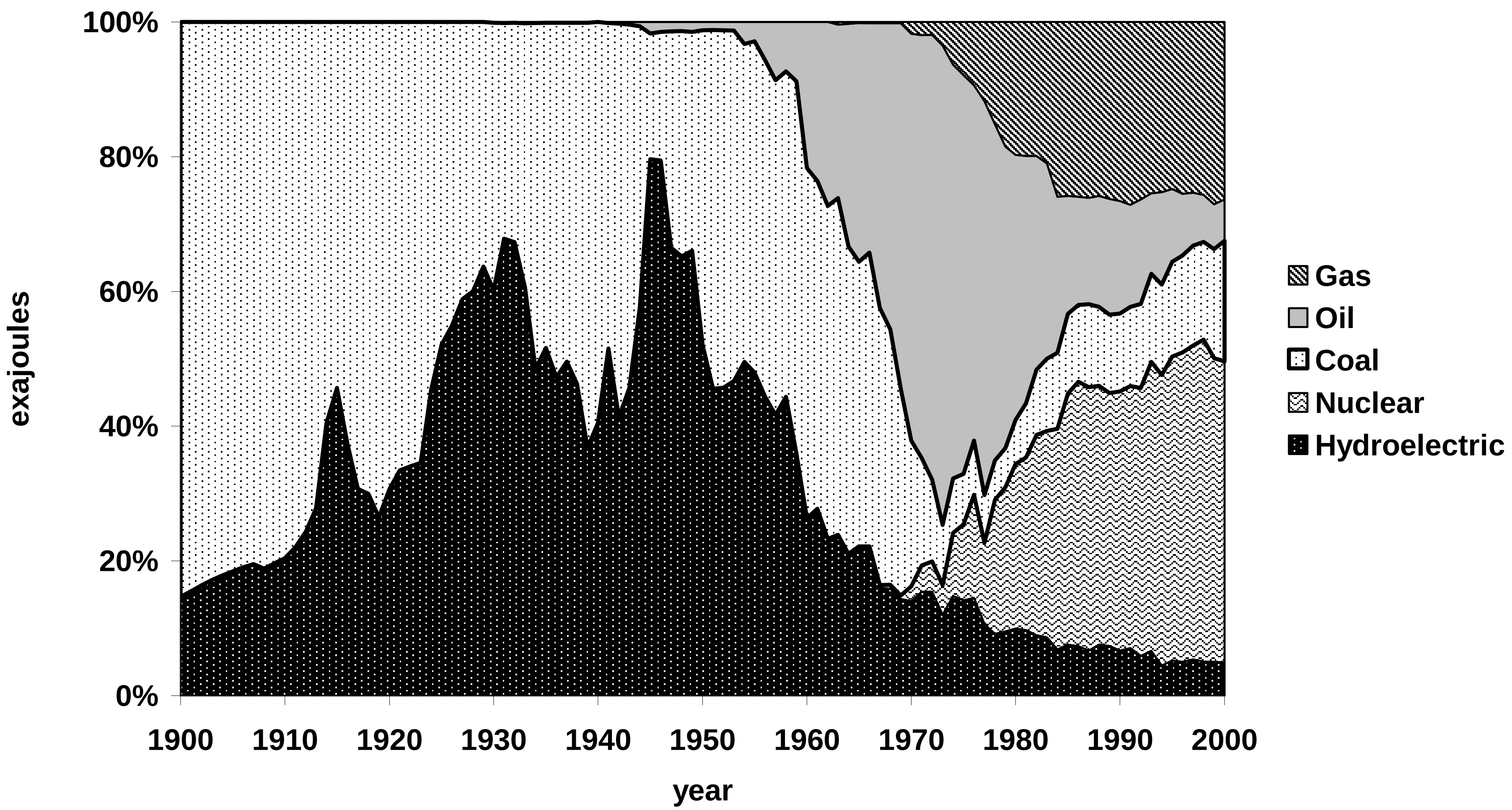


Figure 5a. Efficiency of energy conversion for different types