



Dynamics of Energy Systems: A Useful Perspective

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Dynamics of Energy Systems: a Useful Perspective

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Transitions to New Technologies (TNT) Program,
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Foreword

Long term trends in the evolution of energy systems and their technological transitions have been studied for decades. Invariably, these studies have focused on a supply-side or energy input perspective. Concerns about energy security and scarcity as well as on environmental externalities of energy extraction and combustion ranging from local to global pollution explain this focus on primary energy inputs. Data availability is another main factor. National statistical agencies started to collect and report primary energy extraction and trade data ever since the late 19th century (often motivated by taxation purposes), and the United Nations (or rather: the League of Nations as the UN was called prior to WWII) pioneered energy accounting methods and international data collection at the level of primary energy in the first half of the 20th century. And yet, from an energy systems perspective, primary energy use is a means to an end, but not the ultimate objective of the energy system. Rather, it is the demand for energy services such as mobility, the production of material goods, thermal comfort or illumination that is the most fundamental driver of the energy system. Service demands coupled with continuously changing technologies that link the provision of energy service demands all the way upstream to resulting primary energy needs is therefore a most valuable complementary perspective to understand the long-term evolution of energy systems, and opportunities as well as constraints of their transformation responding to sustainability objectives.

This energy end-use perspective on energy systems is facilitated by the fact that the energy field has developed a measurement and accounting concept that enables a commensurate aggregation of the large diversity of different energy services provided: useful energy. This concept and associated statistics were introduced many decades ago, albeit have largely vanished from the attention of statistical agencies (with a few notable exceptions such as in the case of Brazil) and as a result is underrepresented in studies and models of energy systems and transitions.

This paper by Simon De Stercke thus fills an important statistical data and analytical gap through the development of useful energy balances at the global and national level and over a century long time scale. Such comprehensive, comparable useful energy balances, integrated in consistent energy accounting frameworks at the level of final and primary energy that are the traditional focus of energy statistics, have to date not been available and thus represent an important methodological and empirical advance for energy system studies. In addition, the author illustrates the potential of this new data set by also developing associated exergy balances as well as illustrations of the differences this new perspective provides when assessing measures of long-term technological system transitions.

It is fair to highlight at this stage the extent to which our collective understanding of the dynamics of change in energy systems, or rather its high degree of inertia, has been influenced by the fact that both analysts and methods were captive of one particular, input-oriented, measurement model underlying our traditional energy statistics. The time is now ripe to turn the page and to develop new, complementary service driven perspec-

tives on the evolution of energy systems. It is therefore hoped that this new useful energy balances data set, made publicly available on the IIASA website, will be found useful by many energy scholars inviting an improved understanding of the drivers, constraints and opportunities of accelerating much needed energy transitions.

Arnulf Grubler

Laxenburg, July 2014

Abstract

A long term study of the energy system from an output perspective shows its dynamics in terms of its basic driver: end-use. Long term energy system dynamics have traditionally been characterized using primary energy inputs. They therefore have a supply bias and do not show technological improvements in efficiency and productivity in the downstream components of the energy system, which historically have been both fundamental as well as dominant. How are the dynamics affected by taking an alternative view through an output lens? In this Interim Report, historical useful energy balances since 1900 for key countries and regions as well as the world are presented. The method for constructing them is documented. Rates of change, energy intensities, fuel shares, the sectoral breakup and the attribution according to end-use are compared between the primary, final and useful energy levels. The data show that useful energy measures paint a different picture: they reveal a sharper drop in carbon intensity and a better correlation with economic activity compared to traditional input-based measures based on primary energy inputs. An exergy layer is also added. This shows that there is a vast potential (in thermodynamic terms) to reduce primary energy use while providing the same useful exergy output. The data set is a foundation on which to build in developing new alternative measures of systems change and transitions that are closer to the ultimate output of energy systems: the provision of energy services.

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I would like to thank Arnulf Grubler and my colleagues at the Transitions to New Technologies Program, as well as all the staff of the Energy Program for their support in this research. Their suggestions and reviews were instrumental in bringing this research to its result as presented here. In addition to Arnulf Grubler, my supervisor who sowed a lot of great ideas, I want to mention Peter Kolp, who helped me with any question I had regarding programming, databases and visualization.

