TÉCNICO LISBOA

Mapping the Historical Energy Use of Coal (1800 - 2018)

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Abstract

Coal as an energy source has been integral to the industrial development of many nations in the last two centuries. But how efficient was this historical energy transformation? How and why did the world adopt the coal economy and how was this different at the world level compared to the major coal-consuming countries? This thesis attempts to answer these questions by mapping historical coal data and performing a societal exergy analysis at the world level and for four countries - The United Kingdom, United States of America, Germany, and France.

To perform this analysis, historical datasets were utilized to find primary, final, and useful energy use by sector for the world and the four countries considered. The coal energy transformation chain was developed using which aggregated exergy efficiencies were calculated. The benchmarks were then used to compare the country trends with those of the world.

The results showed that the four countries produced and consumed more than 90 percent of the world's coal at the beginning of the 19th and 20th centuries. By the start of the twentieth century, this value had reduced to 12 percent. Coal was gradually phased out of sectors such as transport and shifted to sectors such as thermal power plants to generate electricity. The results of the societal exergy analysis showed that increased coal consumption coupled with efficient end uses result in higher aggregated exergy efficiencies, while outdated technology, wars, and economic crises reduced the aggregated exergy efficiencies over time.

Keywords

Coal, Historical energy database, Societal exergy analysis , Aggregated exergy efficiency

Resumo

O carvão, como fonte de energia, tornou-se essencial para o desenvolvimento industrial de muitas nações nos últimos dois séculos. Contudo, quão eficiente foi esta transformação energética histórica? Como o mundo adotou a economia baseada no carvão e como esta adoção foi distinta a nível global em comparação com os principais países consumidores de carvão? Esta dissertação procura responder a estas questões através do mapeamento de dados históricos sobre o carvão e da realização de uma análise exergética societal a nível mundial e para 4 países: Reino Unido, Estados Unidos, Alemanha e França.

Para realizar esta análise, foram utilizados conjuntos de dados históricos para determinar o uso de energia primária, final e útil por setor, tanto a nível global quanto nos 4 países em análise. Com base nestes dados, foi desenvolvida a cadeia de transformação energética do carvão, permitindo calcular as eficiências exergéticas agregadas. Foram ainda estabelecidos referenciais comparativos para analisar as tendências dos países em relação às tendências globais.

Os resultados mostraram que os 4 países analisados produziram e consumiram mais de 90 por cento do carvão mundial no início dos séculos XIX e XX. No entanto, no início do século XXI, este valor reduziu-se para 12 por cento. A análise exergética societal demonstrou que o aumento do consumo de carvão, aliado a usos finais eficientes, resulta em elevadas eficiências exergéticas, enquanto tecnologias obsoletas, guerras e crises económicas levaram a eficiências exergéticas significativamente mais baixas.

Palavras Chave

Carvão; Base de dados de energia histórica ; Análise exergética societal ; Eficiência exergética agregadao;

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Acronyms

4C 4 countries - France, Germany, UK and US

IEA International Energy Agency

HTH High temperature heat (>600°)

LTH Low temperature heat (120° - 300°)

MTH Medium temperature heat (300° - 600°)

Mtoe Million tonnes equivalent of oil

OWID Our World in Data

PJ Petajoules

1

Introduction

Contents

1.1 Motivation

Energy supply and social advances are closely interlinked. This is quite intuitive to many, considering the advancement in western societies and how sophisticated their ability to harness energy has improved over time. Our current world was shaped by the preceding three centuries of energy transition, where many fuels gained or lost prominence for many reasons.

In the last two centuries, economic and societal development at the global scale can be attributed to the wide scale adoption of coal as a primary fuel. As George Orwell stated ' Our civilization is founded on coal, more completely than one realizes until one stops to think about it. The machines that keep us alive, and the machines that make machines, are all directly or indirectly dependent upon coal' [8]. Many developed countries such as the UK, US initially invested into coal, later moving into oil and natural gas and other sources. It is notable that many developing countries such as India are following a similar trajectory [9].

With later research into the harmful effects of global warming and the carbon dioxide emissions as a result of coal usage, we are at an unprecedented age to enact the replacement of coal as a global energy source. A large chunk of the world is still dependent on fossil fuels, which strongly influences the global discourse on energy transition. As Vaclav Smil aptly points out - 'Modern civilization has been created by the massive, and increasing, combustion of fossil fuels, but this practice is clearly limited by their crustal abundance, as well as by the environmental consequences of burning coals and hydrocarbons, and high-energy societies can ensure their survival only by an eventual transition to non-fossil sources' [9].

Today's research into carbon sequestration, alternate pathways for Steam Rankine cycles [10] and hydrogen production from iron and steel industries based on coke [11] are all important avenues of research for the future of the coal industry. At the same time, the question of future economic policies of developing economies built around sustained coal usage becomes a serious issue to resolve [12].

This study aims to understand the evolution of coal with respect to geographical, technological factors through different phases in history and how it affected energy services which is essential to understand the future of coal as an energy source.

1.2 Thesis objectives

1. To form a collated database for coal production and consumption for the world
2. To form a collated database for coal production and consumption for the 4 countries - UK, US, Germany and France and compare it with the world database
3. To implement a methodology based on availability of data to develop the coal transformation chain for the world and 4 countries - UK, US, Germany and France
4. To compare the energy flows of the world and 4 countries - UK, US, Germany and France, using sector-wise benchmarks
5. To perform the societal exergy analysis by calculating the aggregated exergy efficiencies for the world and the 4 countries - UK, US, France and Germany

1.3 Thesis outline

1. **Historical overview**: This section offers a historical analysis of the advent of coal as a primary energy source, and its role in the development of industrial economies. Significant historical factors and trends are also discussed.
2. **Bibliographic review**: This section provides a comprehensive bibliographic review that outlines the fundamental concepts necessary for performing a societal exergy analysis using historical energy data. It discusses previous long-term energy studies, technologies highlighting the specific topics they address, as well as their strengths and limitations.
3. **Methods and Data**: In this section, we elaborate on the data sources utilized in the study and detail the specific methodologies employed for collecting data and using the data to find exergy efficiencies for the world and for the 4 countries - UK, US, Germany and France.
4. **Results and Discussion**: Here, we present the findings of the study, where we address the research questions posed at the outset of the thesis, offering thoughtful interpretations of the findings.
5. **Conclusion**: The conclusion summarizes the principal findings and insights gained from this research, emphasizing key achievements and contributions to the field. Additionally, we offer recommendations for future research endeavors, outlining potential avenues for further exploration and development in the study of coal as a primary energy source.

2

Historical overview

Contents

2.1 Coal - Origins and Rise to Prominence

Historically, coal has been known as an energy source to produce heat. Small-scale coal extraction began in England and Wales during Roman times in the 2nd century AD and continued intermittently through the Middle Ages. In certain regions, such as China during the Han dynasty, coal was harnessed industrially for iron production in early blast furnaces [9].

Figure 2.1: Chinese workers operating a blast furnace [1]

However, coal remained a marginal resource in society, often burned inefficiently for heat and limited to areas near mining sites [13]. Its primary users were poorer populations unable to afford wood, indicating its initial role as an economic substitute for biomass fuels rather than an efficient energy source. Many affluent Britishers would refuse to enter homes that burned coal or cooked food using coal stoves [14].

That changed in the 17th century. The transition from wood to coal as the dominant energy source began in England and Wales around 1620. By 1650, coal accounted for 65 percent of England's energy consumption, a figure that rose to 90 percent by 1800 and over 98 percent by the mid-nineteenth century. In France and Germany, coal began replacing wood by the mid-1800s, although biomass energy retained prominence in Russia, Italy, and Spain well into the twentieth century [15]. In Western Europe, reliance on coal intensified early, with France sourcing over half of its fuel energy from coal by the mid-1870s.

In the United States, coal consumption rapidly overtook that of wood by the 1880s, embedding fossil fuels into the core of agricultural production. American farmers transitioned from traditional methods to relying on coal as an indirect subsidy for higher productivity. Coal-driven steam engines powered the production and distribution of tools, machinery, and agricultural products, creating new efficiencies and reshaping the agricultural supply chain. By 1880, advancements in coal mining and steam technology made steam power cheaper than water power in the United States [9]. By the end of the century, water turbines shifted from providing direct power to generating electricity. Even till the 1950s, the US was heavily reliant on coal as an energy source.

Figure 2.2: American steam powered agricultural machines [2]

The coal industry spurred on the iron and steel industry and the utilization of steam engines, apart from building a rich chemical industry. This led to a massive growth across the economy. Developed economies such as the US, UK and Germany accounted for 85 percent of global coal production in 1913 [16]. The transition to coal as a primary energy source heralded two pivotal technological advancements that laid the energetic foundation for the modern industrial world. The first involved innovations in converting coal into usable energy through advanced prime movers, including steam engines and steam turbines. Additionally, fuel-processing techniques, such as the production of metallurgical coke from coal, enabled these fuels to power increasingly sophisticated industrial applications including the iron and steel industry. Together, these advancements enhanced energy production efficiency and facilitated the development of complex manufacturing systems [9].

The second major improvement was the generation of electricity from fossil fuels, creating a versatile and commercial form of energy previously unavailable. By burning coal to produce steam for turbo-generators, industries and households gained access to electricity, which met a variety of needs ranging from lighting to machinery operation. This innovation fundamentally shifted energy consumption patterns, establishing electricity as a central component of modern economies.

2.2 Conditions for Energy Transition into Coal

Recent studies of energy transitions underscore the gradual yet transformative shifts to fossil fuels such as coal, noting consistent factors that influenced this process. Key drivers included prolonged experimentation and upscaling phases, particularly in regions where technical challenges related to mining, transportation, and combustion needed to be overcome. Smaller nations, despite often possessing substantial coal deposits, occasionally bypassed the coal stage altogether, moving directly to reliance on oil imports [9].

The transition to fossil fuels facilitated a significant increase in per capita primary energy consumption, enabling societies to surpass the constraints of biomass fuels and manual labor as they harnessed coal for industrial growth. In the United Kingdom, regional wood shortages in the sixteenth century increased the costs of fuelwood and charcoal, intensifying the demand for an alternative energy source. By the seventeenth century, nearly all major coalfields in Britain had been established, and coal became a vital fuel for households and various industries, including metalworking and construction [9]. This shift necessitated innovations in coal handling, such as water-powered ventilation systems and the use of human labor for mine excavation. Additionally, the development of reverberating furnaces around 1610 allowed coal to replace wood in processes like glass making and, later, iron smelting with coke.

Outside the UK, coal's adoption spread more gradually; it became the principal energy source in parts of Europe, such as France, only in the latter half of the nineteenth century. In colonial America, coal extraction began in the mid-eighteenth century but did not significantly impact national energy supplies until the 1860s. By 1884, coal had surpassed wood as the primary energy source in the United States, cementing its role in powering the country's industrial expansion [9].As figure 2.3 highlights, the advent of coal allowed multiple industries to spring up across the UK, US and Germany.

In Britain and North America, coal's dominance allowed both domestic industry and imperial expansion, enabling increased production and facilitating the transport of goods through coal-powered steamships and railroads. By the early twentieth century, British coal output reached its historical peak at 292 million metric tons. Also, the availability of high-energy-density coal suitable for steam engines was a significant factor in Britain's dominance of nineteenth-century maritime transport, as neither France nor Germany possessed large coal reserves of similar quality [9].

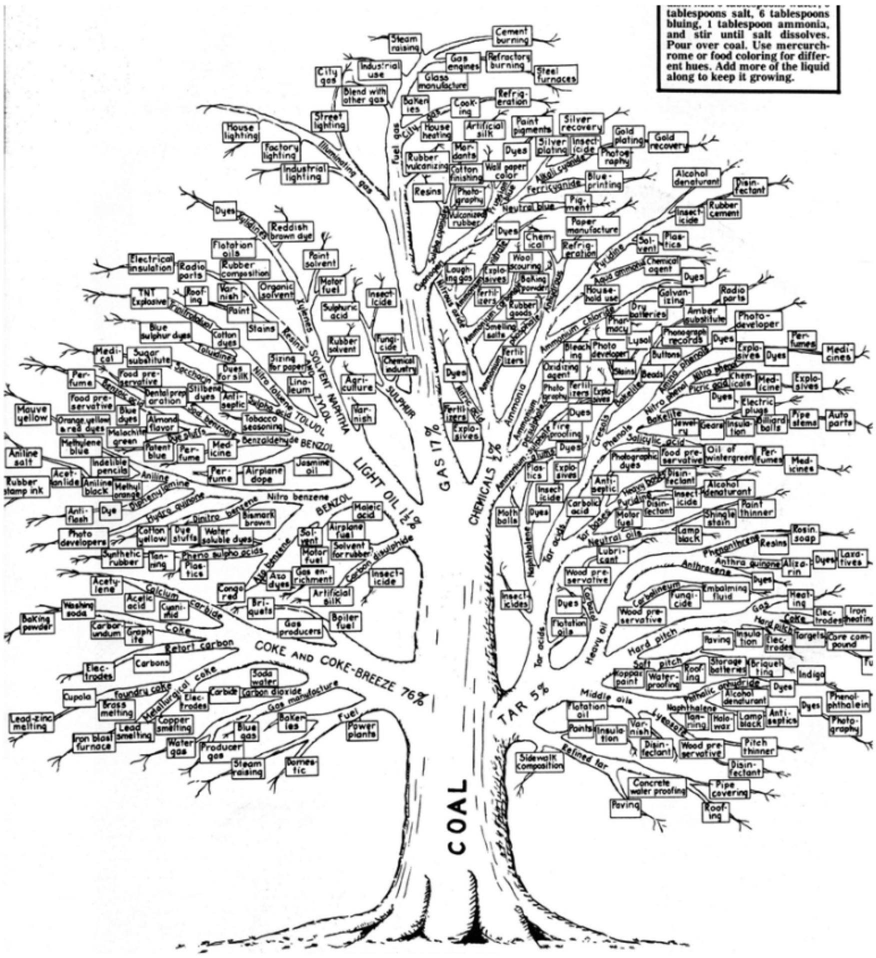


Figure 2.3: Coal tree showing the importance of coal for various sectors in 1935 [3]

The dominance of coal in the UK persisted well into the twentieth century, with coal providing 91 percent of the country's primary energy by 1950. Interestingly, the UK has phased out coal from its economy as of 2024 [17], after more than 250 years of dependence on coal. On the other hand, American coal production peaked in 2001 at 1.02 gigatons, with over 90 percent used for electricity generation by the mid twentieth century though, since then there has been a significant decline.

2.3 How Coke Changed the Game

By the mid nineteenth century, charcoal remained the primary fuel of choice for the iron and steel industry [9]. But, with the increasing scale of production, the industry quickly adopted anthracite and, subsequently, coke as the dominant smelting fuel by 1875. Initially, coke production was inefficient, utilizing enclosed beehive ovens that produced considerable waste .

A significant breakthrough came with the adoption of by-product coking ovens, which allowed for the recovery of valuable by-products: CO-rich gases for fuel, tar, benzol, toluol as raw materials, and ammonium sulfate for fertilizer [18]. This technological advancement began in Europe in 1881 and in the United States in 1895, revolutionizing coke production through improved design and resource efficiency [19]. The puddling process to convert pig iron to bar iron was also developed in the 1780s [3], further improving the capabilities of the manufacturing industries that were dependent on the iron and steel industry.

This started a massive expansion of the iron and steel industry in the UK and US which later took form in other countries such as Germany and France. The adoption of coke-fueled furnaces also supported larger and more productive furnaces. Whereas the best charcoal-fueled furnaces could produce less than 10 tons of pig iron per day, coke-fueled furnaces by 1900 were capable of outputs exceeding 250 tons per day. This leap in productivity helped drive a massive increase in global pig iron production, which rose from approximately 800,000 tons in 1750 to about 30 million tons by 1900. This expansion laid the groundwork for the development of the modern steel industry post-1860, establishing iron as a crucial material for industrialization [9].

Figure 2.4: Blast furnace from Pittsurgh [4]

While the efficiency of coke use in smelting (measured as kilograms of coke per kilogram of hot metal) has steadily improved, the global scale of pig iron production has risen significantly. From around 30 million tons in 1900, worldwide pig iron output reached approximately 1.2 billion tons by 2015. This growth in turn drove an increase in coking coal production to around 1.2 billion tons, underscoring the continued reliance on coal-derived fuels in heavy industry even amidst efficiency improvements and technological advances [9].

Coke, created through coal pyrolysis, offered greater strength and higher energy density, supporting taller furnaces with larger loads and reducing the need for forest resources. This adaptation not only allowed the expansion of the iron industry but also shifted environmental pressures, sparking an era where industrial expansion was closely linked with large scale fossil fuel reliance and further ecological impacts [9].

2.4 Steam Engines and Their Role in Coal Energy Conversion

The steam engine marked a significant breakthrough in energy technology. This innovative machine effectively transformed coal's chemical energy into mechanical energy, representing a pivotal advancement in harnessing fossil fuels for economic growth and industrial development. Unlike wind and water, which relied on solar radiation, the steam engine was the first inanimate prime mover powered by fossil fuels.As coal mining expanded, it created a reciprocal relationship with steam engine development. The demand for deeper coal extraction necessitated more efficient water pumping methods, leading to the invention and implementation of steam engines in mines. The availability of cheaper coal fuel further fueled the proliferation of steam technology, enhancing mining operations with additional powered machinery for winding and ventilation [9].

Initially, Newcomen steam engines spread to English mines around 1750, but their inefficiencies limited their practical applications, particularly in areas where coal had to be transported. However, the introduction of James Watt's improved steam engine in 1769 resulted in immediate commercial success and significantly expanded its applicability beyond mining, impacting manufacturing and transportation industries. Early steam-powered river vessels relied on paddle wheels, similar to fully rigged sailing ships. Over time, larger and faster steamships began to replace sailing vessels on major passenger and cargo routes, particularly across the North Atlantic and eventually on long-distance journeys to Asia and Australia. Coal-fired oceangoing ships played a crucial role in U.S. foreign policy during this period [20].

The adoption of steam engines for overland transport experienced a gradual start but quickly gained momentum with the rapid expansion of railways. This railway boom resulted in an unprecedented de-

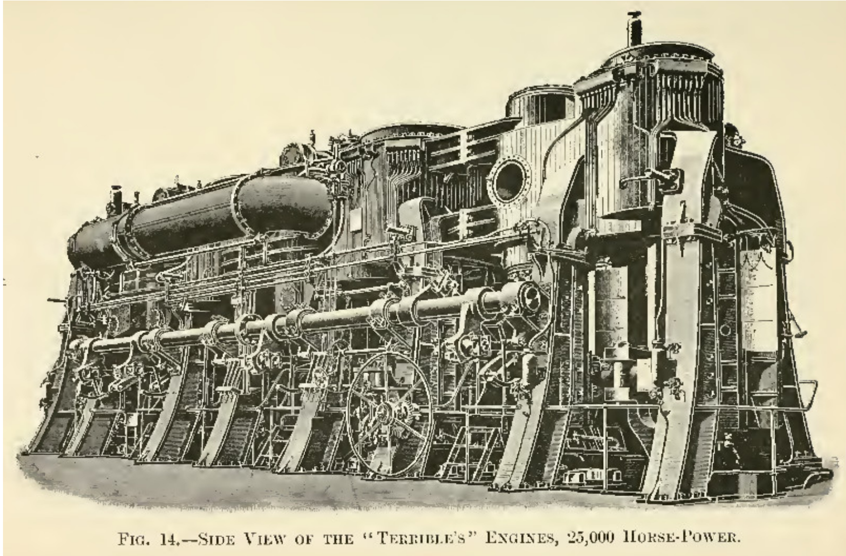


Figure 2.5: The steam engine of a British navy ship [5]

mand for steel during the latter half of the nineteenth century. Various industries required vast amounts of metal: the steel industry for production, the electrical sector for infrastructure, and transportation for the construction of steel-hulled vessels. Rails made from affordable Bessemer steel became the primary finished product, underpinning the expansion of rail networks and further driving industrial growth [9].

Despite their transformative impact, steam engines eventually revealed limitations due to their inefficiencies. By 1900, typical steam locomotives wasted approximately 92 percent of the coal consumed, posing significant challenges for broader mobile applications beyond rail and water transport, where their weight constrained usage [9]. The shift towards internal combustion engines became feasible with the availability of inexpensive liquid fuels derived from crude oil, which offered higher energy density, cleaner combustion, and easier transportation and storage. Although coal remained the predominant transportation fuel during the first half of the twentieth century, the transition to diesel engines in locomotives and ships accelerated after World War II. All new high-speed trains developed since then, including Japan's Shinkansen and France's TGV, have been powered by electric motors [21].