of useful work

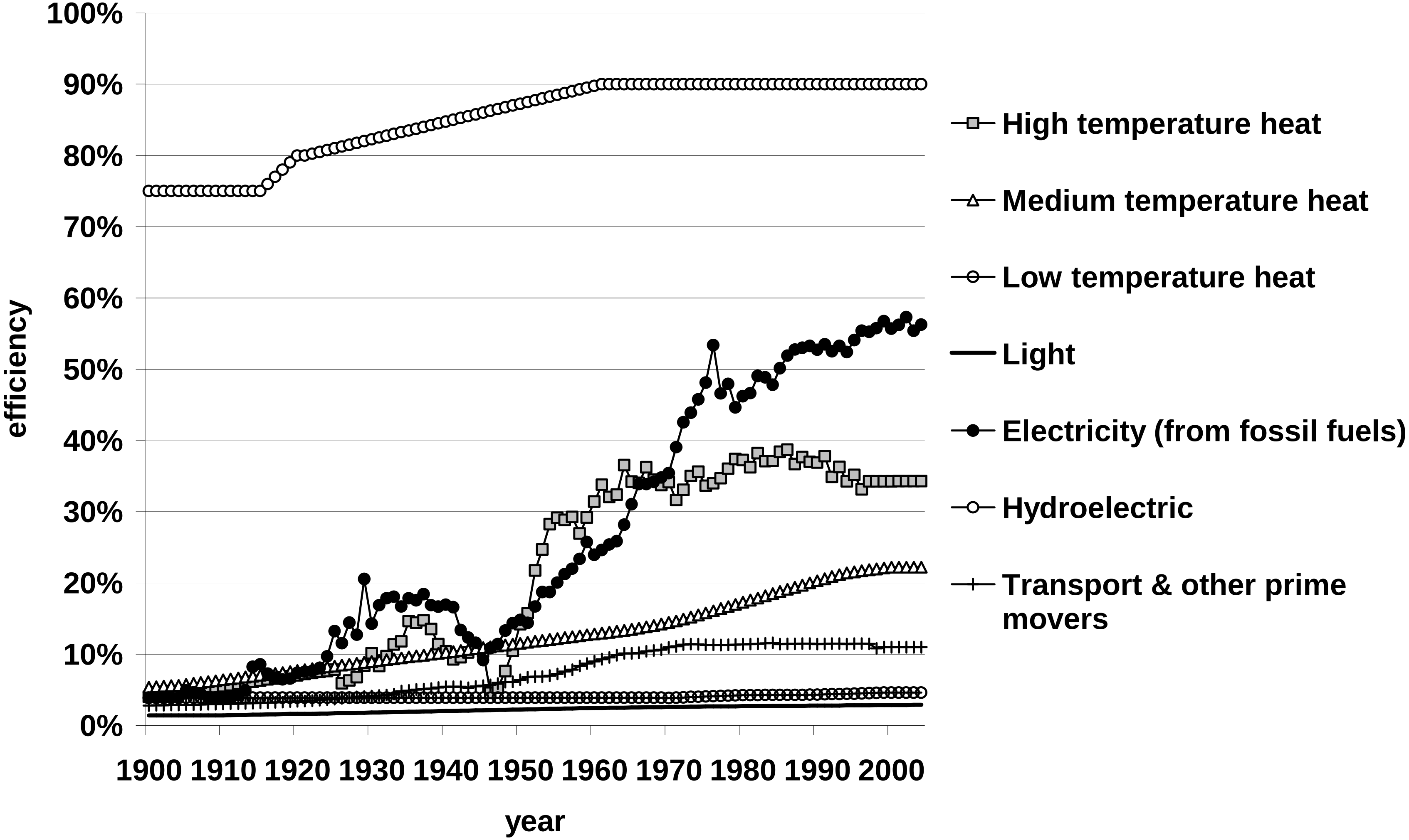


Figure 5b. Cumulative consumption vs. fuel