About the author

Simon De Stercke joined the TNT program at IIASA in July 2012 as a research assistant. He holds Bachelor and Master's degrees in electromechanical engineering from Ghent University in Belgium, where the bulk of his coursework dealt with mechanical energy technologies. Mr. De Stercke wrote his master thesis on automotive engineering at the Politecnico di Torino in Italy. In 2012, he graduated with a Master of Environmental Management degree from the Yale School of Forestry and Environmental Studies where his coursework and projects were mainly related to energy.

At IIASA, Mr. De Stercke carried out research on the dynamics of energy systems from an output perspective, by studying the changes in useful energy composition since the beginning of the 20th century.

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Dynamics of Energy Systems: a Useful Perspective

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1 Introduction

Throughout history, people have required, to varying degrees, illumination, mobility, thermal comfort, cooked food, transformation of materials, ... These are services that energy use provides and require energy in the form of light, motive power and heat. Since the latter directly perform a service that is of use, that form of energy is termed useful energy. It is created by end-use conversion devices (lamps, automobiles, heating systems, etc.) from energy carriers (fuels) sold to consumers, called final energy. That energy in its turn might have been transformed from other forms of energy extracted from nature. Examples are coal and crude oil, but also sunlight and water at an elevation. They are referred to as primary energy.

Conversely, going down the energy chain instead of up, primary energy, passing through an intermediate form of secondary energy, is converted into final energy, the last stage in which the energy is containable, stockable and exchanged in market transactions (sold / bought). Electricity from a socket, gasoline from a gas pump and steam from a district heating duct are final energy forms. Appliances and devices transform that final energy into useful energy: a lightbulb transforms electric energy into radiant energy (light), a car engine transforms the energy released through combustion of gasoline into (mechanical) crankshaft power that propels the vehicle, and radiators transfer the heat from district steam to the air to warm a space. In all these conversion processes waste heat is released to the environment. Useful energy is the last stage in the energy chain that provides energy services which can be quantified in energy units. The purpose of useful energy is the provision of a service, and this is the *raison d'être* of the entire energy system.¹ This study aims to look at the changes in the energy system over time and space, from a useful energy perspective.

The main motivations for this research are threefold. The first is to look at energy systems and how they change from the perspective of services delivered rather than from the perspective of the primary resources extracted and used as input to the conversion systems that ultimately provide the delivered service. Going down the energy chain from primary energy to energy services, energy flows often become harder to quantify and to characterize. This is because with each step, the number of different categories and flows increases, and data, if at all available, is less detailed, less precise and is generally not available for longer historical time periods. For this reason, the energy systems that

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¹A comprehensive introduction to the distinction between these forms of energy can be found in the Energy Primer (Grubler et al., 2012).

transform raw energy forms into services, and their dynamics, have traditionally been characterized in terms of the inputs, i.e. primary energy. However, what people want are services, and not energy *per se*. The driver of the energy system is not its input, but its output. Characterizing the energy system dynamics by an output measure such as useful energy therefore shows transitions in the demand, which can be seen as the causes for transitions in the primary energy inputs. For example, the demand for individual motorized transportation has increased tremendously during the twentieth century, enabled by the birth of the automotive sector and the rapid technological change in it. This resulted in an increased demand for refined oil products, because of their excellent characteristics for mobility purposes - high energy density, high versatility, and low cost - which required extraction of primary energy in the form of crude oil. Though enabled by discoveries and innovation along the entire energy chain, a desire for individual and fast mobility induced the upstream changes, not the other way around. In many ways, the dynamics at the service level are at the core of the dynamics at the primary energy level. Therein lies the value of studying the service side of entire (sectoral, national, international, global) energy systems. Economic arguments such as costs, as well as policies and culture, shape both the energy system dynamics and the preferences for energy services demanded, but even so, the end-use services drive the system.

Second, insights can be gained regarding aggregate technological change in end-use. In this study, we look at long-term trends in primary energy, final energy and useful energy. Distinguishing between these levels allows us to quantify the efficiency of the upstream sector (extraction and transformation) on one hand, and the end-use sector on the other hand. This way, technological change at the end-use level can be studied, quantified and its role in aggregate systems efficiency improvements (productivity growth) isolated. An end-use perspective therefore gives a much better representation of technological change that is ignored when measuring only primary energy inputs. In economics, the resulting bias in estimating long-run prices and output and productivity growth is widely recognized. Nordhaus (1996) provides a powerful illustration in his historical study of the evolution of lighting services:

Traditional price indexes of lighting vastly overstate the increase in lighting prices over the last two centuries, and the true rise in living standards in this sector has consequently been vastly understated.