2.5 Electricity Generation and the Shift away from Coal

Faraday's discovery of converting mechanical energy into electricity through alternating current paved the way for electricity generation independent of traditional, low-energy-density storage systems like batteries. This marked a significant transition in energy use, as coal consumption began to shift dramatically in the industrial landscape [9]. Two principal trends emerged. While traditional markets in industry, households, and transportation diminished, gains in coal-based electricity generation compensated for these losses. The displacement of coal in household heating by cleaner alternatives, particularly natural gas and electricity, highlighted the evolving energy landscape.

Beginning in the 1880s, coal combustion initiated thermal electricity generation in traditional coal-mining nations. This reliance on coal expanded rapidly, especially post-World War II, as large central power plants were constructed, making coal increasingly affordable [9]. By the 1950s, coal was the primary source of electricity generation in the United States, the UK, Germany, Russia, and Japan. Although oil gained traction in the 1960s, the oil crises of the 1970s prompted a renewed dependence on coal, particularly in countries like China, India, and the United States.

Tracking the growth of energy services over time reveals a compelling narrative of efficiency improvements. Early conversions of fossil fuels were characterized by significant inefficiencies, with coal-fired heating and electricity generation achieving less than 20 percent efficiency [22]. The highest losses were observed in thermal electricity generation by low efficiency of steam turbines (eg.Parson's steam turbines) and in transportation.

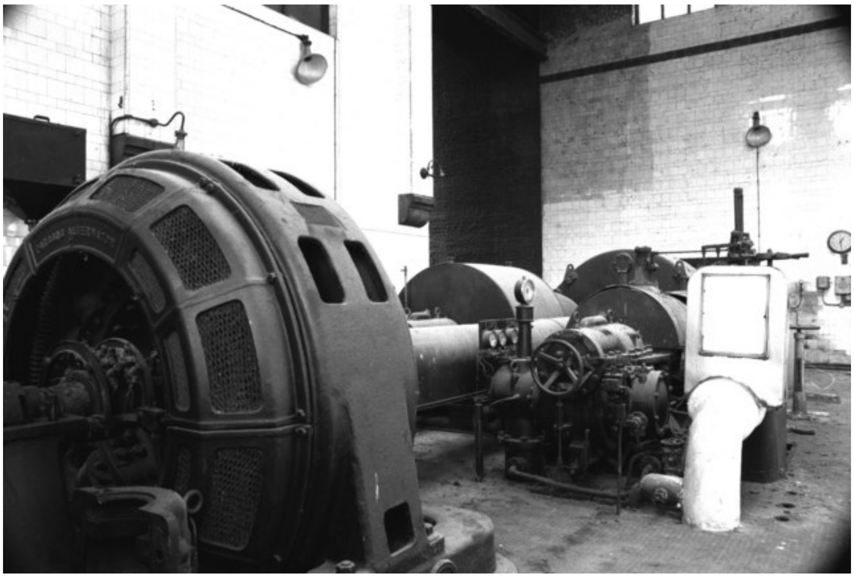


Figure 2.6: Parson's steam turbine [6]

The average efficiency of global energy use increased from 20 percent in 1900 to over 35 percent by 1950 and reached approximately 50 percent by 2015. Notably, the adoption of efficient boilers and gas stoves accelerated the transition to more efficient energy systems within just a few decades [22]. The transition to coal has not only enabled the rise of steam engines and electricity generation, spurring economic growth but also set the stage for ongoing advancements in energy efficiency and productivity.

The discovery of oil and gas fields accelerated the transition away from coal, especially in the UK [23].

2.6 Environmental Impacts of the Coal Transition

Coal's role in the early industrial age highlights the complex relationship between economic development, energy transitions, and environmental costs, as the demands of production and urbanization shaped landscapes, altered ecosystems and caused widespread pollution [9].

Even though coal as a fuel is seen as a major polluting source, it offered multiple advantages over its predecessor, charcoal. In Europe, the environmental implications of industrial coal use became evident as early as the 1820s. Forests had long been essential to iron production, but rising demand led to unsustainable rates of deforestation. For example, Belgium's forests in 1820 were primarily used for charcoal production to supply the metallurgical industry [9]. The transition to coal and coke relieved this intense resource pressure, as ironworks could now operate independent of forest proximity, leading to both industrial and ecological restructuring across Europe.

Similarly, in the United States, pig iron production in the early nineteenth century relied heavily on charcoal from clear-cutting old-growth forests. By 1810, 49,000 tons of iron required nearly 1 million tons of wood, which placed a significant strain on forest ecosystems. By 1840, all American iron production still depended on charcoal. The rapid shift to coke in the following decades provided a viable alternative to wood, aligning with the industrial need for larger furnace capacities to meet rising demand. By 1880, nearly ninety percent of America's iron was produced using coke, mitigating deforestation pressures and enabling more sustainable growth in production [9].

Although coal enabled scalable energy-intensive processes, the combustion of coal, with its sulfur and ash content, led to substantial air pollution. Fly ash and sulfur dioxide emissions contributed to visible particulate matter and acid deposition, heavily polluting urban and industrial areas [21]. This environmental impact persisted for centuries before significant reforms began addressing coal emissions. Since the mid-twentieth century, environmental concerns have been reshaping both policy and technology in many countries. This trend is however not uniform throughout the world.

Countries in the global south such as China and India continue to rely on large scale coal-fired power plants for electricity, despite growing environmental concerns [24]. In cities like Chennai,India coal power plants continue to cause serious environmental issue and deepen societal crises [7]. Southeast Asia's coal boom could cause 70,000 deaths per year by 2030, in countries such as Vietnam, Indonesia and

Figure 2.7: Ennore thermal power plant, a site of conflict between different economic activities [7]

Myanmar, a Harvard study says [25].Despite abundant global coal reserves, the environmental impacts of coal extraction and combustion present a potential limit to its future use [20]. In the longer term, coal extraction is expected to be curtailed due to ecological considerations, reflecting a growing awareness of the environmental costs associated with fossil fuel dependence. This potential transition highlights the complex interplay between energy needs, environmental sustainability, and the evolution of industrial power systems.

3

Bibliographic review

Contents

3.1 Energy flows vs Exergy flows

The first law of thermodynamics states that in every cyclic process either work is converted into heat or heat is converted into work. In this sense, it makes no distinction between work and heat except to indicate a means of measuring each in terms of equivalent units [26]. Once this technique of measurement is established, work and heat become entirely equivalent for all applications of the First Law. In thermodynamics, energy efficiency (η) is defined by the equation:

$$\eta = \frac{\text{Useful energy output}}{\text{Primary energy input}} \tag{3.1}$$

This equation, derived from the first law of thermodynamics only deals with the initial and final states of the process to define the efficiency of the energy conversion. The quality of the transformations that took place between heat and work during this process were not really defined [27]. The Second Law of Thermodynamics, on the other hand, marks the distinction between these two quantities by stating that heat from a single source whose temperature is uniform cannot be completely converted into work in any cyclic process, whereas work from a single source can always be completely converted into heat [26].

The thermodynamic performance at each step can be measured with respect to 'exergy' or the potential of an energy flow to do work till it achieves equilibrium with the environment. Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above-mentioned components of nature" [28]. In other words, exergy offers a measurement of the quality of the thermodynamic process. Thermodynamic losses can be measured in terms of 'exergy destruction' [27] .

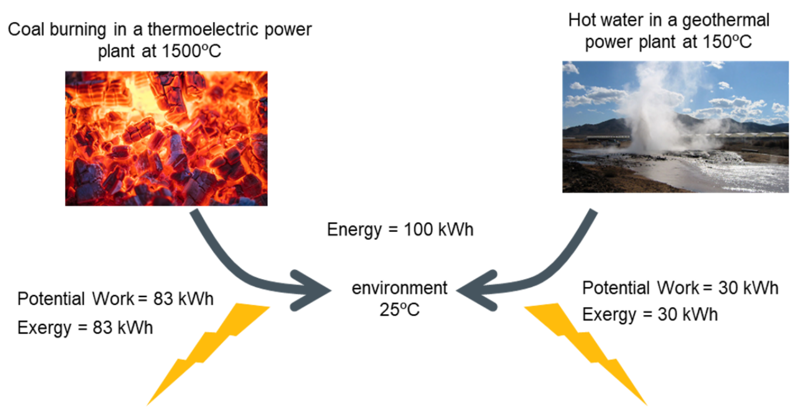


Figure 3.1: Exergy vs Energy - A simple example

Consider the example on figure 3.1. Some coal is burning in a blast furnace at 1500℃ and some hot water in a geothermal power plant at 150℃. Assume that both the coal and the hot water have 100kWh of energy. The coal's heat can perform 83kWh of work, while the hot water can only manage 30kWh of work. Hence, the heat from the combustion of coal is of higher quality than that of the hot water as reflected in the exergy values for coal and hot water - 83kWh and 30kWh respectively.

To sum up, as Keenan stated: 'The efforts of the engineer are very largely directed toward the control of processes so as to produce the maximum amount of work, or so as to consume the minimum amount of it. The success of these efforts can be measured by comparing the amount of work produced in a given process with the maximum possible amount of work that could be produced in the course of a change of state identical with that which occurs in the process' [26].

Exergy efficiency (ε) is defined by the following equation :

$$\varepsilon = \frac{\text{Useful exergy output}}{\text{Primary exergy input}} \tag{3.2}$$

Theoretical maximum of ε is 100 percent.

Energy and exergy efficiencies of some frequent energy transformations with coal as input [27] are displayed in table 3.1. In these equations, $T_1 > T_2 > T_0 > T_3$. B_{in} is the chemical exergy of the fuel, while η and ε are the energy and exergy efficiencies, respectively.

	Input	Work	Fuel	Heat Q_1 added from hot reservoir at T_1
Output		W_{in}	B_{in} (chemical exergy)	$Q_1\left(1 - \frac{T_0}{T_1}\right)$
Work	W_{out}	$\varepsilon = \eta = \frac{Wout}{Win}$	$\varepsilon = \frac{Wout}{B} \approx \eta$	$\varepsilon = \frac{Wout}{Q_1\left(1-\frac{T_0}{T1}\right)} = \eta \frac{1}{\left(1-\frac{T_0}{T_1}\right)}$
Heat Q2 added to warm reservoir at T2	$Q_2\left(1 - \frac{T_0}{T_2}\right)$	$\varepsilon = \frac{Q_2}{Win}\left(\frac{T_0}{T_2} - 1\right)$ $= \eta\left(1 - \frac{T_0}{T_2}\right)$	$\varepsilon = \frac{Q_2}{Win}\left(1 - \frac{T_0}{T_2}\right)$ $\approx \eta\left(1 - \frac{T_0}{T_2}\right)$	$\varepsilon = \frac{Q_2\left(1-\frac{T_0}{T_2}\right)}{Q_1\left(1-\frac{T_0}{T1}\right)} = \eta \frac{\left(1-\frac{T_0}{T_2}\right)}{\left(1-\frac{T_0}{T_1}\right)}$
Heat Q3 extracted from cool reservoir at T3	$Q_3\left(\frac{T_0}{T_3} - 1\right)$	$\varepsilon = \frac{Q_3}{Win}\left(\frac{T_0}{T_3} - 1\right)$ $= \eta\left(\frac{T_0}{T_3} - 1\right)$	$\varepsilon = \frac{Q_3}{B}\left(\frac{T_0}{T_3} - 1\right)$ $\approx \eta\left(\frac{T_0}{T_3} - 1\right)$	$\varepsilon = \frac{Q_2\left(\frac{T_0}{T_3}-1\right)}{Q_1\left(1-\frac{T_0}{T1}\right)} = \eta \frac{\left(\frac{T_0}{T_3}-1\right)}{\left(1-\frac{T_0}{T_1}\right)}$

Table 3.1: Exergy and energy efficiencies of transformations - Coal

3.2 Societal Exergy Analysis

If we apply the exergy approach to study the exergy flows of a society, we can get deeper insights on the thermodynamic quality at different stages of the processes involved. We can find out how and where the losses can be observed in the energy life cycle - from primary to secondary to final to useful exergy of different societies, leading to more nuanced comparisons. Societal exergy studies of the past have been primarily used for two types of applications:

1. **To characterize historical energy consumption or forecast future energy consumption** : There have been multiple studies on estimating exergy efficiencies at the global level and also for countries such as Austria, Portugal, US etc. Some discoveries from exergy analysis studies include the relationship between the usage of less efficient primary energy resources and exergy efficiencies. Societal exergy analyses have also uncovered important effects such as the Efficiency dilution effect. These studies have also been used to perform predictions of the future declines in the rate of exergy efficiency improvement [27].

2. **Studying the role of energy (exergy) in economic growth**:

   Long term studies performed on the useful exergy intensity in Portugal [29] and 15 European countries found that the variation in exergy intensity was based purely on the end usage of high temperature heat and residential heat. There was also a strong correlation observed between the Solow residual (exogenous growth) and the useful exergy [30] [31]. Hence, there is a significant potential in pursuing societal exergy analysis for past and future societies.

3.2.1 Approaches to Data Inputs in Societal Exergy Analysis

Within the methodological frameworks identified for societal exergy analysis, there are two main approaches used to account for input flows: energy resources (ER) and natural resources (NR) [27].

1. **Energy Resources (ER) Approach**: This approach focuses exclusively on traditional energy resources used for energy services, including electricity, fossil fuels, biomass, and some renewable sources like passive solar energy and wind for sailboats. In this method, exergy transformations are tracked from primary energy sources through final and useful energy levels, leading to energy services such as heating or mechanical work.

   For example, in the cement industry, coal (an ER input) is used to produce high-temperature heat, with exergy losses considered at each transformation step. However, distinguishing between the materials used for energy services and non-energy purposes, like the dual role of metallurgical coke in steel production, can be complex. So, this approach can be used during the absence of clearcut datasets for the natural resources involved in the energy flows, and focuses more on the amount of energy that gets transformed. [27].

2. **Natural Resources(NR) Approach**:

   This broader approach includes not only traditional energy resources but also other natural resources, like agricultural products, forest materials, and mined ores. Here, exergy is a universal metric, representing the potential energy available as materials return to a stable reference state, usually the earth's crust.

   For instance, iron ore holds exergy that is consumed when it's converted into steel. Recycled materials retain part of this embedded exergy, which can reduce the need for new exergy inputs; recycling steel, for example, uses much less energy than producing it from iron ore. This method effectively addresses recycling and resource conservation but lacks clear distinctions between end-uses (e.g., heating versus mechanical work), which are better captured in the ER approach.

3.2.2 Issues in Obtaining Exergy Efficiency

Exergy efficiencies in societal exergy studies often lack consistency due to variations in the granularity of end-uses across sectors and insufficient data. This inconsistency, along with differences in how energy resources are allocated to end-uses, affects overall efficiency estimates [27]. To accurately assess exergy efficiencies, we must first allocate final energy resources to their respective end-uses . Higher disaggregation levels typically correlate with more detailed end-use categories.

Aggregated exergy efficiencies can be calculated from primary (or final) to useful energy stages. However, caution is necessary when comparing efficiencies, as thermoelectricity (electricity generated from burning coal, biomass, oil, or natural gas) exhibits lower primary-to-final efficiency than other fuels like diesel or gasoline. Key factors influencing the accuracy of exergy efficiency estimates include the quality of data on:

1. Time-independent allocation of energy resources to end-uses (excluding electricity)
2. Time-dependent allocation of electricity to end-uses across different sectors,
3. First-law efficiencies and process temperatures in various industries [27].

For studies post-1971, the IEA databases provide a reliable mapping method, but for pre-1971, data can be challenging to obtain. Alternative data from past published studies need to be used when necessary.

3.3 Energy Transformation Chain

The energy transformation chain is a framework used to perform societal exergy analysis. This framework helps us understand how energy transitions occur through various stages—from extraction as primary energy to its final useful applications as shown on figure 3.2. The following section will explore the energy conversion chain, illustrating the processes and transformations that occur at each stage.

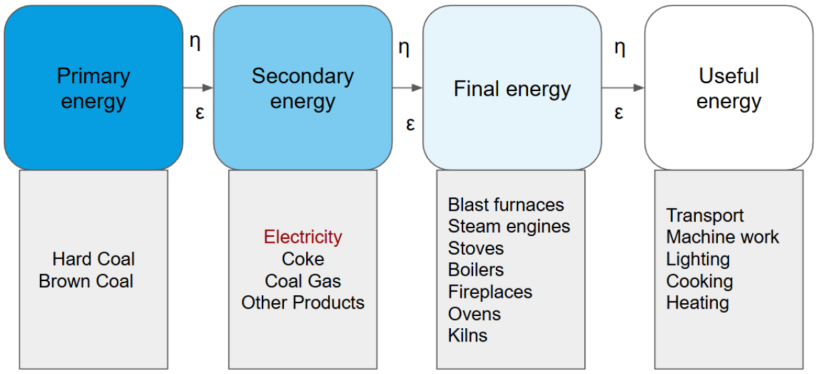


Figure 3.2: Stages of the societal exergy analysis

3.3.1 Primary Energy Stage

The primary energy stage refers to energy extracted directly from natural resources before any conversion processes occur. In the context of fossil fuels, primary energy is often quantified by its heating value, which is the amount of energy released during combustion. For coal, primary energy is derived from mining activities, which can occur through surface or underground methods, depending on the type of coal being extracted. The primary energy of coal is studied only for two categories in this research : Hard coal, and brown coal.

Using standard units such as Joules or Megawatt-hours to measure coal's energy flows for different types of coal could be misleading. This is because such measurements might fail to capture critical qualitative differences among various energies. Two kinds of coal may have an identical energy density, but one may burn very cleanly and leave behind only a small amount of ash, while the other may smoke heavily, emit a great deal of sulfur dioxide, and leave a large incombustible residue [9]. For the purposes of this research, Anthracite, Bituminous coals are considered to be hard coal, while lignite is considered to be brown coal. Peat is excluded unless included in the general values for coal. Considering this,the standard values in table 3.2 are assumed [9].

The extraction process involves significant energy input for both the mining operation and subsequent

Coal Type	Energy Density (MJ/kg)
Anthracites	31–33
Bituminous coals	20–29
Lignite	8–20
Peats	6–8

Table 3.2: Energy density of different types of coal

transport, and understanding this stage is crucial for assessing the overall energy efficiency of coal as an energy source [32].

3.3.2 Secondary Energy Stage

A part of the mined coal undergoes transformation into secondary energy forms such as coke, coal gas and electricity. This transformation occurs in various facilities, such as coke furnaces, gas plants, and coal power plants.

The key secondary energy stage products include:

1. **Coke**: Produced in coke ovens, coke serves as a vital reducing agent in the blast furnace during the iron and steel manufacturing process. The production of coke involves the pyrolysis of coal, where volatile substances are removed, leaving behind carbon-rich material.

2. **Coal Gas**: Historically produced in gas plants, coal gas (or town gas) consists primarily of hydrogen and carbon monoxide and was widely used for heating and lighting in urban areas before the widespread adoption of natural gas.

3. **Electricity**: Generated at coal power plants, this electricity is derived from the combustion of coal to produce steam, which drives turbines to generate electricity.

4. **Other Coal Products**: These products includes coal bricks and similar processed solid forms of coal. Solid fuel plants transform raw coal into value-added products through methods such as briquetting or carbonization. Coal that did not undergo transformation is also included here and will directly enter the final energy stage.

3.3.3 Final Energy Stage

The final energy stage represents the energy available for end-use applications . It should be seen as the preceding stage to end uses.

1. **Coke for Heat**: Coke was used for multiple heating applications. Industries and other end users sourced coke from coke oven for providing sustained heating.

2. **Coal Gas for Light and heat**: Historically, coal gas was used in gas lamps for lighting in residential and commercial sectors, providing essential illumination before the advent of electric lighting. After production in gasworks and coke works, coal gas was supplied to end users for consumption.

3. **Solid Coal and Solid Coal Products for Heat**: Solid coal and solid coal products were shipped to various end users such as coal furnaces, coal boilers, and stoves. These devices converted the chemical energy in coal into heat for different heating purposes.

4. **Solid Coal and Solid Coal Products for Mechanical Work**: Coal is also transformed into mechanical work through steam engines which generate mechanical energy for transportation, including steam trains and ships. Many industries employed static steam engines to do mechanised work.