specific conversion efficiency

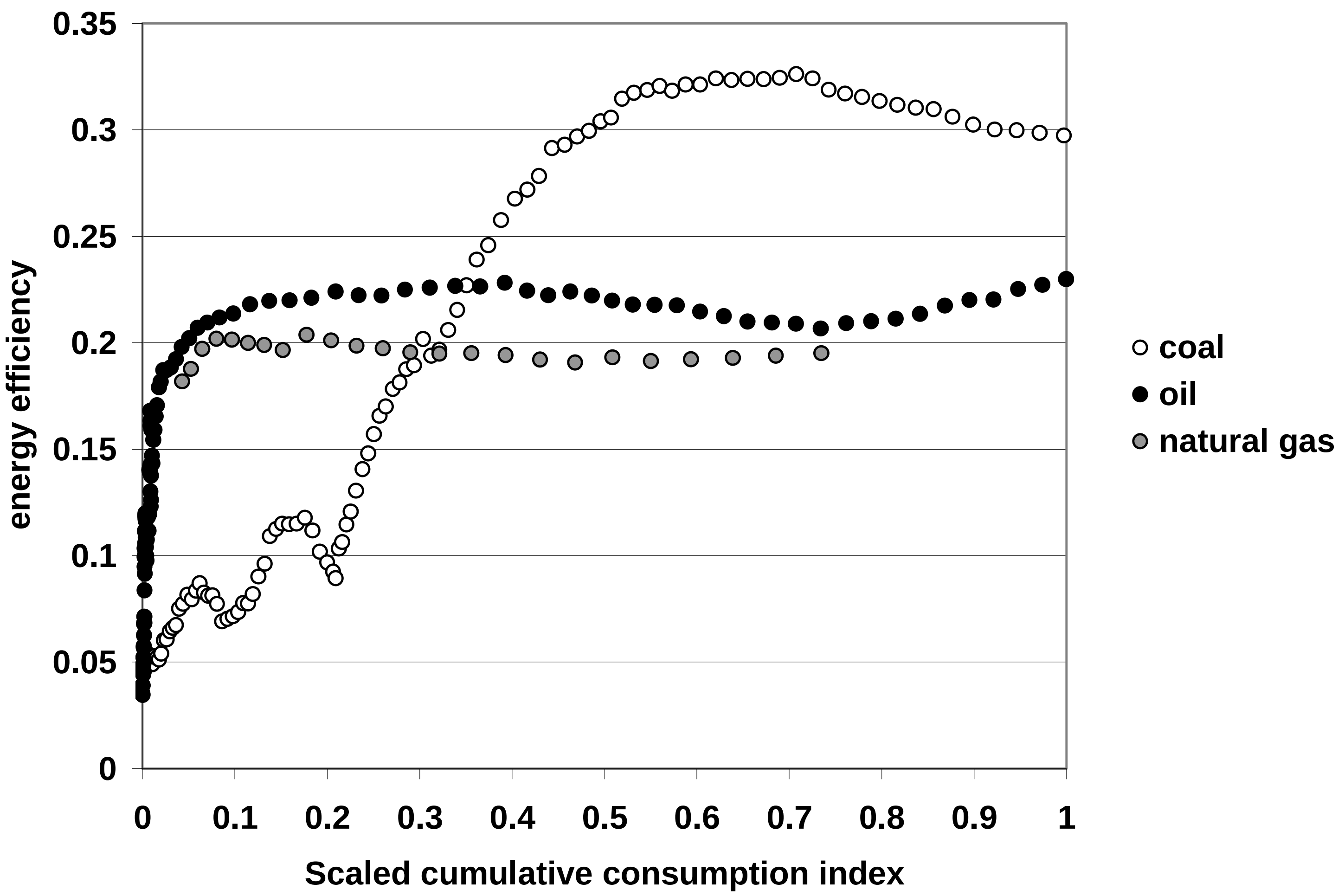


Figure 5c. Aggregate efficiency of exergy to useful work

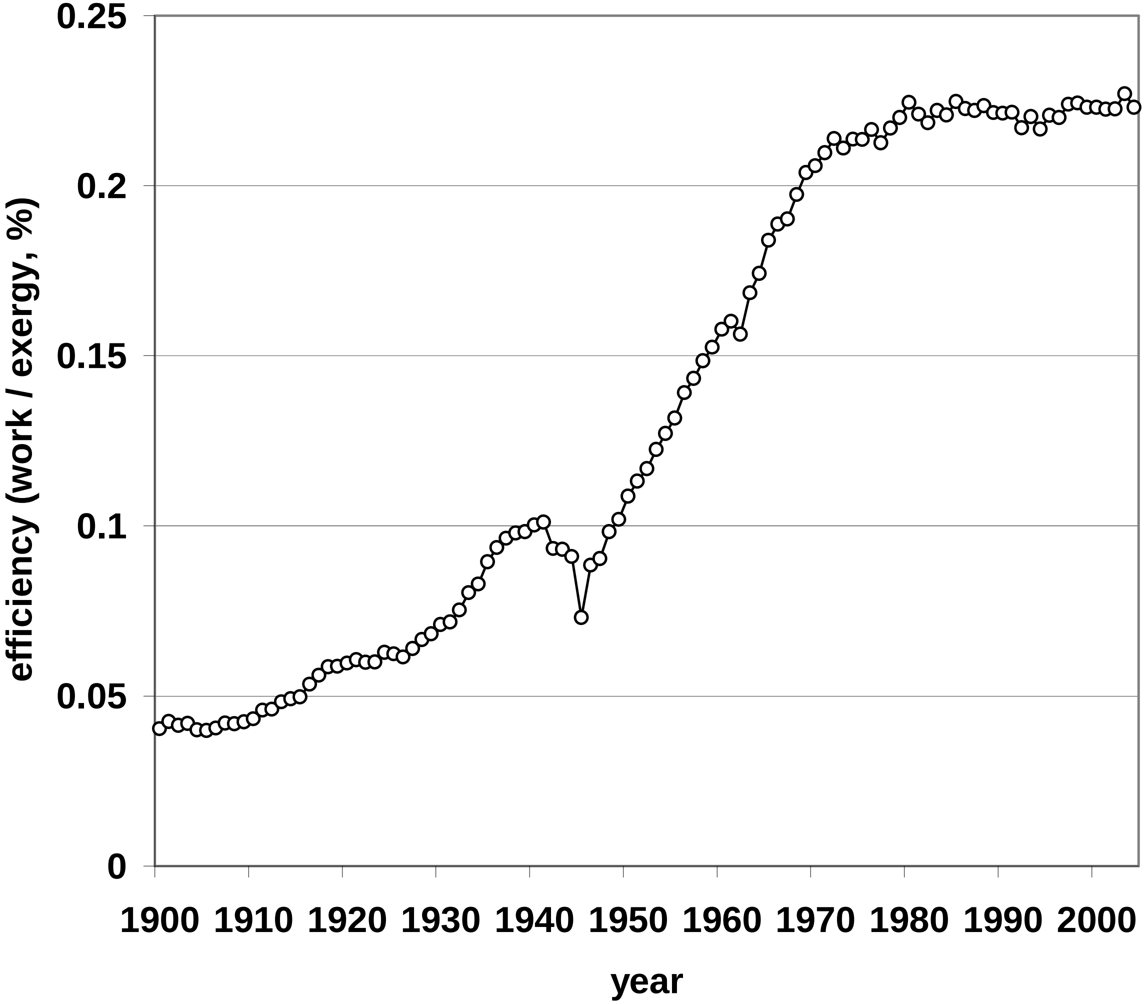


Figure 6a. Empirical and estimated GDP