3.3.4 Useful Energy Stage

The useful energy stage refers to the final energy that is effectively utilized by end-users. This stage focuses on the practical end uses of energy, such as:

1. **Heat**: Residential, Commercial, Public and industrial sectors obtain the heat after consuming the coal-based energy sources. For example, the iron and steel industry utilizes the heat generated from combustion of coke in the production of pig iron using blast furnaces.

2. **Light** : Various sectors such as residential, commercial and industrial sectors benefit from the light produced by the combustion of town gas in lamps.

3. **Mechanical Work** : The transportation sector harnesses mechanical work from coal-powered steam engines for providing transportation services for ships and trains. Other sectors use static steam engines for performing mechanical work.

The final energy delivered to various sectors serves diverse needs and each sector can have a multitude of requirements . For instance, the iron and steel industry relies heavily on coke-derived heat but also needs mechanical work from steam engines. Residential and commercial sectors benefit from light and heat from different energy carriers. Additionally, coal and coal products provide heat and work for agriculture, fishing, and forestry sectors, while coal and coal products for mechanical work support the transportation sector and mining operations. [33] .

3.4 Databases

The volume of data in the study of historical energy trends is massive, and hence selecting the appropriate datasets is crucial to obtain relevant data. Each database offers unique methodologies, timelines, and geographic scopes, leading to distinct interpretations of how energy consumption and production have influenced economic and industrial development. As Mulhall mentions in the section 'Statistics' in his 'Dictionary of Statistics': 'The library of the Royal Statistical Society comprises 27,000 volumes, and is far from complete. There are at least 50,000 statistical works extant, and if a student were able to examine three of them daily he would require 50 years to get through them. More than 500 new works in Statistics are published yearly' [34].

The data obtained has to fit into the exergy methodology and should not require too much additional processing and should be consistent with other datasets. Datasets here refer to historical databases, economic studies and other literature. However, no single dataset comprehensively captures all aspects of global energy trends. Some focus on consumption, while others emphasize production, imports, or exports, and the coverage of fuels can vary widely. Furthermore, different datasets offer varying levels of granularity, from global overviews to detailed country-specific data. Comparing these databases becomes essential to identify the strengths and limitations of each, fill in missing data gaps, and select the most appropriate sources for specific research needs. Hence, a comparison table was created to make the process easier, as seen on table 3.3.

Database	**Consumption/ Production**	**Energy units / Mass units**	**Global/ Region/ Country**	**Timeline start**	**Timeline end**	**Coal/ Oil/ Gas / Wood**	**Comments**
Malanima	C	E	G/R	1820	2018	C/O/N/W	Extensive database with improvements over older datasets, particularly for woodfuel data.
Luciani	C/P	E/M	G/R/C	1750	1985	C/O/N	Pre-1800 data available at times. Extensive database.
Mitchell	P	M	R/C	1750	1993	C/O/N	Outdated values but extensive data coverage.
IEA	C/P	E	G/C	1971	2020	C/O/N	Highly accurate and recent data.
OWID	C	E	G	1800	2023	-	Online, discrete datasets providing global coverage.
Yearbooks	C/P	M	C	1853	2022	C	Government statistics, reliable and historical records.
Victor Court	C	E	G	1800	2014	C/O/N/W	Minor improvements on older databases, woodfuel modelled.

Table 3.3: Comparison of different databases

Paolo Malanima's database and Victor Court's work both emphasize global energy consumption, spanning from 1800 and 1820, respectively, to recent years (2014 and 2018). Malanima includes data for coal, oil, natural gas, and wood, with the additional estimation of woodfuel data [35], while Court includes malanima and collates the data with other similar energy sources [36]. Both datasets offer global insights, but Malanima covers regions, providing a more granular breakdown.

Luciani's Production Energy Mondiale focuses on regional and country-level energy consumption, particularly for coal and natural gas. The synthesis section of Luciani shifts the emphasis to production data), across a similar historical timeline (1800-1985) but also providing data on peat and lignite [37]. Unlike Malanima and Court, Luciani provides detailed insights into specific coal types and their role in industrialization, especially in European countries.

B.R. Mitchell's historical databases extend beyond consumption to include both production and import/export data [38] [39] [40]. His dataset relies on government statistics, offering reliable, country-level data from 1750 to 1993. Similar to Luciani, Mitchell covers coal, oil, and natural gas, but his focus on both production and trade allows for a more comprehensive analysis of energy flows within national economies.The dataset formed the basis for many later studies, but some datasets have since been updated.

The International Energy Agency (IEA) database provides consistent data on production and consumption for different fuel sources at global, regional and national levels. The period covered by this database is between the years 1960-2022. However, consistent data is found after 1971, which is also the year which is used as the point of division between earlier datasets and the IEA data [41]. For coal, an extensive dataset including coal products, transformation and sector wise usage is available on the IEA database.

Our World in Data provides a global overview of energy consumption trends from 1800 to 2023. While similar to Malanima and Court in its focus on consumption, it lacks data on imports and exports but is highly accessible and regularly updated for modern energy consumption studies [42].

For the analysis of the 4 major coal producing countries - UK, US, France and Germany - historical statistics published by the governments were used. The UK Government's dataset mirrors the IEA's focus but is limited to the United Kingdom, offering detailed historical data from 1853 to 2022, specifically on coal, oil, and natural gas production and trade. Previous research by MARETEC members was quite instrumental in collecting relevant datasets. Data on transport at the world level was sourced from earlier research by Bernardo Tostes [43]. Data on iron and steel at the world level was sourced from the thesis by Aurora Carvalho [44], and electricity from coal data was sourced from earlier work by Ricardo Pinto [45]. The datasets mentioned without references are from Prof.Sofia Henriques' unpublished economic research.

4

Methodology

Contents

4.1 Societal Exergy accounting - Core methodology

The methodology employed for this study involves the ER (energy resources) approach, which involves the building of the complete energy flows of coal from the primary stage to the final stage [27]. Energy used for non-energy services are excluded in this approach. In the scope of this study, this would mean the development of global and national energy flows from primary to final stage, followed by the calculation and allocation of exergy for each stage and end-use, and then calculating the individual exergy efficiencies followed by the aggregated exergy efficiencies.

4.1.1 Coal Transformation Chain

The coal transformation chain is the reference framework used for performing the societal exergy analysis. To obtain a complete energy dataset from end to end based on available historical data was a challenge. To overcome that, and to find the stage-wise energy flows, the coal transformation chain, as shown on figure 4.1 was used .

The equations to be used in the framework were defined in table 4.1. Some of the variables were known from previous datasets, while some were newly defined to allow better handling of data.

Table 4.1: Coal Terms, Sectors, and Process Terms.

Coal Terms	Variable	Sectors	Variable	Process Terms	Variable
Coal production (mass)	P	Iron and Steel industry	IS	Energy for Heating	H
Coal consumption (mass)	C	Other industries	IO	Energy for Work	W
Hard coal (mass)	HC	Residential, Commercial, Public	RCP	Energy for Lighting	L
Brown coal (mass)	BC	Agriculture, Fishery, Forestry	AFF	Energy Losses	Xn
Coke in mass	CC	Transport	T	Chemical Energy	E
Coal gas	CG	Mining	M	Final energy	F
Remaining coal	CP	Non-Iron and Steel Industries	OS	Useful energy	U
Electricity	CE	Bunkers	B	Carnot efficiency	η
Coke in blast furnace	CCF	Steam ships	SH	Exergy efficiency	ϵ
		Steam trains	ST		
		Static Steam Engines	SS		

Using the variables, figure 4.1 was developed. It represents the coal transformation chain showing the different steps involved in the coal energy flows.

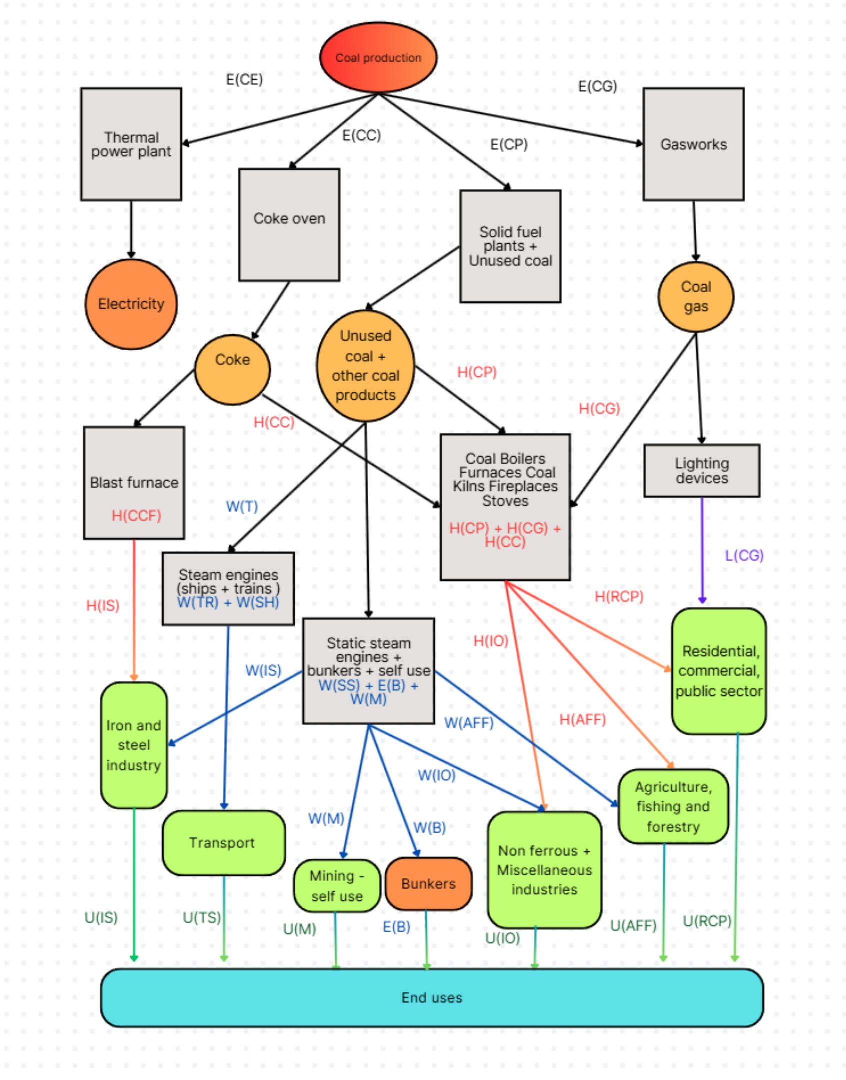


Figure 4.1: Coal Transformation Chain

4.1.2 Mathematical Formulation - Coal Transformation Chain

The following table explains the step by step methodology applied using the variables to obtain the data points required for the societal exergy analysis .

No.	Methodology	Equations	Description
1	Find the total coal production and consumption as a primary energy source for the world for the timeline 1800 AD - present using the available datasets	$E(P) = E(C) + Xt$	Coal Production = Coal Consumption + Total Losses
		$P = BC + HC$	Coal Production = Sum of production of Hard coal and Brown coal
		$E(P) = E(CE) + E(CC) + E(CG) + E(CP) +$ Losses	Energy of coal = Energy of 4 products in the form of coke, coal gas, electricity and other coal products + transformation losses
2	Remove the amount of coal used for electricity production at the global level from the remaining coal	$E(P) - E(CE) = E(CC) + E(CG) + E(CP) +$ Losses	Since the end product is electricity unlike other steps which involve heat and work, the conversion of coal based electricity till the useful stage is not pursued. Coal for electricity production values obtained from research by R.Pinto [45]
3	Split the energy from coke for iron and steel industries and for other heating purposes	$0.75E(CC)\eta = H(CCF)$	75 percent of the energy from coke (converted from coal) = Energy available in blast furnaces. Split based on US 1935 values [46].
		$0.25E(CC) = H(CC)$	25 percent of the energy from coke (converted from coal) = Energy from coke for heating non-iron and steel sectors
		$H(CCF) = H(IS)$	Energy of Coke sent to blast furnace = Energy allotted for heating for Iron and Steel industry.
4	Find the coal used for industrial production for non-iron and steel industries and sectors by deducting coal used for electricity and iron and steel industries (as coke)	$E(P) - E(CE) - E(CC) = E(CG) + E(CP) +$ Losses	The energy obtained from coal gas and other coal products provides the energy utilized by non-iron and steel sectors which is the sum of energy from other coal products and coal gas.
5	Allocate the energy from coal products into energy for heat and work	$E(CP) = H(CP) + W(CP) + XCP$	Energy in other coal products = Energy for Heat from other coal products + Energy for Steam engine work using other coal products + Losses in the transformation process.
6	Split the energy for work done by the steam engines into two - Steam engines for transport and Static steam engines	$W(CP) = W(T) + W(SS)$	Energy for steam engine work using coal and other coal products = Energy for work done by engines in transport sector + Energy for work done by static steam engines.

7	Find the installed power of static steam engines and convert into energy delivered per year to static steam engines for work	$W(SS) = 300 \times 24 \times (1 - D) \times P$	P is the installed static steam engine capacity [34], D is the proportion of downtime [22], 300 days is on the assumption of 6 work days per week, and 24 is the number of hours per day.
8	Find energy for work done by steam engines in ships and trains	$W(T) = W(TR) + W(SH)$	Energy used for work done by steam engines in ships and trains is equal to the energy from coal for transport. Coal used for transport values obtained from research by B.Tostes [43]
9	Allocate the remaining energy for work done by static steam engines for industries, agriculture, forestry, fisheries, mining self-use, and for transport and bunkers	$W(CP) - W(T) = W(IS) + W(AFF) + W(IO) + W(M) + W(B)$	Remaining coal and coal products not used for transport = Sum of energy of coal and coal products for work, used for iron and steel industry, agriculture, fisheries and forestry industry, other industries(refer to 4.5), mining self-use, and energy for bunkers.
10	Find the coal used for performing mechanical work in iron and steel industries by deducting the energy for heat supplied by coke	$E(IS) = H(IS) + W(IS)$	For the iron and steel industry, final energy used = Energy for Heat from blast furnace + Energy for work done by static steam engines.
11	Find the coal gas used for lighting and heating	$E(CG) = H(CG) + L(CG)$	Energy from coal gas is split between coal gas used for heating and lighting in the ratio 4:1 , based on UK 1936 values [46].
12	Find the energy used for heating in agriculture, forestry, fisheries, and other industries by deducting the energy for work and light supplied using other coal products and coal gas, respectively	$H(CP) = E(CP) - W(CP)$ $H(CG) = E(CG) - L(CG)$	Heat from coal products is obtained by deducting energy of coal products used for work from the total energy of coal products. For coal gas, the energy of coal gas used for lighting is deducted from total energy available as coal gas.
13	Combine other industries and agriculture, forestry, and fisheries to create a new category - All Other industries, denoted by OS	$E(OS) = E(IO) + E(AFF)$	Decision made due to missing data.
14	Allocate remaining energy for work and energy for heat terms to complete datasets	$W(SS) = W(OS) + W(IS)$ $W(OS) = W(IO) + W(AFF)$ $H(OS) = H(IO) + H(AFF)$	Combined equation displaying energy for work done by static steam engines, allowing use of ratios to split $W(SS)$ based on data availability.

15	Split the energy for heat based on the type of industry or sector into low temperature heat (LTH), medium temperature heat (MTH), and high temperature heat (HTH) - with temperatures (celsius) of 120, 300 and 600 degrees	$H_i = a(LTH) + b(MTH) + c(HTH)$	H_i refers to the type of industry or sector (residential, all other industries, iron and steel industry, etc.). a, b, c are proportions decided based on standardized 1929 energy usage by industry or sector for the US [46].
16	By this step, variables till the final energy stage have been calculated. Find useful energy delivered to end user by applying Carnot efficiency (heat) and mechanical efficiency (work)	$U = F \times \eta_i$	U is the useful energy for that specific sector or industry. F is the final energy for that specific sector or industry. η_i is the efficiency based on values provided by Serrenho et al(2014) [47]. Carnot efficiency applied for heat, mechanical efficiency applied for the device performing the work).
17	Convert energy values into exergy for primary, final and useful energy stages	Exergy = Energy $\times k$	k is 1.05 for coke, 1.06 for coal, and 1 for mechanical work based on research by L.Felicio [29]
18	Find total primary, final, and useful exergy across all sectors and find the aggregated exergy efficiency for the world and the 4 countries - US, UK, Germany, France for available consistent data	$\varepsilon_1 = \frac{\text{Final Exergy}}{\text{Primary exergy}}$ $\varepsilon_2 = \frac{\text{Useful Exergy}}{\text{Primary exergy}}$ $\varepsilon_3 = \frac{\text{Useful Exergy}}{\text{Final exergy}}$	$\varepsilon_1, \varepsilon_2, \varepsilon_3$ values are calculated and analyzed based on relevant studies [27].
19	Use linear interpolation and historical sources to complete the exergy efficiency calculation for the entire historical period in consideration (1800 - present) for the world and the 4 countries in consideration	$\varepsilon_1 = \frac{\text{Final Exergy}}{\text{Primary exergy}}$ $\varepsilon_2 = \frac{\text{Useful Exergy}}{\text{Primary exergy}}$ $\varepsilon_3 = \frac{\text{Useful Exergy}}{\text{Final exergy}}$	For the scope of this study, correlation between historical developments and interpolated data is considered to complete data points.

4.1.3 Coal Transformation Chain - Finding Exergy Efficiencies

This section involves a deeper explanation of the steps 15-19 of the methodology to explain the calculation of useful energy and exergy values after obtaining the final energy values. If we consider figure 4.1, we can observe the following : There were 4 different conversions of coal from primary stage into coke, coal gas, electricity and other coal products. As mentioned earlier, the 'other coal products' are a combination of cut coal, coal bricks and other unused coal . The strategies to find missing information are explained in section 4.2.

From the coal transformation chain, work and light were converted into useful energy using efficiencies as described by Serrenho(et.al 2013) [47]. These values are presented in table 4.3.For the energy flows involving work by steam engines, the efficiency of the steam engines was utilized to convert final energy into useful energy based on whether the steam engine was a static steam engine or based on ships or trains [34]. The energy values were then converted into mechanical drive work, a form of useful energy . Similarly, energy efficiency values were used from 4.3 to find the amount of light energy produced from the final energy. The primary energy conversion into electricity was also found out using the efficiency values from table 4.3 .

Mechanical Work/Light	Efficiency
Static steam engine	10%
Train steam engine	6.40%
Ship steam engine	31.60%
Light bulb	2%
Steam turbine	20%

Table 4.3: Efficiency for different mechanical work/light technologies.

For energy flows involving heat, the Carnot efficiency was used to convert the different types of heat into exergy, as elaborated by Serrenho (et.al 2013) [47]. The Carnot efficiency, η, is given by:

$$\eta = 1 - \frac{T_c}{T_H} \tag{4.1}$$

where:

T_c is the temperature of the cold reservoir (298 K)

T_H is the temperature of the hot reservoir.

LTH was defined for the interval (120℃ - 300℃) , MTH for (300℃ - 600℃) and HTH for >600℃. Blast furnace was considered to operate at 1650℃. For calculation purposes, reference temperatures were defined and corresponding carnot efficiencies were calculated as listed on table 4.4.

Heat	Carnot Efficiency	Temperature (℃)
LTH	24.10%	120
MTH	48%	300
HTH	66%	600
Blast furnace	85%	1650

Table 4.4: Carnot efficiency for heat processes

A slight variation of Serrenho's method was employed to fit the available datasets, inspired by the exergy accounting of Portugal [29]. The percentage allocation of coal consumption for heating by industry was obtained from 'Coal in the Industrial Economy' for the year 1929 [46]. This was used as a reference for heat allocation. The percentage of energy from coal required by different sectors was obtained for 1935, in the form of sector wise percentages for the UK, US and Germany. By averaging out the values,the world's sector wise coal usage data was approximated as they made up close to 85 percent of the world's coal consumption in 1929. This is represented in table 4.5.

Non-iron and steel industries	Germany	US	UK	Average (Global)
Food	10.3	13.2	11.7	11.73
Textile	9.7	8.3	23.6	13.87
Forest	3.2	0.4	1.8	1.80
Paper	8.8	11.2	8.8	9.60
Printing	0.5	0.7	0.6	0.60
Chemical	13.9	11.3	12.6	12.60
Petrochemical	3.8	0.7	2.25	2.25
Rubber	1.9	2.5	1.2	1.87
Leather	1.6	0.8	1.2	1.20
Stone/clay/glass	17.5	24.1	26.6	22.73
Miscellaneous	12.8	2.0	1.2	5.33
Other Iron Non-ferrous Machinery Transportation equipment	25.1	18.2	22.5	21.93

Table 4.5: Breakdown of energy usage by sector (1929)

Since each industry listed had different heat requirements,it was necessary to split them into temperature heat (LTH), Medium temperature heat (MTH) and High temperature heat (HTH) usage. The final energy values of each industry and sector was alloted splits as defined on table 4.6 based on historical references . Using efficiencies from table 4.4, useful energy was calculated.

Using the values for useful, primary, and final energy across all sectors, exergy was calculated. The expression for exergy is given by:

$$\text{Exergy} = \text{Energy} \times k$$

$$k = \begin{cases} 0.6 & \text{for coal-based process} \\ 0.5 & \text{for coke-based process} \\ 1 & \text{for mechanical drive (work)} \end{cases}$$

Three types of exergy efficiencies – ε_1, ε_2, and ε_3 – were subsequently calculated :

$\varepsilon_1 = \frac{\text{Final Exergy}}{\text{Primary Exergy}}$	$\varepsilon_2 = \frac{\text{Useful Exergy}}{\text{Primary Exergy}}$	$\varepsilon_3 = \frac{\text{Useful Exergy}}{\text{Final Exergy}}$

Industry/sector	LTH	MTH	HTH
Iron and Steel Industry (IS)			1
Residential, Commercial, Public Sectors (RCP)	0.9	0.1	
Non-iron and steel industries (OS)			
Food	0.5	0.5	
Textile	0.25	0.45	0.3
Forest	1		
Paper	0.5	0.5	
Printing	0.5	0.5	
Chemical	0.5	0.5	
Petrochemical	0.1	0.3	0.6
Rubber	0.25	0.45	0.3
Leather	0.5	0.35	0.15
Stone/ clay/ glass	1		
Other iron	1		
Non-ferrous	1		
Machinery and transportation equipment	1		
Miscellaneous	0.5	0.5	

Table 4.6: Split factor for industries/sectors and heat types (LTH, MTH, HTH).

4.2 Missing Data - Workarounds

4.2.1 Coke

After collation of the different datasets, especially after mapping the energy flows, missing data started to become a big barrier to obtaining reasonable conclusions. One important dataset that was missing was the amount of coke produced from coal. Data was available in some cases for the amount of energy delivered to the iron and steel industry from blast furnaces which were using coke. In other cases, the data was limited to the amount of coal used for coke production. Hence, depending on which data was available , the following conversion factors were applied :

For the pig iron industry in the UK, in 1879, 46000 tonnes of coal were used to make 26000 tonnes of coke. The conversion ratio of tonnes of coke per tonne of coal was hence used as 1.77. This was assumed to be the standard for the pig iron industry [48]. For tonnes of coke per tonne of pig iron production, a conversion factor of 2.14 was applied [49]. In all other cases, conversion ratios were sourced from Prof.Sofia's research, which are mentioned in table 4.7.

Table 4.7: Coal and Coke to Pig Iron Ratios (1875 - 1965)

Year	Coal/Pig Iron	Coke/Pig Iron
1875	2.45813	-
1885	2.06177	-
1895	1.97650	-
1905	2.00416	-
1915	2.14970	-
1925	2.12861	-
1935	1.85993	1.09835
1945	-	1.13207
1955	-	0.96687
1965	-	0.66942

4.2.2 Bunkers and Self-use

For cases where data was not available , a factor of one percent of the total production was applied for the bunkers and 4 percent of the total production for self use. From available historical datasets, the self use by mines was between 1-6 percent of total coal production for the UK . Hence, an assumption to choose 4 percent was applied to all the other datasets. This was a choice made to simplify the larger process of estimating missing data. In the 19th century or earlier, self mining use can reach upwards of 15 percent of the coal production depending on the geography, type of mine, technology, type of coal etc.

4.2.3 Agriculture , Forestry and Fishery

Most datasets for this industry were unavailable, and hence an assumption was made that the energy use for this industry would be fifteen percent of the Non-iron and steel industries. This was based on the ratios between other industries and agriculture, forestry and fishing industries in 1935 for the US. This was applied to all other datasets assuming similar levels of industrial development.

4.2.4 Steam Engines

Data was available from 1840 to 1915 for the capacity of installed steam engine power in 1000 horse-power for the world, UK, Germany and France [34]. To convert this data into energy units for the database, the steam engines were assumed to work for 300 days a year, 24 hours a day. The following formula was used :

$$W(SS) = 300 \times 24 \times (1 - D) \times P \qquad (4.2)$$

- $W(SS)$ is the energy utilized by static steam engines
- D is the downtime factor (proportion of time the steam engine was not operational, in %).
- P is the capacity of the steam engines (1000 HP).
- 300 days per year is assumed, considering 6 workdays per week.
- 24 hours per day accounts for unit conversion of day into hours.

Data for the Downtime factor, which is, was sourced from Fouquet's Heat, Power and Light for 1760 - 1910. The remaining values were estimated using linear interpolation.

Table 4.8: Downtime Factor for Steam Engines

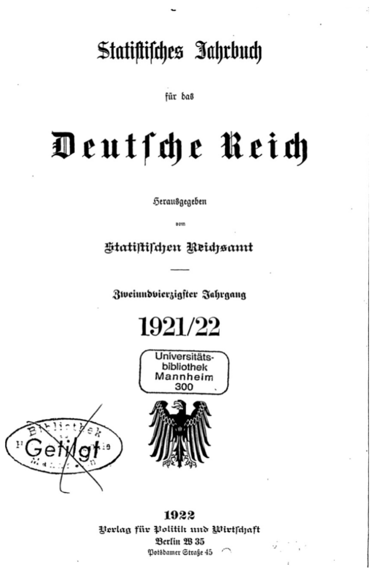
Year	Downtime
1840	0.54
1850	0.52
1860	0.50
1870	0.48
1880	0.46
1888	0.44
1896	0.42
1907 and onwards	0.40

Linear interpolation was utilized for missing data like in the case of energy used by static steam engines at the start of the 20th century. A logical assumption was made to justify the replacement of the technology with electric motors and machines. Hence, a depreciation factor was applied to reduce the number to zero within the next few decades.

4.3 Data extraction - General Tools, Methods and Barriers

Google sheets and excel spreadsheets were the primary tools utilized for storing the collected data and for processing the data. A number of the historical databases were available as excel spreadsheets, like Mitchell. After importing, the cells had to be restructured and data had to be cleaned. Most of the others had to be processed after copying from embedded online sources. For instance, Malanima's database was imported into excel and the errors during copying were manually corrected for all the data points. For the IEA database, data was available on the BES software. In depth data from primary to final energy was obtained by changing the filters on the BES database [41].

In some cases, Excel OCR (mobile) was used to extract the data from old documents and archives. This was particularly useful for data sources from books, such as the British Historical Statistics by Mitchell, or the Production Energy Mondiale, by Luciani [37]. For old archives and documents preceding the 1960s, the OCR often struggled to read the values due to the differing font or lack of clarity in those documents. This was a big issue with the yearbooks for Germany and France for instance due to the use of a different font as seen on figure 4.2. In these cases, manual entry from the documents was employed, which was a lengthy process.


Statistisches Jahrbuch

für das

Deutsche Reich

Herausgegeben

vom

Statistischen Reichsamt

Zweiundvierzigster Jahrgang

1921/22

1922
Verlag für Politik und Wirtschaft
Berlin W 35
Potsdamer Straße 45

Figure 4.2: A page from the german archives displaying the Fraktur font

Another issue was how the governments or organizations of different countries changed the nomenclature of their statistical publications over time. Certain datasets evolved over time to become more elaborate, or rearranged in different sections. In some cases, the datasets gave indirect datasets contrary to the requirements of the energy accounting database, which was a big hurdle.

There were also occasional disparities in the databases(eg. Luciani) for the same years. This was mostly due to the averaged out triennial or centennial values at milestone years - which were mentioned on the footnotes. Or, there were corrections at the administrative level in the successive years, leading to a different set of statistics. In some cases, the yearly statistics were found to start mid year (or at differing months), another cause for confusion. To resolve such disparities, the different versions had to be studied together and values corrected. This was especially a profound issue while handling the old yearbooks.

4.4 The Global Coal Database: Primary Energy Production and Consumption

The hypothesis used to develop this part was that at any given year, the global primary energy consumption must be equal to the production. Disparities based on imports and exports which arise at a national or regional or continental level should disappear at the global level. A common global database for coal must be developed to provide a structured dataset for coal trends - based on historical consumption and production of coal. The trends can then be used to characterize the global behavior of regions with respect to primary energy over the required time periods. Future and past databases can then be studied for anomalies based on specific years or periods when there were deviations from this common global database. To build the global primary energy database, the following databases were consulted and collated.

- Production Mondiale D'energie, 1800 -1985, Etemad and Luciani [37]
- International Historical Statistics - Africa, Asia and Oceania (1750 -1993), B.R.Mitchell [40]
- International Historical Statistics - Europe (1750 -1993), B.R.Mitchell [38]
- International Historical Statistics - The Americas (1750 -1998), B.R.Mitchell [39]
- World Energy Consumption - A Database (1820 - 2018) - Paolo Malanima [35]
- IEA statistics (1971 - 2012) [41]
- OurWorldInData Database (OWID) - (1800 - 2023) [42]
- Victor Court (1800 - 2014) [36]

As mentioned earlier in the database descriptions, the IEA database only offers data after 1971. To obtain data previous to 1971, a thorough review of existing databases had to be performed in an attempt to develop a single, consistent database. There were 2 clear sets of datasets - based on production and consumption on a global scale. The databases usually provided data based on specific regions, continents and fuels. In some other cases, data from different regions or nations had to be aggregated to obtain global values. For example, the Mitchell database for coal production at country level was summed up to obtain a global database.

Another important point to note is the definition of coal as a fuel. Some of the databases do not differentiate between different types of coal such as Hard coal, Brown coal, Peat, Lignite and so on and offer data for coal in general. When there was separate data available, as was in the case with Luciani [37], hard coal and brown coal data were collated to form one uniform dataset. From available data, a collated database was developed for global primary energy production , using Mitchell, Luciani [37] and IEA databases. Similarly, a global primary energy consumption database was developed using data from Malanima, Luciani [37], IEA, OWID and Victor Court.

Within databases, regions were often separated in different ways, so some restructuring of data was required. For instance, Malanima's database provides the distinction of 'Middle East' but Luciani's Mondiale doesn't. In this case, the data for Iran and Turkey had to be separately obtained and accounted for in the 'Middle east'. Such contradictions based on 'region' require a clear standardized framework to prevent data discrepancy.

For the final and useful energy estimation at the global level, the following resources were considered. Some datasets are from currently ongoing research by Prof.Sofia, and cannot be referenced at the time of writing.

Table 4.9: World Coal Production and Consumption : Data Sources

Name of Source	From	To
The Coal Problem, League of Nations [50]	1924	1981
Coal production data (world)	1800	2014
Economics of energy and power [16]	1936	1936
Coal consumption benchmarks	1934	1936
Global fuel consumption	1846	1868

4.5 National Coal Databases

In the Malanima database, which provides data at the global or regional level, data is often aggregated making it difficult to analyze primary energy flows at the country level. For example, if the UK were the focus of a study, one would need to examine the dataset for Western Europe and attempt to isolate the relevant data. A similar trend is observed across the other global or regional databases. Also, to understand the transformation from primary to final energy, sector-specific datasets are required -

something which is absent from historical global or regional datasets. In order study national coal trends, national databases for coal were developed. In this section, 4 developed economies were studied :

1. The United Kingdom
2. The United States
3. Germany
4. France

All of these countries became powerful industrial economies during the 19th and 20th century as highlighted in the historical context section. For each of these country databases, data was sourced from statistical yearbooks, journals, research papers etc to form collated national databases with sector wise data. The specific methodology followed for the different national databases is explained in the corresponding sections.

4.5.1 The United Kingdom

At the start of the 1800s, the UK alone accounted for 80 percent or more of the global coal production while as of now, the UK has phased out coal completely from its energy mix [17]. Hence, to develop the national exergy database would be of great importance to study the societal exergy use at different historical periods.Unlike other databases, the periods considered were extended all the way back to 1700. Most of the data preceding 1913 were found to be discrete entries of average data - usually collating data for multiple years. This was due to availability of data from Luciani's database and Mitchell's book - British Historical Statistics [51].Similar to the approach at the global scale, a collated database for the UK was developed from different data sources .
The databases considered for primary energy production and consumption data are mentioned in table 4.10. The collation of the dataset at the early years (1700-1850) had issues due to the usage of statis-

Table 4.10: Data Sources for Estimation of UK's Primary Energy (Coal)

Database	From	Till	Production/Consumption
Luciani [37]	1750	1985	P/C
Mitchell [38]	1830	1993	P
Government statistics [52]	1853	2018	P/C
British Historical Statistics - Mitchell [51]	1700	1870	P

tical pentennial averages, especially the data from Luciani's database. Due to this, there were double values in some years (due to the way in which data was presented). One table provided the discrete value at that year and another provided the average value of the preceding years at the same year. In such cases, the discrete values were plotted separately (for the entire dataset).The data from British colonies was excluded from the datasets for the UK. The data from the colonies were hence assumed to be a part of the datasets of the present day status of these colonies as nations or kingdoms.

For obtaining data for different sectors and to find final and useful flows, more extensive data sources were necessary. For instance, to obtain the total useful energy for the UK, data from Fouquet's book 'Heat, Power and Light' was initially used [22]. The data was used to obtain ratios between total energy usage and end uses which were then extended to missing data. But the data also included other primary energy fuels such as oil and natural gas . This was considered out of the scope of the current research timelines and hence the data was not used.

A list of other datasets considered for the UK can be found in the annex in table A.1 .

4.5.2 United States of America

For the United States, official government statistics provided data from 1789-1985 .The primary energy datasets used are summarized as follows :

Table 4.11: Data Sources for Estimation of US's Primary Energy (Coal)

Database	From	Till
Luciani [37]	1800	1985
Mitchell [39]	1800	1993
Government statistics [53]	1789	2018

Similar to the UK, for finding the final and useful energy flows for the US, a more extensive list of datasets was used, which can be accessed in the annex in table A.2.

4.5.3 Germany

After the second world war, Germany was split into the DDR and the FDR. Between the periods 1945-1991, the data was obtained from official statistics separately and then summed up. A collated dataset for combined Germany was obtained using this data. The following datasets were considered for the primary energy data:

Table 4.12: Data Sources for Estimation of Germany's Primary Energy (Coal)

Database	From	Till
Luciani [37]	1792	1985
Mitchell [38]	1818	1993
Government statistics [54]	1860	2018

For the final and useful energy flows, more extensive datasets [55] [56] [57] were sourced. These sources can be accessed in the annex in table A.3.

4.5.4 France

The primary energy statistics of France were obtained from the following sources :

Table 4.13: Data Sources for Estimation of France's Primary Energy (Coal)

Database	From	Till
Luciani [37]	1800	1985
Mitchell [38]	1815	1993
Government statistics [58]	1811	2018

For the final and useful energy flows, more specific datasets were used. These resources can be accessed in the annex in table A.4 .

4.6 4C vs World Hypothesis

In historical studies using different datasets, inaccuracies can be observed with respect to national statistics. This could be to the fact that the datasets were updated in the consecutive years or much later, sometimes coupled with averages over a few years. In some databases, the authors employed mathematical models or linear interpolation to find missing data which could have variations. At the country level, we can ascribe this issue to the mismatch between import/export data or the coal wasted or stored in bunkers.

However, since only a few countries made up the bulk of coal production and consumption until the last century, inflated coal statistics in these national databases could result in inaccurate global level statistics. Hence, a hypothesis was made that the historical global production and consumption of coal must exceed the sum of the historical coal production or consumption by the 4 major nations - United States, United Kingdom, Germany and France. Datasets that violated this hypothesis can be considered to be erroneous or would require further analysis to improve accuracy of the dataset. For this analysis, the collated datasets of the 4 major countries were plotted alongside the global values for primary energy production and consumption for coal to test the hypothesis.

4.7 Benchmarks

Since complete, discrete datasets were not available , benchmarks for milestone years were used to analyze the historical coal economy development for the world and the 4 countries. This section elaborates the benchmark analyses performed as part of the study, with the reasons behind performing the analyses.

4.7.1 Demonstration of the Model - 1935

To test the methodology represented in 4.1, the first iteration was developed for the year 1935, and the methodology to find exergy as described in the coal transformation chain was applied. Primary, secondary and final energy flows were defined from the coal production stage all the way to the end use (useful energy) stage. Some of the missing values were completed using linear interpolation to aid the process. The energy flows were also split based on type of heat and weights allotted to the different sectors. Once the dataset was completed categorically, exergy profiles for step wise transformation and for the aggregated primary to final, final to useful and useful to primary were obtained at the global scale. This was achieved after the application of conversion efficiencies where necessary.

An important thing to note is that some of the missing values were figured out through linear interpolation. This could have an impact on the accuracy of the values. To reduce the error, historical examples were used to narrow down the timeline of introducing phasing out of coal in certain industries. For instance, due to the unavailability of specific coal thermal plant data for France, the starting point of large scale electricity generation was assumed to be the year 1900. This coincides with the start of coal based electricity production in France .The first coal-fired thermal power plant in France, Ronchamp , was inaugurated in 1906 [59]. The preceding years were assumed to have values of zero, and the gaps with later years were filled through linear interpolation. The relevant datasets for exergy values can be accessed in the annex in table A.5.

4.7.2 Benchmarks - World and 4C

The second part of the analysis involved making benchmarks for the 4C countries versus the world for final and useful energy, and aggregated exergy efficiencies based on the demonstration for 1935. Due to unavailability of coherent, complete datasets across the entire timespan of 1800-present, the datasets were instead characterized for benchmarks for every 10 years, or at discrete intermediate years. The usage of discrete data simplified the problem with missing data. It also allowed the study of the historical trends for different sectors.

The following benchmarks were developed :

1. **Benchmarks - World** : Energy benchmarks for the period 1865-1995 were presented at the global level from primary to final to useful energy stages.
2. **Benchmarks - UK** : Energy benchmarks for the period 1875-1965 were developed at the country level for the UK, for primary to final to useful energy stages. Benchmarks for the other 4C were computed but not presented in this document.
3. **4C vs World**: Percentage share of the 4C in comparison to the world values was studied between 1925-1985. Only iron and steel industry and transport sector are presented in this document.
4. **Benchmarks - Aggregated exergy efficiencies**: For the 4C and the world, the three aggregated exergy efficiencies were compared using benchmarks for the period 1925-1965. Reasons behind the changes to the three exergy efficiencies were analyzed.

5

Results and Discussion

Contents

5.1 Regional Trends - Global Historical Energy Databases

Global historical energy databases such as Malanima, Our World in Data and Victor court offered historical statistics of the usage of different fuels such as coal, oil, gas and wood. There were minor differences when comparing databases, due to the way in which data was collected or approximated. As a result, there were often disparities, something which needs to be documented before building the collated database. From figure 5.1, this becomes quite evident. Especially in the year 2000, when the amount of gas consumed exceeds the amount of coal consumption. OWID data showed similar trends, but the dip is more significant compared to Victor Court's.