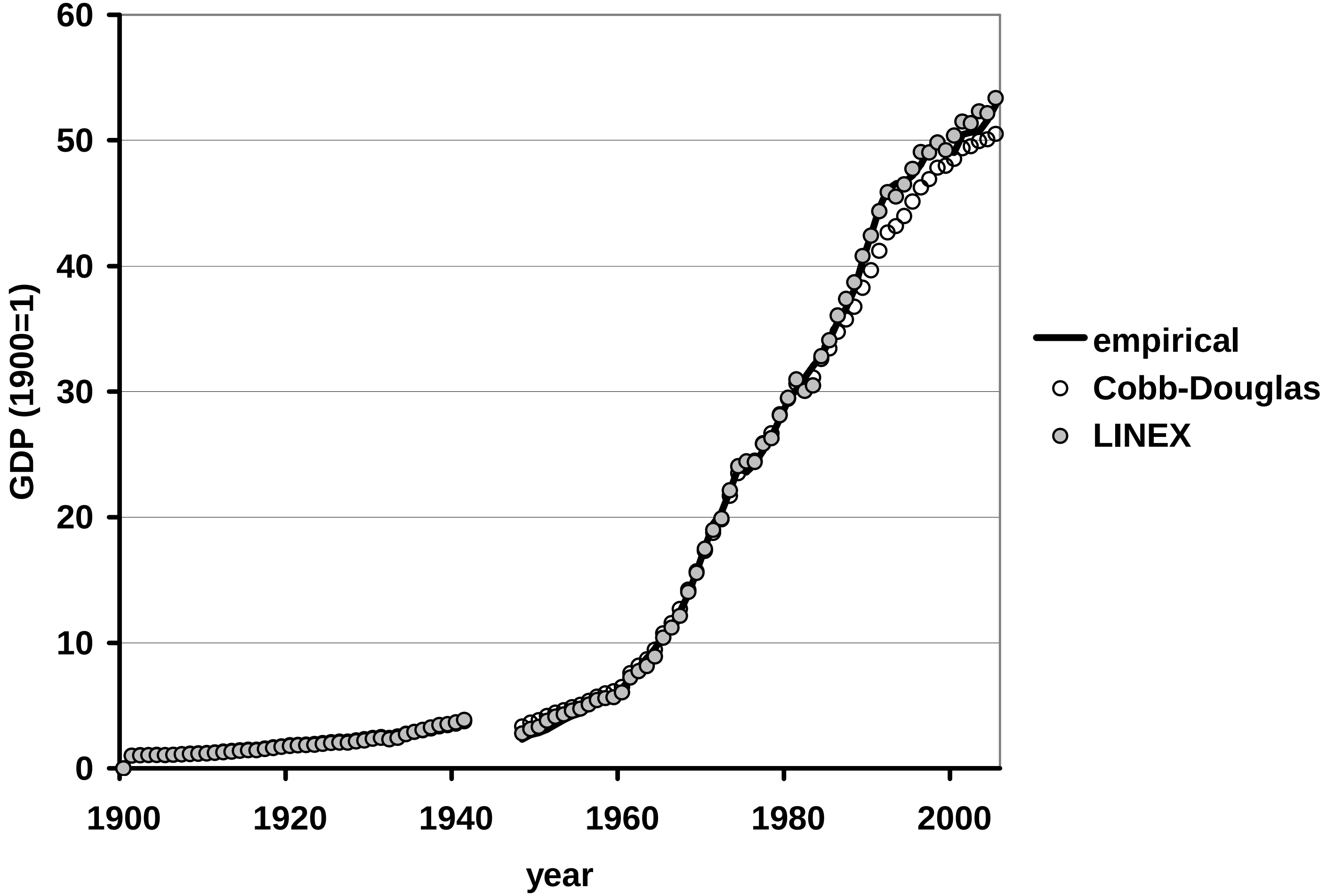


Figure 6b. Elasticities of factors of production (Linex)