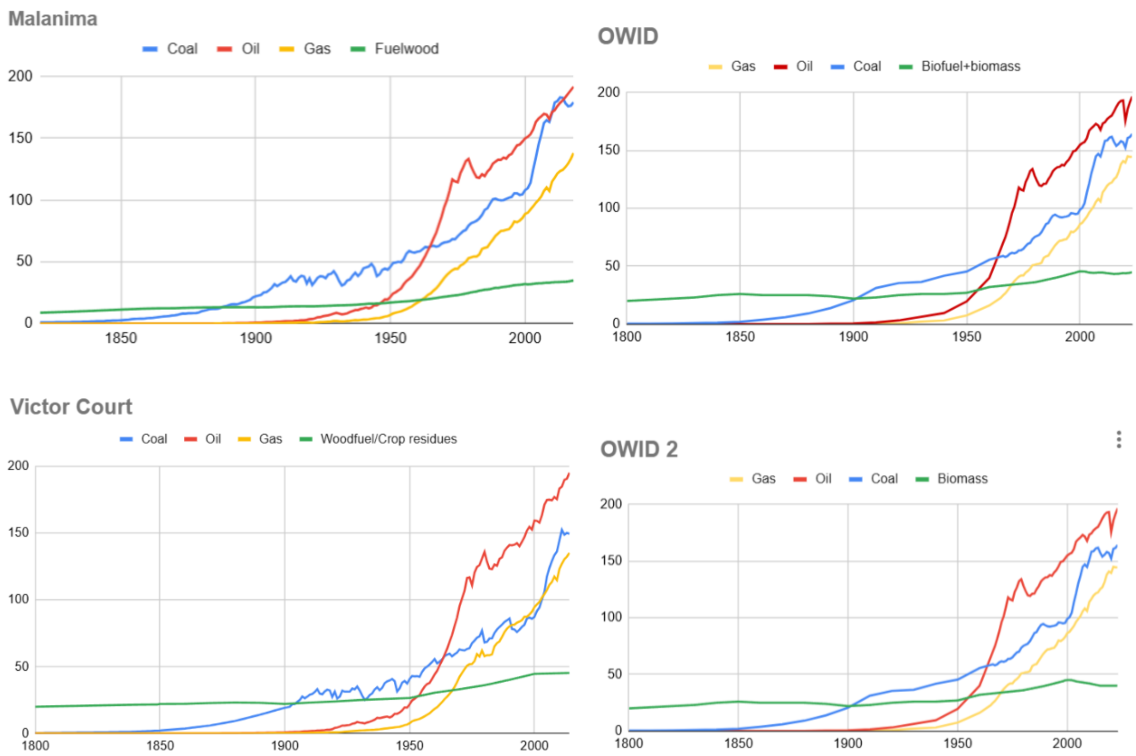


Figure 5.1: Databases - Victor Court, Malanima and OurWorldinData (with and without biofuels)

Meanwhile Malanima's data showed a slightly higher value for coal than the other databases, especially after the 1980s. The reason for this is that Malanima considers different national databases in collation with historical databases such as Mitchell and applies corrections for errors in values using updated sources [35]. Missing data has also been calculated in different ways in different databases. The raw data from OWID is based on Mitchell [42]. There is also a difference on the calculation of historical woodfuel values in Malanima compared to Victor court [36] .

5.2 Primary Energy Consumption and Production by region

Another important differentiation that historical coal databases offered were based on the geographical region considered. Some databases also offered data at regional level, offering deeper insights. The plot of Malanima's global energy consumption database for different regions is presented as figure 5.3. Figure 5.2 shows the historical coal production for different regions as presented by aggregated B.R.Mitchell's database (combining values from the 3 different Mitchell databases) [39] [38] [40].

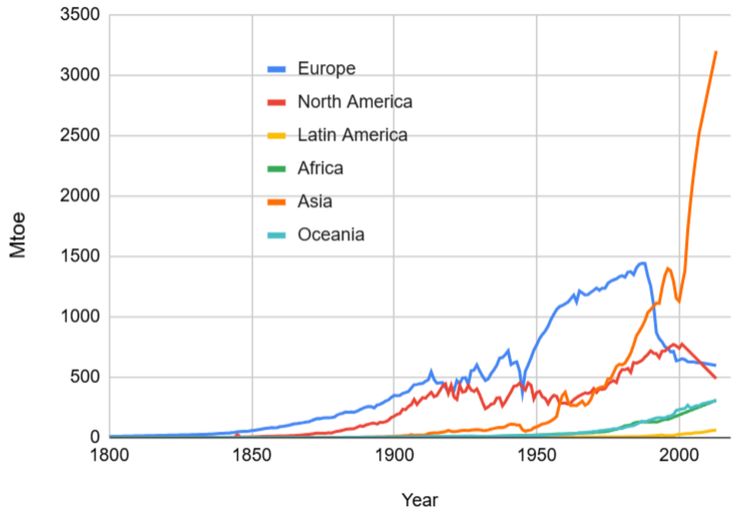


Figure 5.2: Primary energy production by region (coal) - Mitchell

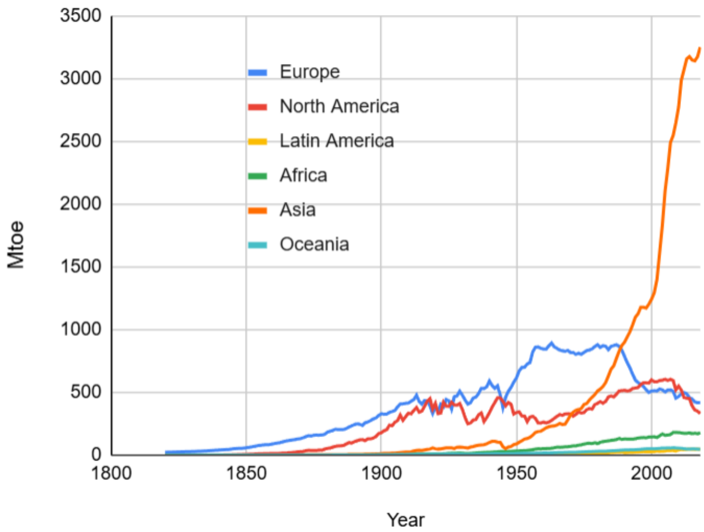


Figure 5.3: Primary energy consumption by region (coal) - Malanima

Europe was the dominant coal consumer in the 18th and 19th centuries. The UK was the world's largest producer and consumer of coal then, and countries such as France and Germany were expanding their coal production and consumption as well. North America, which primarily refers to Canada and the US, became a primary force after the 1850s and expanded quite remarkably to match Europe's coal economy by the end of World War 1 [9]. North America matched Europe's 500 Mtoe energy production mark around 1913.

At the advent of World War 1, Western Europe and North America were the world's most fertile coal economic regions, with other parts of the world still at the early stages of development or at a lower level of production and consumption. The continued development of coal production and consumption across the 20th century was birthmarked by the rise of strong European economies such as Germany, France, Italy and the USSR. Europe peaked in coal production by 1990, reaching 2000 Mtoe/year. After this, a significant drop in production happened due to the advent of climate change advocacy, transition to oil and natural gas and the adoption of renewable energy [60]. Many mines also closed due to economic reasons, as they became unprofitable [61].

Asia showed significant improvements to production and consumption from the end of the first world war. These regions continued rapid development of coal production and consumption post the second world war, though plagued by political barriers till the 2000s [9]. Asia eventually became the world's single largest exploiter of coal as an energy source, overtaking all the other regions . This can be attributed to the growth of Japan, China, India, South Korea as powerful economies in the last century. China especially is a giant in the coal economy today and consumes close to half the world's coal [21].

Africa's graph shows a great increase in coal consumption after the 1950s, reaching western europe's levels in 1870 by the turn of the 21st century. The greatest contributors to this rise are South Africa and Morocco, though many other nations are expanding at a rapid pace. [9]

Oceania and Latin America have both seen a significant rise in production and consumption of coal, especially after the 1950s. The trends show a steady increase and now signs of slowing down. In Oceania, a large amount of coal production comes from countries such as Australia, which also have a high amount of coal consumption. Australia in particular is one of the world's largest coal exporters. In Latin America, Colombia is the largest exporter of coal. Brazil is the largest consumer. Coal is still not the dominant power source for many countries in this region due to the move into renewables such as hydropower [9].

5.3 Global primary energy database (coal)

The global coal databases were then collated together. Data for coal was separated from the other fuels, enabling the building of the collated coal primary energy database. The letter after the name of the database denotes whether the data is for consumption (C) or production (P).

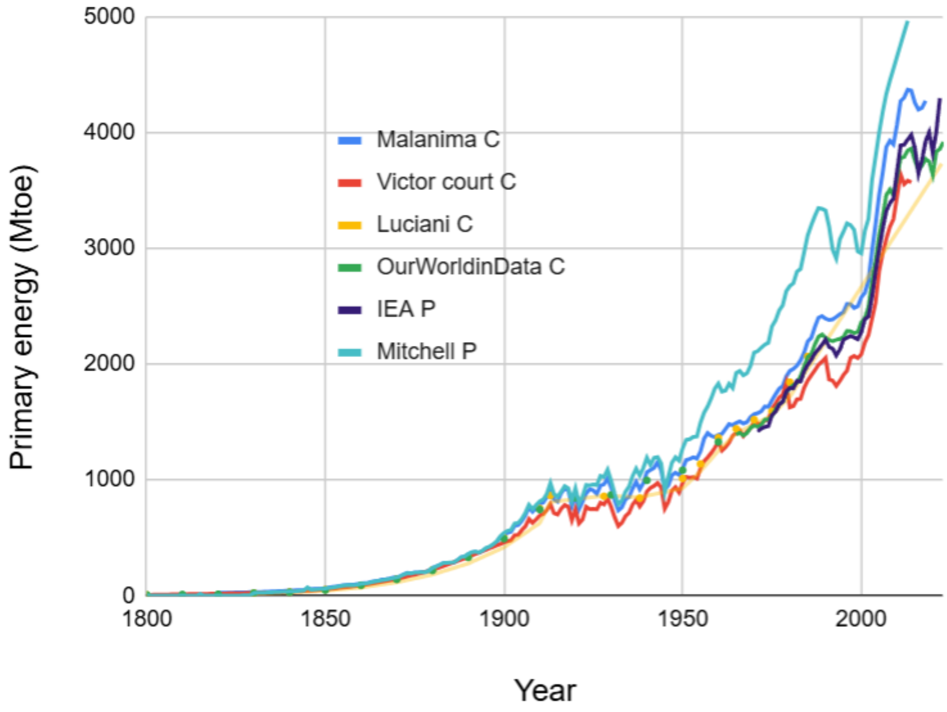


Figure 5.4: Global collated database for coal (1800 - 2015)

Based on the hypothesis that global coal primary energy databases for production must have the same values as that of consumption, the different databases were plotted together. The trends were quite similar across the historical timeline of 1800-2018, with some significant points of deviation. The data after 1971 from the IEA database acted as reference data to find the margin of difference between databases.

The data for Mitchell was a bit higher than the others between 1945 to 1980. This is due to the fact that the Mitchell production database was built by aggregation of country wise data for different regions. This means that the overestimation of data by certain countries has inflated the global values, specifically for Europe. This is quite evident from the behavior of the dataset at the year 1971 where the IEA data is in sync with other databases, but the Mitchell data is quite high. Later databases use more recent datasets to avoid this.

Global production reached 600 Mtoe at the beginning of the 20th century, leapfrogging to 2700 Mtoe by the beginning of the 21st century. By 2010, the value had increased to 4000 Mtoe . This surge was due to the increased coal production and consumption by India, China and many other developing economies [21].

5.4 National Primary Energy Databases

5.4.1 The United Kingdom

The primary energy data for national databases for the UK was collated into a single collated dataset. The production databases were in sync with the consumption databases for the majority of the historical periods considered. Discrete data points from Luciani and the UK government data were plotted and a centered trendline was used to represent the data . The values of coal production were slightly higher than the values of coal consumption in the period 1880-1945, especially the statistics for coal from the UK government when compared to Mitchell. The datasets were found to be in sync for post 1945 values.

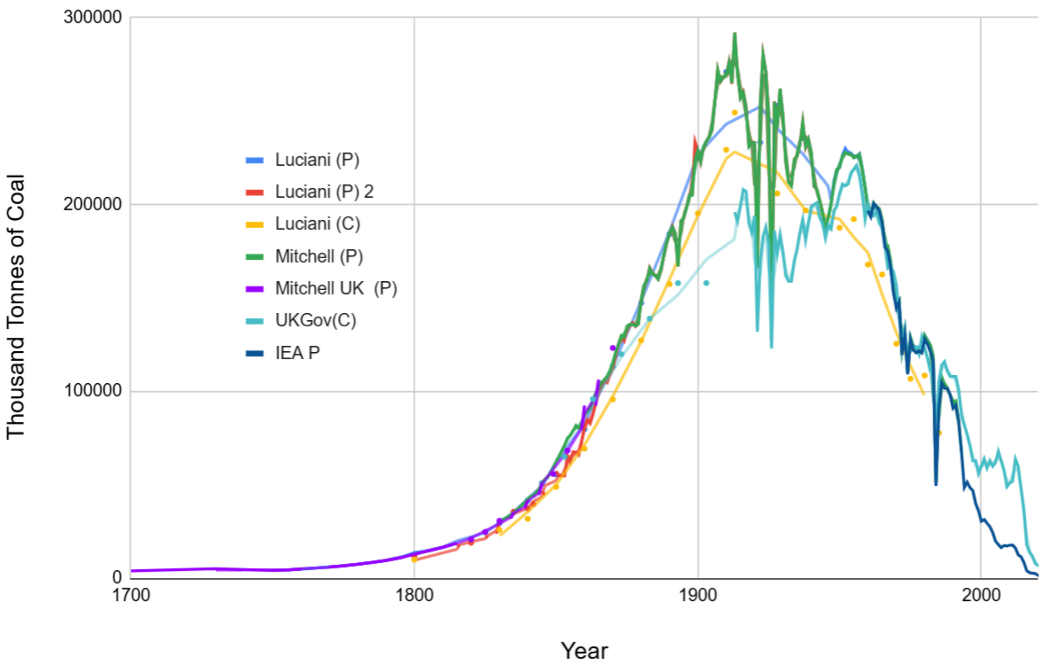


Figure 5.5: UK - Collated database for coal (1700 - 2018)

UK's large-scale production started in the mid 1700s, due to the introduction of new technologies such as the Newcomen engine and the Puddling process [50]. Then after, the UK moved away from

Charcoal and wood for residential and industrial heating purposes, while also expanding its steam locomotive and ship industries. The expansion of the iron and steel industry from the 19th century and the introduction of coke only further accelerated UK's impeccable growth. The higher grade British coal also played a part in this energy transition [9].

At the beginning of the 18th century, the UK produced around 20 million tonnes of coal annually as seen on figure 5.5. By the 19th century, the UK was producing more than 200 million tonnes of coal every year. The production increased till the peak in the year 1910, when 270.9 million tonnes of coal were produced per year. The values dip after this point due to a reduction in productivity and improved efficiency of processes, coupled with adoption of other fuels [9]. Coal became prominent in the mid 1750s during the expansion of the British Empire's trading activities . Later it fuelled the British colonial project, to power transport and industry, later expanding across the world.

However, after the first world war, production went further downhill, as the demand for coal reduced and cost of production increased. Oil and natural gas were becoming prominent for heating and industry, while steam engines were replaced with electric machines and diesel engines [46]. The trend continued after the second world war, with coal being phased out of every sector except electricity production, where there was an increase in usage of coal, again well represented in figure 5.5. At the end of the 20th century, the UK had reduced its production of coal well below 100 million tonnes annually, reaching the levels of the year 1820. The continued use of coal for thermal power plants and industry kept the coal industry running till the start of the 21st century. Coal is no longer in use for electricity generation in the UK [17]. That concludes 250 years of coal as a primary energy source for the UK's economic development.

5.4.2 United States of America

The US started out a bit late compared to the UK in the coal industry. The US was still developing its coal economy at the beginning of the 19th century, when the UK produced around 80 percent of the world's coal. The expansion of coal around the agricultural and manufacturing industry, alongside the iron and steel industry created wonders for the American economy [9].

At the start of the 20th century, the US was producing around 250 million tonnes of coal. The value increased during the first world war, when it reached 600 million tonnes per year. A slump, possibly due to the great depression of 1929 was observed after this. Following this, the US coal economy expanded throughout the second world war. Use of coal for generation of electricity took prominence, and other fuels started playing a bigger role in the energy economy of the US.

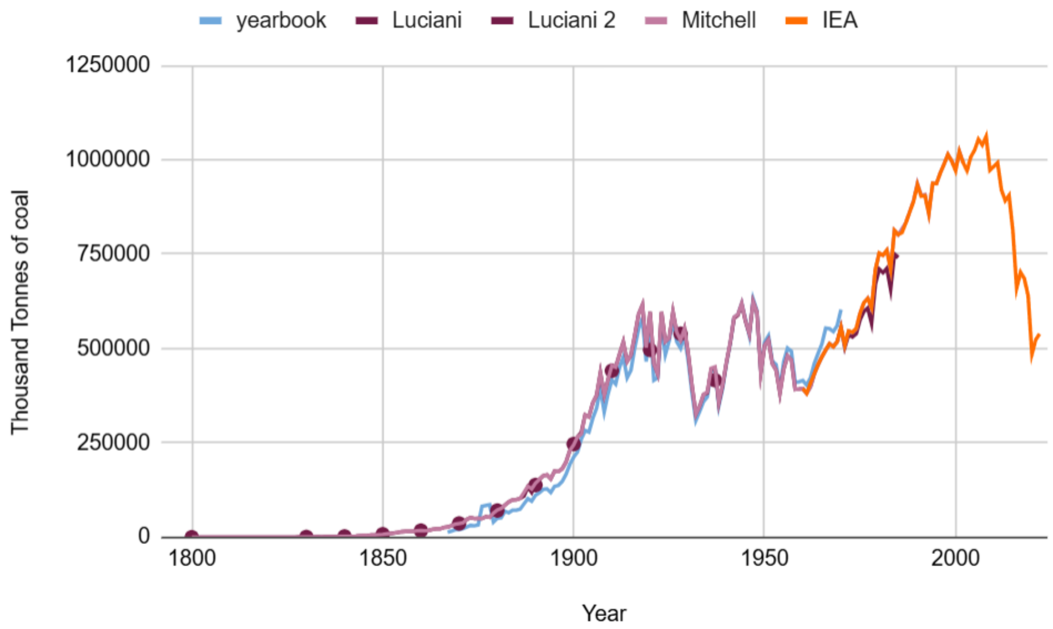


Figure 5.6: US - Collated database for coal (1800 - 2015)

US Coal production peaked in the 2000s, crossing 1 billion tonnes of coal per year. This was far more than the 270 million tonnes annual peak that the UK had, and this trend continued until the 21st century. The industrialization of the US saw a massive expansion in industrial production using coal in the late 19th century, and the early 20th century. The development of machinery powered by steam engines across multiple industries allowed the US to dominate the production. Since the 2008 crisis, the amount of coal consumed declined by half. As of 2022, US consumed 0.5 billion tonnes of coal annually.

5.4.3 Germany

Germany's coal mines were quite prominent in the middle of the 19th century. The production of coal from the mines in the regions of Ruhr and Bavaria was massively increased in the next few decades as Germany produced more than 170 million tonnes of coal annually at the start of the 20th century [9]. During the second world war, Germany's coal production reached 400 million tonnes per year - the highest till then.

After the war, Germany performed fairly well in coal production as the yearly production reached a peak of around 580 million tonnes per year in 1965. The coal production dropped significantly at the end of the 20th century, after the reunification of Germany, falling below 200 million tonnes per year in the early 21st century. The low economic viability of maintaining the coal mines, coupled with technological advancements led to this change. Subsidy reductions and the adoption of renewable energy were also seen as a strong reason for the phasing out of coal in Germany [62].

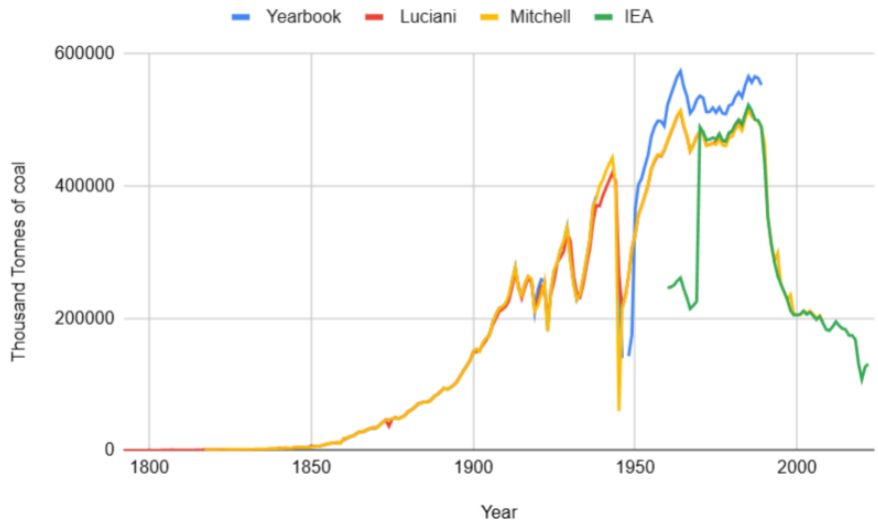


Figure 5.7: Germany - Collated database for coal (1700 - 2018)

5.4.4 France

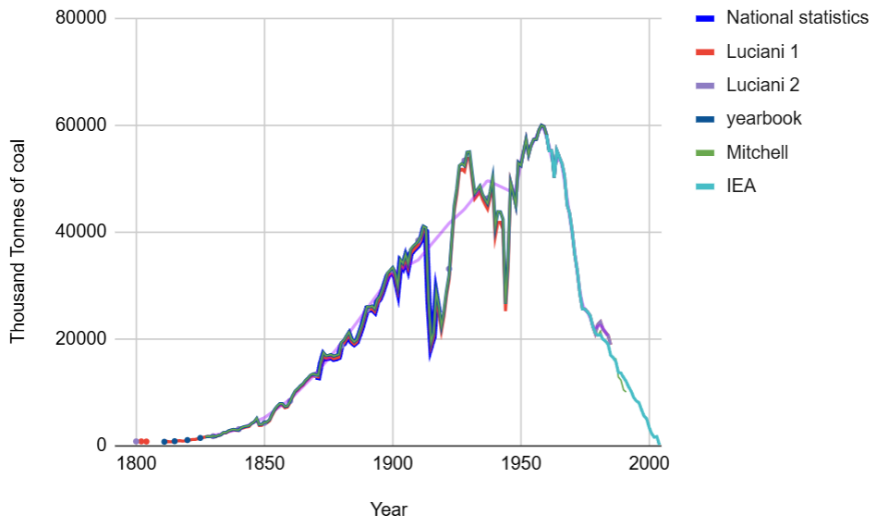


Figure 5.8: France - Collated database for coal (1800 - 2018)

The French coal economy started developing in the early 19th century. The mines in Northern France provided ample resources to industrialize their economy. The production of coal rose to 40 million tonnes in 1913, just before the first world war. The war destabilized the French coal production as it dropped to less than 20 million tonnes per year. After that, a period of resurgence and industrial manufacturing allowed production to peak at around 55 million tonnes at the beginning of the second world war. Considering the great depression of 1929, their production was a great recovery.

Once again, the war crippled the coal economy, majorly limiting its coal production. By the end of the war, France's coal production had fallen to 25 million tonnes per year. The post war period saw another period of increased production till 1960. During this time, France phased out its steam engine ships and trains, and moved to hydropower and nuclear power [45]. This was followed by a gradual drop in coal production .France still uses coal but aims to phase it out by 2027 [63].

5.5 Sum of the 4C countries vs Global - Primary energy

The sum of the 4 countries - UK, US, Germany, France was compared across databases with the global values for coal production and consumption .

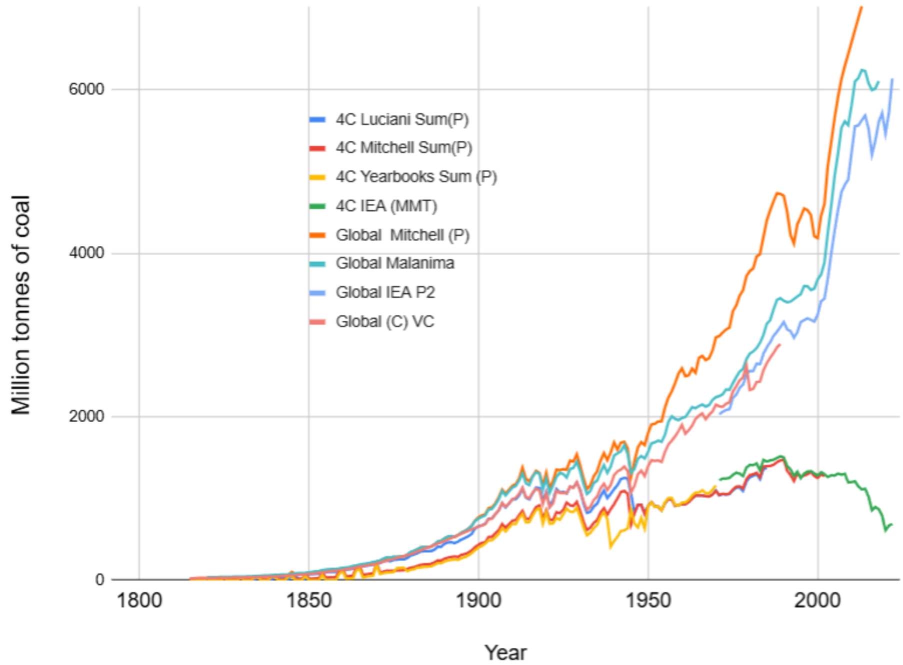


Figure 5.9: Collated databases - Global vs Sum of 4C

As theorized, the 4C databases did not exceed the global databases. But in some cases, they were equal to the global databases, like in some values from the Victor court's dataset being equal to the values from Luciani. This is due to the large share of the 4C values during those periods. However, this was only for a small interval. Other global database datapoints were comfortably exceeding the values of the 4C datapoints. The difference is quite clear after 1971, when the coal production (IEA) data for the world compares to the 4C IEA data.

5.6 Benchmarks - 1935 Demonstration

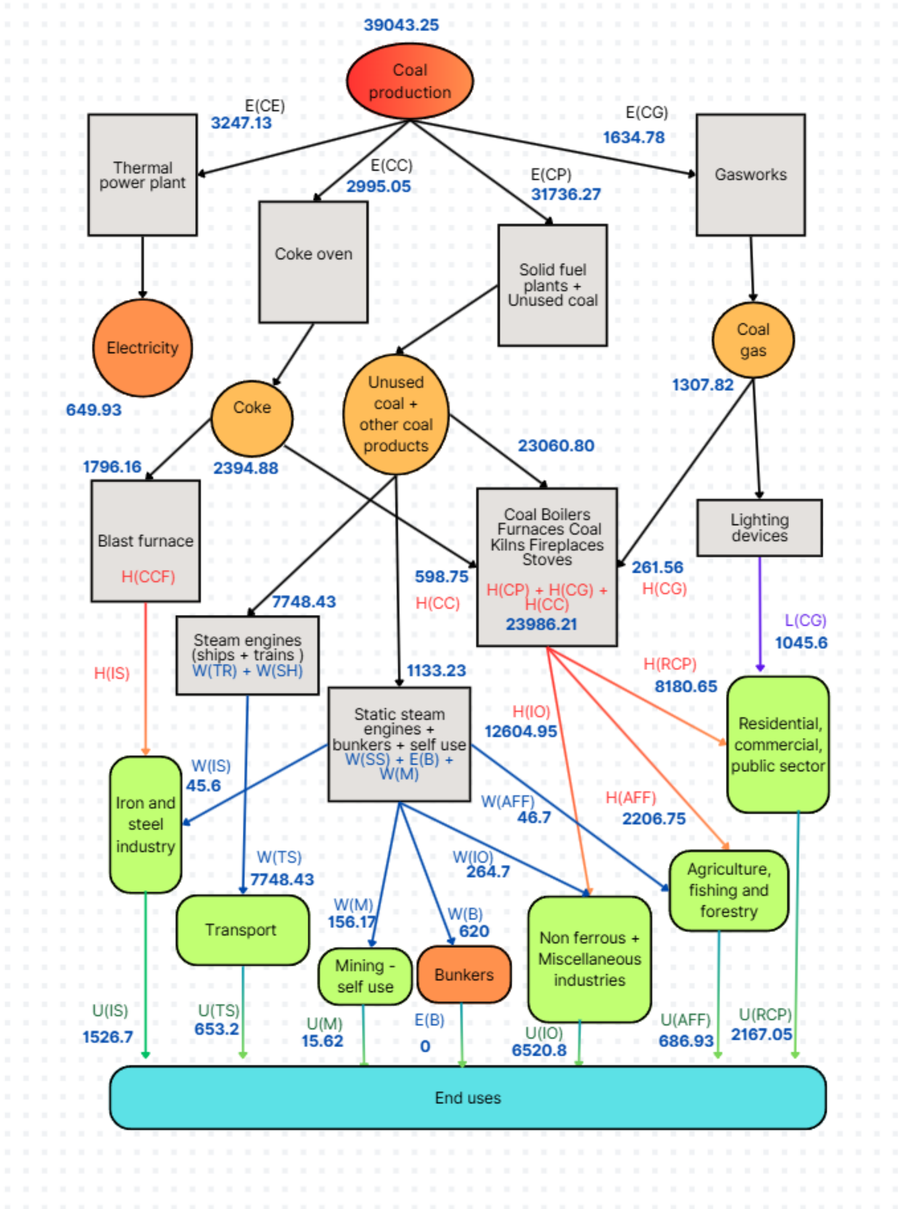


Figure 5.10: Demonstration of the exergy analysis methodology - 1935

The first iteration of the exergy analysis was done for the year 1935, at the world level. For the demo year, the model allowed the calculation of all the values required for the societal exergy analysis. The three exergy efficiencies were obtained within limits. The model's results were then expanded to the other years, and missing data issues were addressed. The results are discussed in the upcoming sections.

5.7 Benchmarks - Secondary, Final and Useful Energy by sectors

After finding out the sector wise allocation of energy, graphs 5.11 and 5.12 were obtained for the years 1865-1985 for the primary to secondary energy stage and the secondary to final stage respectively. This time period was historically significant due to the Great Depression (1929) and the two world wars between the periods 1914-1918 and 1939-1945. The mathematical formulation enabled the completion of datasets from primary to secondary to final to useful energy transformation over time. Benchmarks for the world and the UK are represented here, considering that a high percentage of the data was sourced from cross-verified datasets.

5.7.1 Benchmarks - World

Global coal production increased from 5300 PJ in 1865 to 23850 PJ by 1900.The value increased to 39820 PJ in 1925. After the great depression of 1929 and the second world war, coal production slumped but after the war, production surged to 100,000 PJ by 1985. After a slight dip at the beginning of the 1990s due to the fall in Eastern European coal production as seen on figure 5.3, the increasing trend has continued till present day.

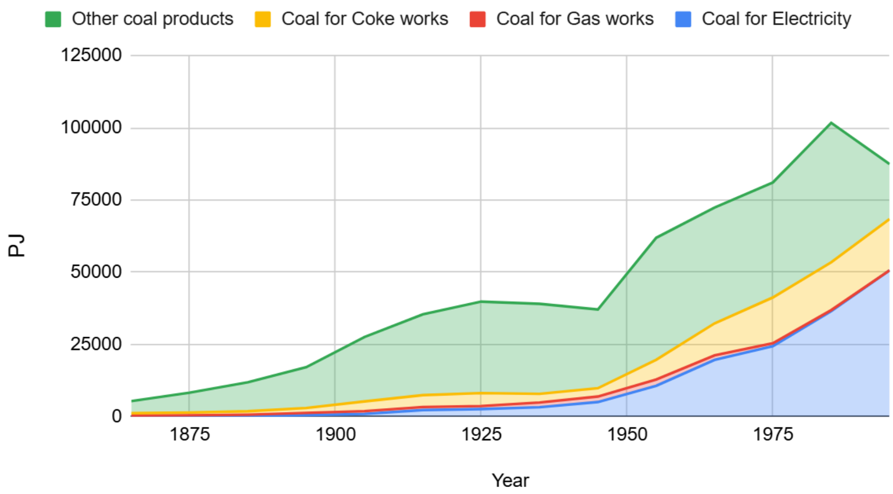


Figure 5.11: Global Trends in the production of coal products

In 1935, the breakdown for the global coal consumption was dominated by the use of coal products for industrial manufacturing and residential and commercial heating , apart from steam engines for transport. The use of coke increased over time significantly, growing to more than 25 percent of the total share by 1965. There is a stable increase in coal gas supply, though this is the end of the coal gas for lighting era, as natural gas and electricity were prominent in many countries. Coal for electricity saw a massive increase over time , especially after the second world war - as coal paved the way for electricity [45].

Final energy breakdown of global coal consumption shows different sectors reacting very differently over the time period 1865-1995. Initially the final energy of coal for transport sector (steam trains and ships) surged from 420 PJ in 1865 to around 8000 PJ in 1925. But then, the steam train and ship consumption dropped to around 1000 PJ by 1965, a period when the steam engines were replaced by internal combustion engines and the jet engines.

Coal was increasingly used for the iron and steel industry and other manufacturing industries since 1865, but the real growth happened after 1955, when the coal consumption skyrocketed. Other industries also saw a growth in coal usage from 1865, with small dips in 1970. Agriculture, bunkers and self use stayed almost the same over the entire of this period as they were defined as relative to the stable other industries sector. Residential and commercial use of coal products gradually increased till 1960, even during the second world war.After this, coal's usage for coal gas and coke for domestic purposes declined and was possibly replaced by other energy sources.

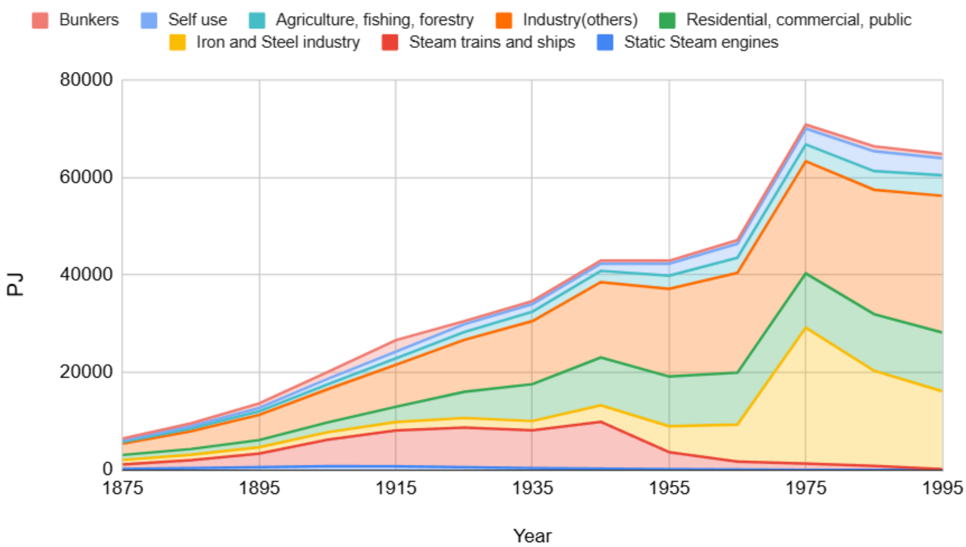


Figure 5.12: Global trends - Sector wise final energy mix

The global useful energy in 1865, as seen on figure 5.13 was mostly utilized by residential,commercial and public sector and the iron and steel and non-iron and steel (other) industries. The trend continued till 1985, with gradual expansion of the three sectors over time.

The residential, commercial and public sector useful energy consumption increased from 300 PJ (1865) to 1678 PJ (1925) to 4120 PJ (1985). Similarly, the useful energy consumption by other industries increased from 600 PJ (1865) to 5600 PJ (1925) to 14430 PJ (1995). Due to the usage of linear efficiencies, the changes over time for end use efficiencies for sectors such as residential, commercial and public sectors and other industries cannot be ascertained.

On the other hand, the iron and steel industry values were plotted using specific efficiency values for different years as explained in chapter 4. The end use of coal for this industry increased from 5000 PJ in 1900 to 18000 PJ by 1985, with a peak reached by 1975. The massive expansion in the usage of steam ships and trains by the industrial economies formed only a small part of the useful energy from 1875 till 1935, due to their low end use efficiency.

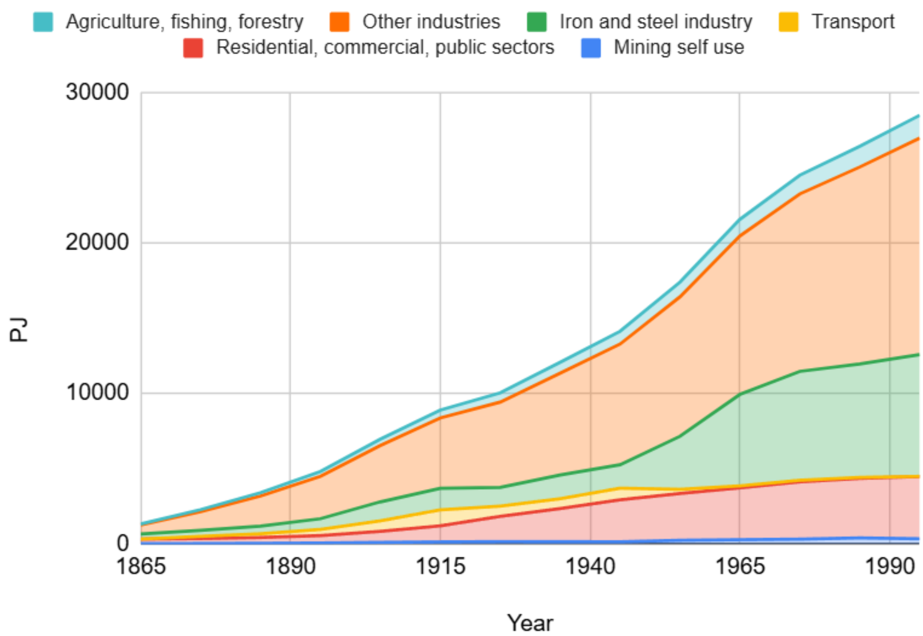


Figure 5.13: Global trends - Sector wise useful energy mix

5.7.2 Benchmarks - UK

Out of the 4 countries studied, only UK's data is presented here. The final energy by sector is shown in figure 5.14 and the useful energy by sector is presented in figure 5.15.

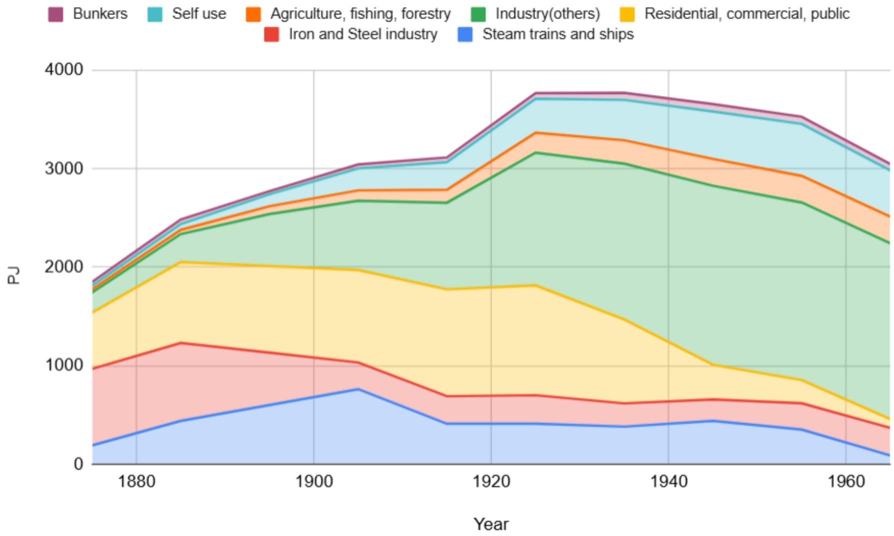


Figure 5.14: UK - final energy by sector

The UK's rapid development of its transport sector coincided with the growth of the industrial sectors from 1875-1915. After the first world war, UK started moving away from coal in certain sectors - most notable the steam ships and trains and the the iron and steel industry. There was significant growth of the residential, commercial and public sectors till the great depression of 1929, after which there is a sharp decline due to the adoption of natural gas instead of coal gas, and electricity based applications. The non-iron and steel industries, which were growing side by side with the other sectors became the major coal consumer after the 1930s, extending all the way till 1965. Notably, self use is a significant contributor to coal consumption , close to 10 percent in some years.

The useful energy graph in figure 5.15 for the UK shows slight changes in the trends compared to the final stage. The high share of the transport, residential, commercial and public sectors in final energy has significantly reduced in the useful stage. This is due to the usage of low temperature heat, which has low efficiency. With the decline in these sectors over time, their shares further dwindle, especially between 1920-1960. The iron and steel industry's useful share increases over time, showing the increased shift of coal for industrialization. Its share is quite high (relative to the final energy share) due to more efficient machinery and technological improvements . An increasing trend is seen with other industries , mirroring the final energy trends. The higher share of the other industries similar to the iron and steel industry must have been due to end use improvements, considering that more than 60 percent of the other industries was assumed to use low temperature heat. The agriculture sector is probably overestimated considering that it linearly depends on the values of the other industries.