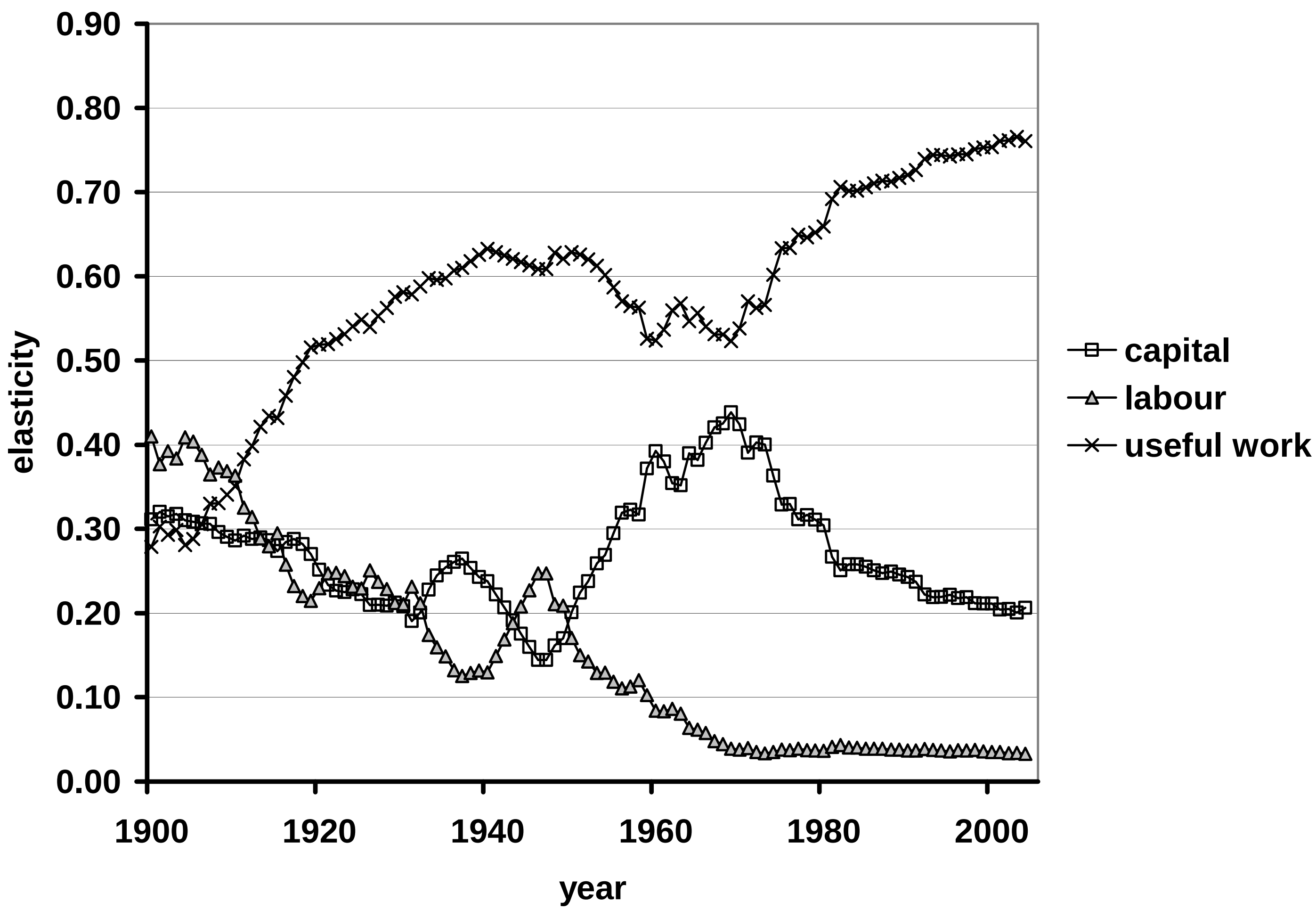
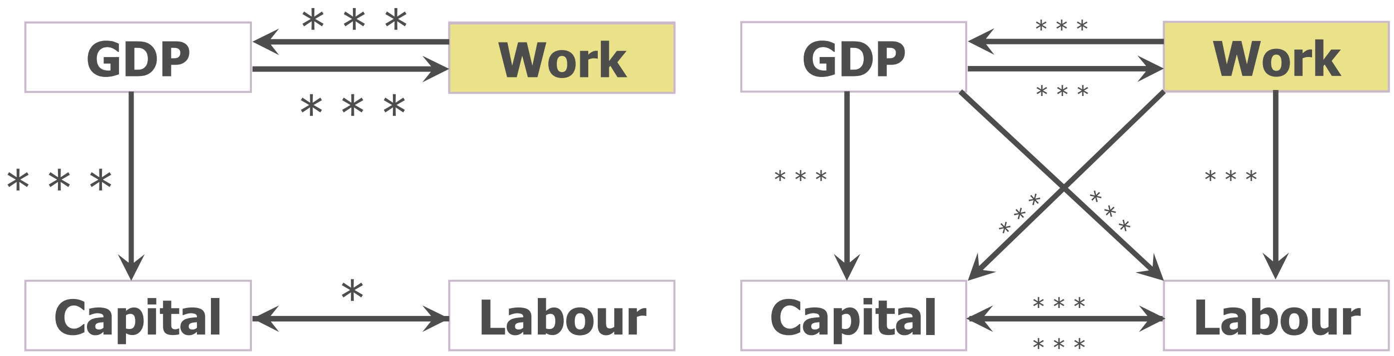


Figure 7. Causality relations between output and factors of production.



Short-run **Long-run**

Asterisks indicate the degree of statistical significance (***99%, **95%, *90%)

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