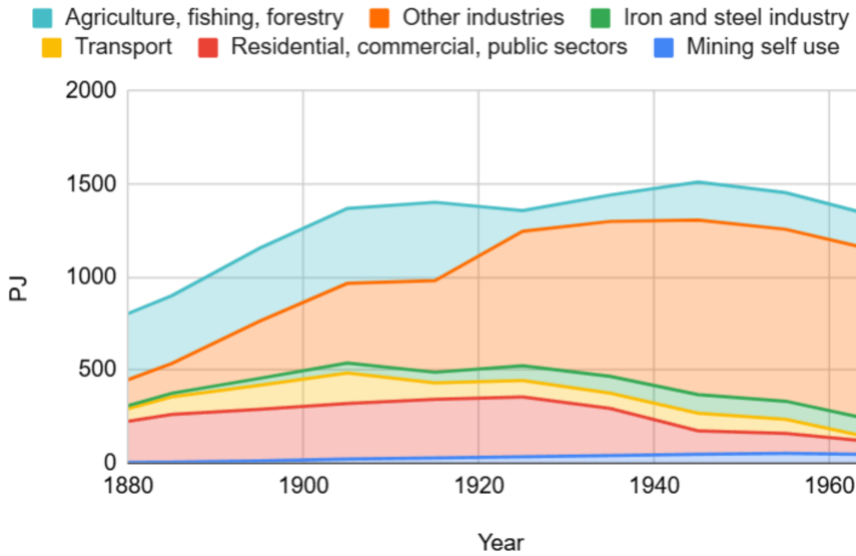


Figure 5.15: UK - Useful energy by sector

5.7.3 Final Energy Benchmarks - 4C vs World

For each final energy sector, the sum of the 4 countries was compared to the global levels to understand the prominence of these nations with respect to coal . Figures 5.16 and 5.17 show the amount of global consumption that the 4C countries share (together and individually) for the iron and steel industry and the steam driven transport sector.

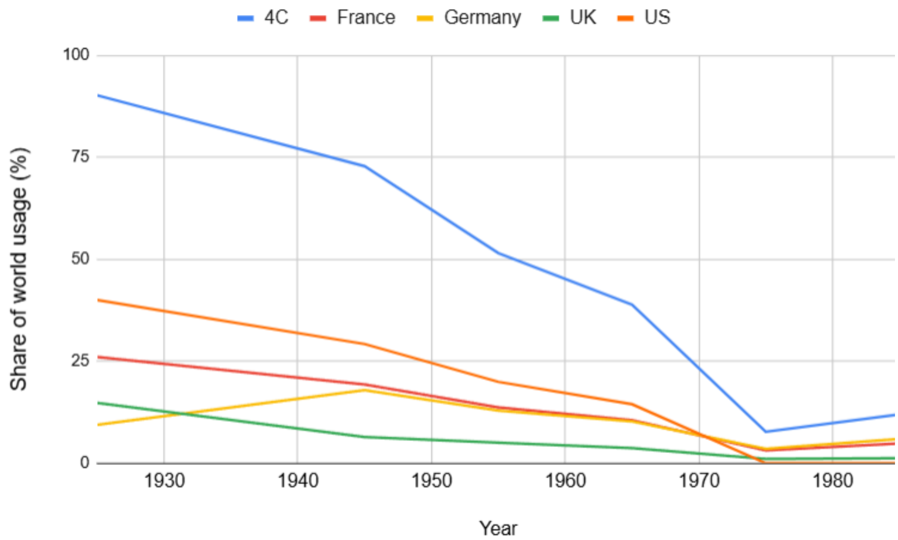


Figure 5.16: Share of the 4C in the world's final energy (coal) for the Iron and Steel Industry

The 4C dominated the iron and steel industry at the beginning of the 20th century as seen in figure

5.16. The US and UK had already reached historical levels of coal production and consumption and their manufacturing industries, especially the iron and steel industry, were growing at a rapid pace. It is hence no surprise that in 1925, almost all of the iron and steel production in the world (close to 85 percent) was coming from 4 countries - UK, US , Germany and France. At the eve of world war 2, this number was at 75 percent.

After the second world war, the 4C's share of global coal consumption for iron and steel reduced gradually. Though this does not mean that the production was reduced, but rather that other countries were able to develop their iron and steel industries. By 1975, the 4C only had around 13 percent share of the global coal consumption. By this time, many countries around the world had built up their coal economy and the 4C were replacing coal with natural gas and oil, along with electricity powered machines. Coal plants also became less profitable compared to other energy sources [46].

The coal transport industry declined around the world due to the advent of oil driven engines and the decline of steam powered ships and trains as shown in figure 5.17. Famously, Winston Churchill ordered the British Navy to modernize and adopt oil as a fuel source even though the UK had no tested efficacy in using the fuel while coal was the prominent energy carrier in the UK [64]. The trend followed in the US, France and Germany as well, with newer oil engines taking over the transport industry with huge drops between the two world wars. Meanwhile other parts of the world were still phasing out coal in the transport sector, even as late as the 1980s.

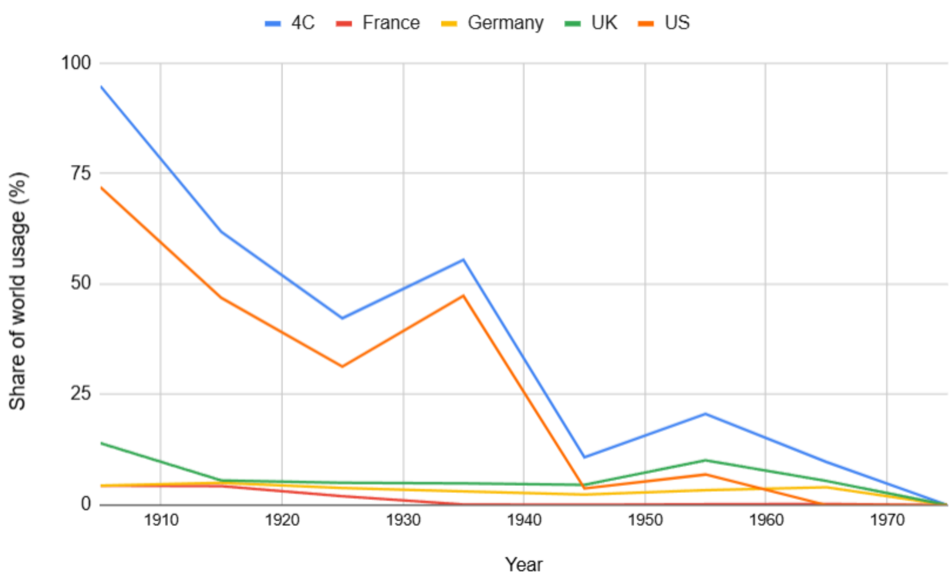


Figure 5.17: Share of the 4C in the world's final energy (coal) for the Transport Sector

5.8 Benchmarks - Aggregated Exergy Efficiencies

5.8.1 Aggregated Exergy Efficiencies - World

This section provides the calculated results at the world level for the aggregated exergy efficiencies ε_1 (Final to Primary), ε_2 (Useful to Final) and ε_3 (Useful to Primary) . Results are presented in figure 5.18.

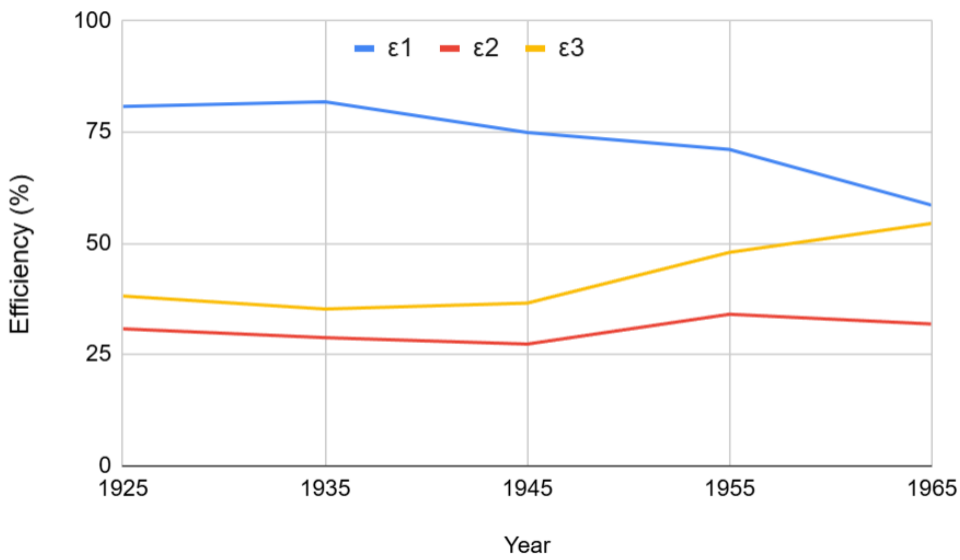


Figure 5.18: Comparison of the aggregated exergy efficiencies (world)

ε_1 dropped significantly in the years 1925-1965 from percent to less than 60 percent. ε_2 had a generally increasing trend , while ε_3 increased gradually.

Early industrial systems, particularly in 1925, achieved ε_1 values exceeding 80 percent, indicative of a resource-driven approach to energy usage [65]. However, by 1945, this efficiency fell below 70 percent, signifying war time losses and disruptions. Relevant studies document a decline in ε_2 between the 1940s-50s [66], aligning with the stagnation in ε_2 by 1945, which underscores significant thermodynamic inefficiencies as industrial complexity grew [29]. The value improved later as technological advancements brought higher efficiency end uses.

Similarily, ε_3 decreased between 1925-1945, followed by a positive trajectory due to advancements in technology, with a marked increase post-1950 [27].

Collectively, these findings illustrate that while early 20th-century energy efficiencies were characterized by a simpler paradigm of energy use, the mid-20th century experienced a notable decline followed by gradual improvements, driven by technological innovations that enhanced energy system efficiency [67].

Various studies provide insight into historical energy conversion efficiencies across economies, illustrating how the industrial and technological shifts, especially in the mid-20th century, influenced the transformation of primary energy into useful work [27] [47]. Such shifts are due to mechanization in agriculture, improvements in manufacturing, and energy system advancements. By the 1950s and 1960s, increased energy savings at the final stage are noted, as indicated by ε_3 in the data.

5.8.2 Aggregated Exergy Efficiencies - UK

The energy system in the UK in 1925 was predominantly reliant on coal, particularly for high temperature industrial heating. This resulted in relatively high values for ε_1 at the time. he data reveals a general decline in the ε_1 values, from 79 percent in 1915 to 54 percent by 1965. As electricity became more widely utilized and alternate fuels were introduced [49], the $\varepsilon 1$ began to decline as seen in figure 5.19.

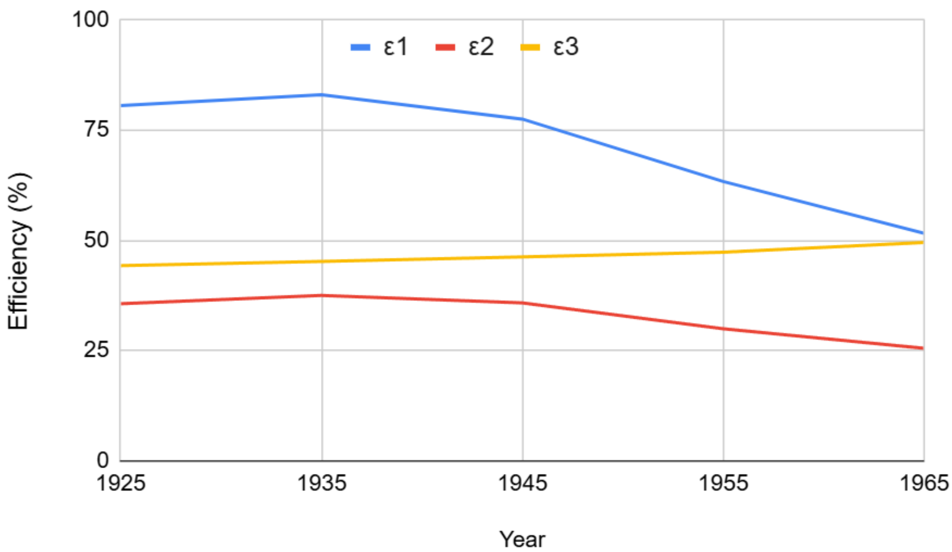


Figure 5.19: Comparison of the aggregated exergy efficiencies (UK)

ε_2 demonstrated an increase between 1925 and 1965, from 45 percent to around 50 percent. This behavior reflects the changing composition of energy end-uses, where advancements in machinery and appliances gradually improved end user efficiencies. Energy policies favoring post-war recovery and economic growth led to intensified energy consumption with better efficiencies, thus impacting ε_2 [45]. Unlike ε_1 and ε_2, the useful-to-final ratio ε_3 reduced a bit from 48 percent in 1915 to 42 percent in 1925. This decrease signifies that the progressive advancements in end-use efficiency, supported by technological improvements in heating, transport, and household appliances were not largely focused on coal based applications [27].

5.8.3 Aggregated Exergy Efficiencies - US

Results are presented in figure 5.20. In 1925, ε_1 was measured at 81 percent. However, by 1965, this value had declined to 57 percent. This trend reflects the gradual shift from coal to a more diversified energy mix that includes electricity, oil and natural gas [67] .

The data also shows a steady increase in ε_2, which must be due to the move away from low end-use

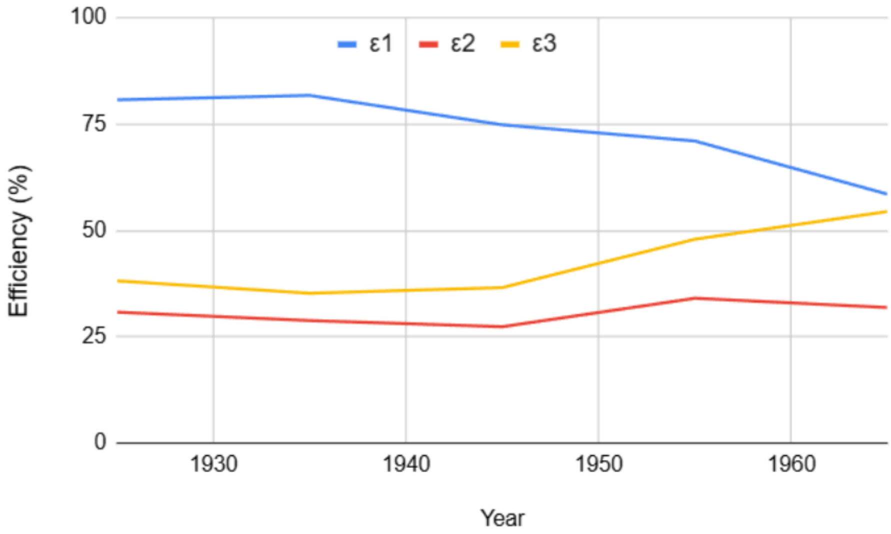


Figure 5.20: Comparison of the aggregated exergy efficiencies (US)

efficient usage of coal, such as steam ships . For instance, ε_2 saw a rise to 35 percent in 1945, likely due to wartime industrial optimization that emphasized efficient energy use for production.The high degree of industrialization contributed to this as well [68] .

Similarly, ε_3 showed an increase from 37 percent in 1925 to 50 percent in 1955. This growth indicates improvements in the efficiency of end-use applications, such as appliances and industrial machinery, despite the reliance on more complex energy systems [23]. The rise in ε_3 values after 1955 suggests that advancements in technology and energy utilization practices was balanced by increased low-efficiency use of coal for the residential sector [29].

5.8.4 Aggregated Exergy Efficiencies - Germany

The results are presented in figure 5.21. Germany's ε_1 reduced after the great depression of 1929, during which the coal utilization by industries such as iron and steel industry fell rapidly. The period of the second world war also continued the trend due to rapid destruction of infrastructure. [15].

The ε_2 in Germany saw a modest decrease from 42 percent in 1925 to around 37 percent by 1945

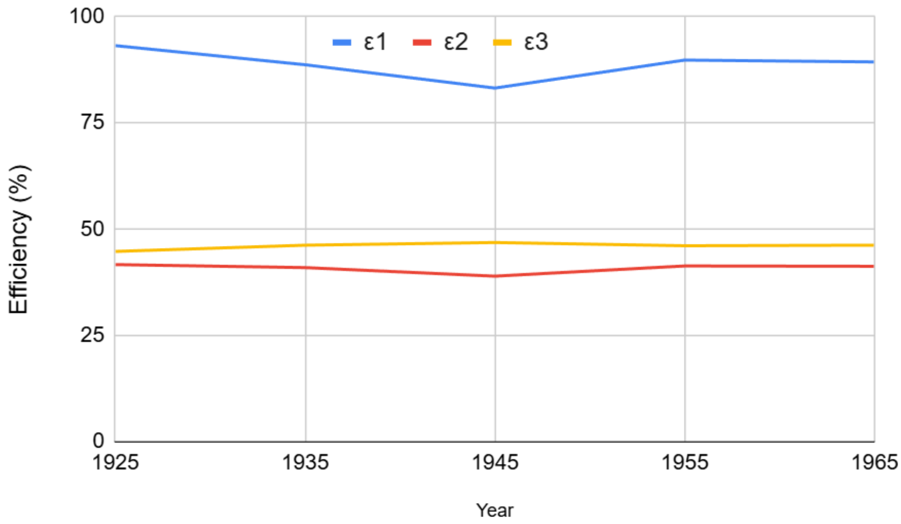


Figure 5.21: Comparison of the aggregated exergy efficiencies (Germany)

possibly due to thermodynamic complexities [69]. Germany's emphasis on heavy industry and wartime resource strains limited overall energy utility at the primary-to-useful stage [70]. Post war technological improvements stabilised the trends.

The ε_3 value fluctuated slightly between 46 percent in 1925 to 48 percent by 1945 and then falling back to 46 percent after the second world war. This stability in useful-to-final efficiency suggests that end-use coal applications, such as heating and industrial processing, experienced gradual efficiency improvements through equipment upgrades. Post-war efforts in reconstruction contributed to maintaining and stabilizing the values, though technological constraints could have limited gains [70] .

5.8.5 Aggregated Exergy Efficiencies - France

Considering the transition of France to nuclear electricity , the coal was mostly used for industrial and domestic heating and industries with low efficiencies. Hence the relatively lower values for exergy efficiencies when compared to the other 4C countries or the world - as seen on figure 5.22.

In 1915, due to the advent of the first world war, production of coal was very low. ε_1 was at 54 percent in 1925, which is on the lower side . The recovery after the first world war were brought down by the second world war as evident in the 1945 values. This value increased to 69 percent by 1965 which can be attributed to the gradual transition to high efficiency end use and technological improvements after the war [71].

The ε_2 values in France remained relatively stable and was quite high throughout the period con-

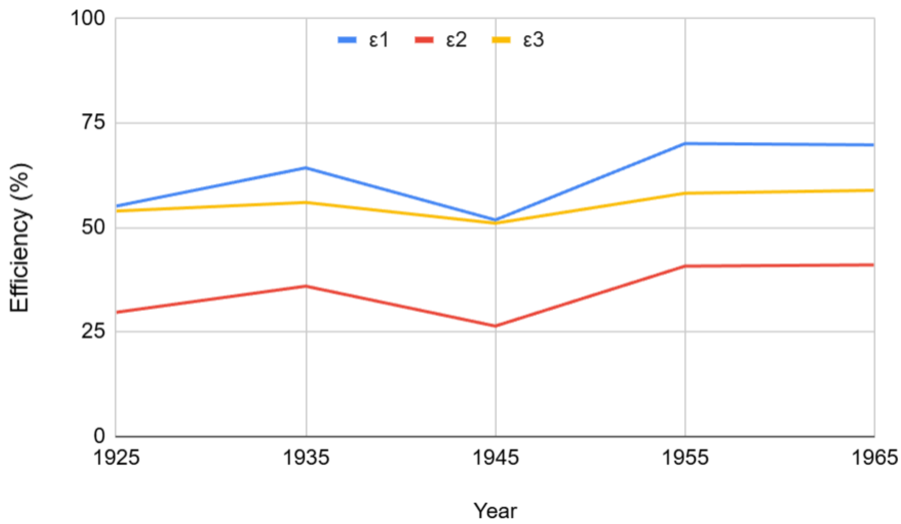


Figure 5.22: Comparison of the aggregated exergy efficiencies (France)

sidered. A slight rise in ε_2 during the interwar period corresponds with improved industrial efficiency. However, the subsequent decline were possibly a result of disruptions during the second world War. [45]. France's recovery in ε_2 efficiency can be attributed to its gradual adoption of processes with high industrial efficiencies like its European counterparts [21].

The Useful-to-Final Exergy Efficiency (ε_3) in France demonstrated significant growth from 28 percent in 1925 to 35 percent by 1935, but economic slowdown after the great depression of 1929 and the conquest by Germany dropped the value to 25 percent in 1945. After the war, the value improved to a peak of 45 percent, stabilizing thereafter.This increase reflects gradual improvements in end-use efficiency across industrial and household applications [72].

Globally, similar upward trends in ε_3 have been observed after 1945, driven by advancements in end-use technologies such as electric appliances and more efficient industrial machinery. Other industrialized nations, including the United States, also reported increases in ε_3 during the early 20th century, highlighting a broader trend of technological innovation that improved final energy usage. France's improvements in end-use efficiency thus paralleled those of other industrialized countries, benefiting from similar innovations in machinery and household devices [73].

5.8.6 Aggregated Exergy Efficiencies - Comparison between 4C and the World

The exergy efficiencies of the 4C countries - UK , US, Germany and France were compared to the aggregated exergy efficiencies of the world for the years 1925-1945. The comparison is explained in the following sections.

1. **Aggregated Final to Primary Exergy Efficiency (ε_1)** :

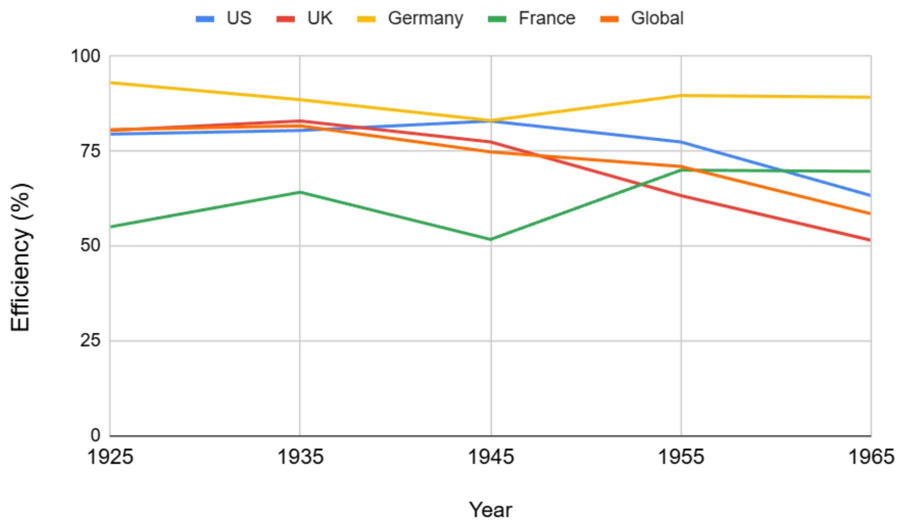


Figure 5.23: Comparison of final to primary exergy efficiency ε_1 (4C countries vs world)

The global results obtained for ε_1, as shown in figure 5.23 is quite similar to that of the US and UK. The high proportion of coal consumption by large scale manufacturing industries explains the initially higher values, as the utilization of high temperature heat was involved.The great depression followed by world war destruction and shortage of resources must the reason for the high efficiencies dropping after the war [23].

Germany had a much higher exergy efficiency compared to the world, but with similar trends. From around 90 percent, the exergy efficiency of Germany dropped to 82 percent after the war due to resource scarcity, war devastation and economic disruption [74].

France recovered after the first world war due to reconstruction efforts, but the German invasion halted the efficiency improvements. This explains the poor efficiencies after the first and second world wars [65]. After the war, adoption of better end use technologies and shifting coal into industrial sectors improved the efficiencies [69].

2. **Aggregated Useful to Primary Exergy Efficiency (ε_2)** : As seen on figure 5.24, Germany maintained a high useful-primary efficiency during the course of these 20 years . The war only slightly affected the efficiency, which must due to the war-industry boom during these years. The technological advancements of the German industry allowed it to have a higher efficiency than its counterparts. As seen on figure 5.24, Germany maintained a high useful-primary efficiency during the course of these 20 years . The war only slightly affected the efficiency, which must due to the war-industry boom , when resource utilization became more efficient during these years [75].

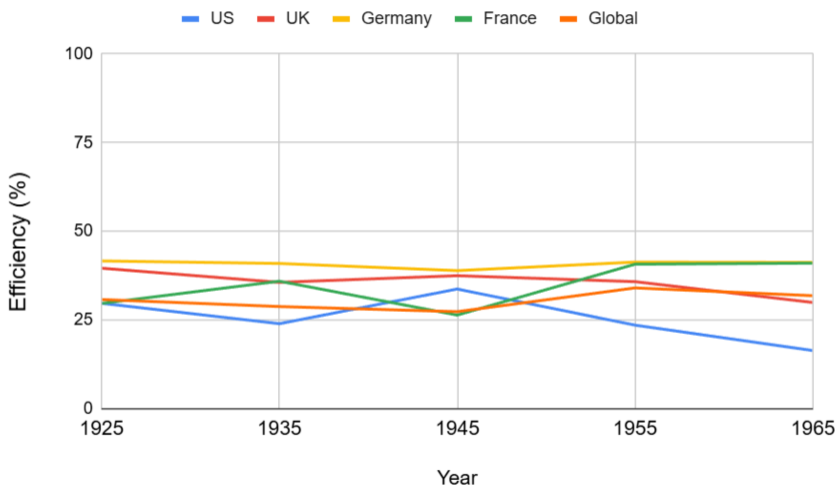


Figure 5.24: Comparison of useful to final exergy efficiency ε_2 (4C countries vs world)

Meanwhile, the UK had a relatively stable efficiency during this period, due to the stable coal production [23]. While the US saw a decline during the great depression, it caught up during the second world war and reached high exergy efficiency because of its sophisticated consumer products driven end uses [23]. Similar to ε_1,France recovered until the end of 1935 but later had a drastic drop in ε_1 because of German invasion. The values are a bit higher than expected because the industries were not mapped based on French industrial breakdown, but rather an average of the UK, US and Germany.The world level ε_2 after 1936, dropping below 25 percent by the end of the second world war.

3. **Aggregated Useful to Final Exergy Efficiency (ε_3)** :

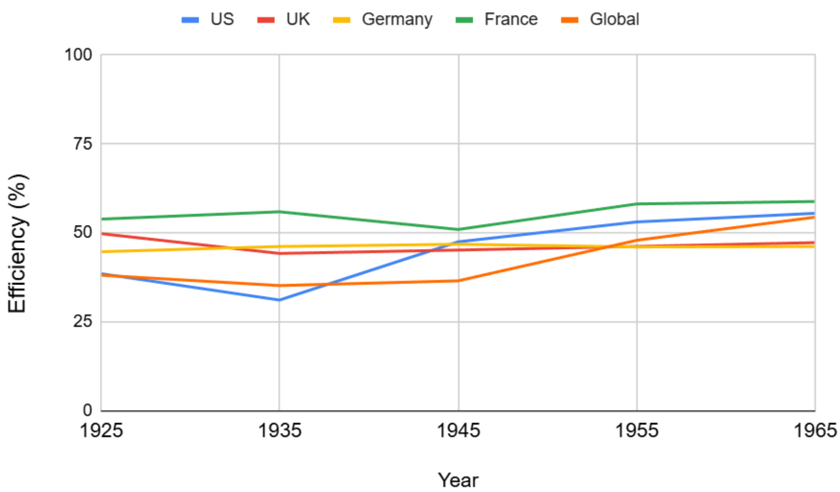


Figure 5.25: Comparison of useful to primary exergy efficiency ε_3 (4C countries vs world)

France initially had a higher ε_3 value. This means that the end use technologies were sophisticated relative to the rest of the world and efficiently utilized the final energy. After a slight reduction (due to war time losses), Germany maintained its efficiency. On the other hand, US and the UK had decreasing exergy efficiencies after increasing till 1935 . France picked up pace after the second world war period and attained 47 percent efficiency. The world's useful final exergy efficiency dropped drastically after the second world war, falling well below 40 percent - showing the impact on the coal economy immediately after the war [76]. But a recovery happened in the subsequent decades due to reconstruction and modernization of the energy economy. [23]

6

Conclusions

Contents

6.1 Summary

Coal has played a pivotal role in the development of industrial societies, with three significant upswings in its utilization shaping the trajectory of energy use and economic growth [9]:

1. **The Age of Stationary Steam Engines (1787–1814)**: This period marked the beginning of coal's prominence with the advent of stationary steam engines. These engines facilitated more efficient manufacturing processes, laying the groundwork for the Industrial Revolution. The coal industry in the UK doubled its production in this period, resulting in the global production reaching 15 Mtoe at the end of this period .

2. **Mobile Steam Engines and Iron Metallurgy (1843–1869)**: The second surge in coal utilization was driven by advancements in mobile steam engines and improvements in iron metallurgy. These innovations enhanced transportation and construction, further embedding coal into the fabric of industrial activities. The global coal production quadrupled during this period from 35 Mtoe to 150 Mtoe. The rapid increase in adoption of coal spilled over to the US, Germany and France.

3. **Electricity Generation and Electric Motors (1898–1924)**: The final key period arose with the rise of commercial electricity generation and the widespread adoption of electric motors. This transition not only changed how factories operated but also transformed urban landscapes, with coal-dependent cities growing significantly. By the early 20th century, nine of the ten largest cities relied heavily on coal, reflecting its critical role in urbanization [9]. From around 450 Mtoe of coal in 1898, the global coal production doubled to 918 Mtoe by 1924. 85 percent of the world coal production was contributed by the US, UK, Germany and France at this point.

Table 6.1: Coal Production by Year and Country (in million tonnes)

Year	World	UK	US	Germany	France
1800	10.5	8.5	0.1	0.3	0.1
1814	21.1	18.7	0.2	0.9	0.9
1843	61.4	45.5	2.9	3.6	3.5
1869	222.2	109.9	34.3	34.0	13.0
1898	654.2	203.0	197.6	126.6	31.5
1924	1298.4	267.3	478.2	240.6	43.6

This period was succeeded by the 1929 economic crisis, and the subsequent second world war. Some countries moved away from coal, while some continued their dependence on coal.

- The US, shielded from direct attacks on its homeland during the wars, was able to recover economically and improve its technological capital. This allowed the development of efficient end-user systems based on electricity and advanced heat technologies, alongside a vastly expanded grid infrastructure. From the 1920s onwards, the US became the world's largest coal producer, reaching an annual output of one billion tonnes with no close competitor by 2004. Only after the economic recession of 2008, the US has significantly moved away from coal.
- The UK, which was historically dependent on coal, changed drastically during the second world war and started moving towards oil and gas. A gradual decline in coal production was observed, which continued till 2024, when coal was phased out entirely.
- Germany also got affected by the 1929 crisis, and took 7 years to recover to 1929 levels of coal production. Then, the second world war crippled the coal economy further. Coal usage increased in East Germany and West Germany till 1990. From the end of the 1980s, followed by the reunification of Germany, coal production saw a heavy decline.
- Unlike the other 3 economies, France's coal economy did not show massive growth. In 1844, France produced the same amount of coal as the US per year. By 1894, the US was producing 4 times the coal production of France, which increased to 10 times by 1914. The subsequent 2 world wars and the 1929 economic depression were interlaced with a few years of recovery. From 40 million tonnes of production in 1914, production reached a maximum of 60 million tonnes by 1958. Soon after, France started moving away from coal and is about to phase out coal by 2027.

Year	World	UK	US	Germany	France
1910	980.33	269.00	417.11	222.37	38.35
1920	1056.87	194.00	568.67	243.24	25.26
1929	1186.97	184.00	534.99	337.90	54.98
1939	1152.69	190.00	394.86	384.72	50.25
1950	1377.98	206.00	516.81	364.15	52.52
1960	1881.79	200.00	415.51	522.66	58.24
1970	2125.39	157.00	602.93	536.70	40.10
1980	2301.40	123.00	710.38	523.77	20.70
1990	2905.05	108.00	936.90	205.07	10.50
2000	2946.36	60.00	975.70	181.49	3.46

Table 6.2: Coal production data 1910 -2000 (Million tons)

The aggregated exergy analysis provided some more clarity on the role of the geopolitical events shaping energy transition.

- Before 1925, the UK, Germany, and the US exhibited high ε_1 efficiencies due to advanced industrial practices, as shown in Figure 5.23. France, however, lagged due to the destruction and economic strain of World War I. As these countries accounted for 85 percent of global coal production, their efficiencies had a significant global impact.

- The Great Depression of 1929 resulted in reduced coal production across all major economies. However, coal utilization shifted toward sectors with higher exergy efficiency, temporarily increasing ε_1 and ε_2 values. France redirected coal use from transportation to industrial applications as part of its post-war reconstruction , improving its ε_2 efficiency until the German invasion during the second world war disrupted this progress. In contrast, the US experienced a slight decline in ε_2 efficiency during the Depression due to its reliance on less efficient coal uses such as the residential and other industries sector which have low temperature heat requirements. This can be seen on figure 5.24 .

- During the second world war, ε_1 efficiencies declined globally, particularly in France, Germany, and the UK, as widespread destruction and economic disruptions impacted coal utilization. The US, unaffected by direct conflict, expanded its industrial sector, leading to relatively higher ε_1 and ε_2 values. Post-war recovery saw France and Germany achieving substantial improvements in ε_1, ε_2, and ε_3 efficiencies through technological innovations and the adoption of high-efficiency industrial applications.

- Post-1945, the UK and US moved away from high-efficiency coal applications, focusing on coal-powered electricity and residential heating, contributing to declining ε_2 and ε_1 efficiencies. However, global trends did not entirely follow this trajectory. Emerging economies and broader industrial transitions into high-efficiency coal uses significantly boosted ε_2 and ε_3 globally. The US, despite its focus on lower-efficiency sectors, achieved advanced ε_3 sophistication due to investments in industrial applications as seen on figure 5.25.

  In conclusion, for the selected period (1925-1965), the world experienced a decreased ε_1 and ε_2 but an increased ε_3 - showing that after economic disruptions by geopolitical events, a wave of innovation was observed in the coal economy, leading to more efficient end uses [23]. The four countries studied followed this trend for ε_3, but displayed different approaches to the Great Depression (1929) and the two world wars, resulting in differences in ε_1 and ε_2.

On the question of transitioning away from coal, a few key points need to be noted. We consume more wood today than we did after coal 'replaced' firewood as the primary energy source. Similarly, the transition to oil and gas by many countries did not replace coal. In fact, the historical advancements ensured the continued adoption of coal as a fuel. This is because energy transitions have majorly co-existed as transformations and additions to existing energy systems, instead of radical replacements or changes. Economist Stanley Jevons noted in 1865 that more efficient steam engines led to increased coal consumption [9]—a phenomenon confirmed by later studies. Despite the efficiency gains from technology upgrades lowering operational costs and reducing environmental impacts, history demonstrates that increased efficiency does not always result in energy savings and might counterintuitively result in increased coal consumption [77].

It is important to recognize that for two centuries, the European coal industry spurred rapid industrial growth, creating powerful economies . Today, the same countries have committed to phasing out coal, as reflected in their Nationally Determined Contributions to the UNFCCC [78]. On the other hand, the multipolar global landscape is populated with developing economies relying on coal for its affordability to propel their economic growth. Countries like Myanmar and Indonesia are evolving as key suppliers, while India and China are still heavily reliant on coal [21] .

Societal exergy analysis is a powerful tool to understand the efficiency of energy transitions across sectors and could be instrumental in designing future energy transitions with sustained economic growth. As the global climate change crisis worsens, it is important to rethink coal's continued existence as a harbinger of economic growth.

6.2 Summary - Self Reflection

The thesis work managed to complete the following objectives :

1. Identifying relevant historical data sources and characterize them to set up a global primary energy database for coal
2. Identifying pitfalls and barriers to obtaining clean data from the past
3. Creating a workable methodology to develop a complete primary to useful exergy energy flow at the world level and at the country level
4. Understanding the technological, economic and historical factors involved in the energy transitions of the past two centuries
5. Overall, performing a societal exergy analysis for the world and comparing it to 4 developed economies , offering insights on the impact of these countries at the world level

6.3 Future Work

1. There was an opportunity to include Canada in the 4C list, but then the datasets for Canada were very sparse and offered little promise in the long run. So, the part involving Canadian statistics was eventually taken off the country vs world analysis. But the methodology can be extended to study other major coal economies as well.

2. To address missing data, machine learning methods can be employed and this would result in more complete datasets to perform societal exergy analysis. A similar approach was undertaken in Bernardo's thesis on 'The Evolution of World Land Transport From 1800 Onwards: Energy Use, Efficiency, and Carbon Emissions'

3. Databases such as Fouquet's Heat, Power and Light offer data for the UK without differentiating between the primary energy fuels. With more time, there is a possibility to include such databases into the methodology and build better datasets.

4. Exergy efficiency study at the world and country levels can be explored further and expand the present understandings of the societal exergy analysis field.

5. The future of the research should aim to get better datasets and develop more rigid frameworks to get better results.

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A

Annex

Region	Dataset label	From	To
UK	Woytinsky	1936	N/A
UK	Benchmarks from ‘Coal in the industrial economy’	1830	1913
UK gov	Coal consumption	1853	1913

Table A.1: Data sources for estimation of UK’s final and useful energy (coal).

Region	Dataset label	From	To
US	Mining industries – production	1886	N/A
US	Mechanical power	1870	1880
US	Fuel use by industry	1914	N/A
US	Fuel use by industry	1954	N/A
US	Steam engine HP	1869	1914
US	Coal consumption	1909	1914
US	Blast furnaces/steel prod	1921	N/A
US	Coal consumption/Blast furnace/steel	1937	N/A
US	Coal consumption/Blast furnace/steel	1947	N/A
US	Steel/iron production	1905	N/A
US	Coal for transport/electricity production	1920	1979
US	Value added by manufacturing	1899	1919
US	Industry output + labor	1899	1939
US	Industry output + labor	1899	1937
US	Iron and steel, electricity production	N/A	N/A
US	Iron and steel production + fuel consumed	1854	1911
US	Labor productivity	N/A	1947
US	Coal consumption	1914	1937

Table A.2: Data sources for estimation of US's final and useful energy (coal).

Region	Dataset label	From	To
Germany	Static steam engines	1895	1907
Prussia	Static steam engines	1837	1878
Prussia	Static steam engines	1905	1922
Bavaria	Static steam engines	1907	1914
Germany	Coal consumption	1902	1906
Ruhr province	Coal sold	1905	1932
Germany	Blast furnace numbers/run time	1871	1913
Germany	Coke consumption	1871	1913
Germany	Pig iron production vs blast furnaces	1871	1913
Ruhr province	Fuel distribution for railways - coal	1900	1932
Germany	Consumption of coal, coke, briquette	1911	1912
Germany	Consumption of coal, coke, briquette	1934	1935
Germany	Consumption of coal, coke, briquette	1928	1932
Germany	Total coal consumption	1860	1974
Germany	Total coal production	1900	1932
Germany	Cereal, potatoes, textiles, sugar industry	1905	1906
Germany	Coal output (mining)	1860	1912
Germany	Metal and salt production	1860	1912
Germany	Iron production and foundry establishments	1905	1906
Germany	Mining output	1860	1878
Germany	Pig iron production - fuel breakdown	1848	1870
Global/Major countries	Pig iron/steel/iron ore production	1825	1926
Global	Pig iron production - fuel breakdown	1850	1914
Dortmund, Saar	Coal production	1816	1913
Prussian kingdom	Coal production	1816	1913
Germany	Blast furnace, pig iron, smelting	1860	1912

Table A.3: Data sources for estimation of Germany's final and useful energy (coal).

Region	Dataset label	From	To
France	Benchmarks	1839	1950
France/Paris	Gas consumption	1844	N/A
France	Coal consumption for transport	1847	1938
France	Fuel usage (P/C/I/E)	1839	N/A
France	Fuel consumption by iron industry	1847	1852
France	Coal consumption	1860	1864
France	Coal consumption	1870	1938
France	Iron and steel industry	1847	1858
France	Fuel consumption	1846	1868
France	Coal for Mining	1888	1920
France	Pig/bar Iron production	1820	1870
France	Pig/bar Iron production	1819	1870
France	Coal for iron and steel production	1904	1913

Table A.4: Data sources for estimation of France's final and useful energy (coal).

Table A.5: Year-wise ε_1, ε_2, and ε_3 for Different Regions

Region	**Year**	ε_1	ε_2	ε_3
UK	1925	80	40	50
	1935	80	36	44
	1945	83	38	45
	1955	77	36	46
	1965	63	30	47
US	1925	80	36	44
	1935	83	38	45
	1945	77	36	46
	1955	63	30	47
	1965	52	26	49
Germany	1925	93	42	45
	1935	89	41	46
	1945	83	39	47
	1955	90	41	46
	1965	89	41	46
France	1925	55	30	54
	1935	64	36	56
	1945	52	26	51
	1955	70	41	58
	1965	70	41	59
Global	1925	81	31	38
	1935	82	29	35
	1945	75	27	37
	1955	71	34	48