A third motivation is to provide the historical energy research community with a unique long-term database with higher resolution in terms of geography, energy carriers, sectors and end-uses than is usually available in historical data sets. Historical primary energy data are available and so are recent (post 1971) final energy balances. However, the latter do not go back to 1900. Useful energy balances are limited to less aggregated estimates without global coverage, or 'snapshot' estimates, such as those provided by Nakićenović et al. (1996) and the European Useful Energy Balances (Eurostat (1978; 1980; 1983; 1988)). The database presented in this Interim Report offers long-term, global, disaggregated and consistent data on 3 energy levels intended to provide a basis for further research. The importance of this kind of data is discussed by Grubler (2012).

This Interim Report first covers the construction of the database, starting with a final-to-useful energy conversion efficiency model followed by the reconstruction of historical final energy balances that apply the results of the final-to-useful conversion efficiency model to construct useful energy balances. Then, a number of analyses are performed including also an exergy analysis.

2 Efficiency of the conversion of final energy into useful energy

2.1 Efficiency and economic development

Over the course of history, processes delivering energy services have become more efficient. Whether the output be useful energy in the form of heat, light or propulsion, with technological improvements they have been provided with less and less (final) inputs. Newly introduced technologies, such as the steam engine, might have been less efficient initially than established technologies (e.g. animal traction) but had advantages such as the potential for larger scale and higher energy density, as well as round-the-clock operation and controllability. The efficiency of all technologies improved over time due to technological innovation. Steam engines for locomotion, for example, have seen their thermal efficiency increased from 0.5% for Newcomen's steam engine in 1712 (Smil, 1991) to 8% and more in the 20th century (Stobart, 2007). Individual processes have become more efficient over time, but they are aggregated into sectors, whose structure changes. Aggregate end-use efficiencies can therefore decrease over time, despite each individual conversion process increasing in efficiency, if there is a structural shift within a sector towards less efficient processes. In this paper the combined effects of process efficiency improvements and structural change are studied.

Instead of looking at individual processes and aggregate efficiencies over time, however, the degree of economic development was employed as the independent variable, with income (Gross Domestic Product) per capita used as a proxy. The reason for choosing per capita income, an indicator for the degree of economic development, as the independent variable is that heterogeneity is expected, in the technical and aggregate efficiencies across regions and economies at each point in time. Therefore, a metric of the level of economic development can be understood to combine temporal and regional differences in end-use efficiency. In other words, it is assumed that for regions and for times with the same level of economic development, the levels of end-use efficiency per sector, energy carrier and end-use are comparable, which is not the case with a simple time dimension.

2.2 Data sources

A variety of sources were used for estimating energy conversion process efficiencies between final to useful energy forms, covering estimates for 19 countries or groups of countries and the period 1947 through 2004. The compiled database contains all the sources of comprehensive useful energy estimates identified in an extensive literature research, but nonetheless it is not pretended to be exhaustive. Over the different sources there is a high degree of heterogeneity in the presentation of the data: the categorization of final energy into sectors, processes and fuels makes it necessary to aggregate the reported final energy numbers so that they can be treated in a common framework. The aggregation is discussed in detail in section 2.3.

2.2.1 Final and useful energy

The data sources that were of value for the study were the ones that reported final energy use as well as an estimate of the quantity of useful energy into which it is converted

- for a given period of or moment in time

- for a region for which a Gross Domestic Product per capita can be defined
- broken down at least into the sectors of industry, transport, and other (residential, commercial, ...)
- by energy carrier in sufficient detail: at the very least solids fuels, fluid fuels, electricity, and others
- approximately disaggregated by form of useful energy: visibly radiant (light), kinetic (motion), thermal (heating and cooling) and other forms including uses such as electrolysis.

Table 1 contains the data sources found that satisfy these criteria. The number of different fuels and different processes in different sectors is an indicator of the resolution of the data source. However it should not be taken as an indicator of accuracy. The study on Canada by Rosen (1992) contains estimates for all sectors, but only electricity in industry could be included in this analysis because electricity and fuels are not separated in transport; because there is no distinction among fuels in the residential, commercial and industrial sector; and because in the residential and commercial sector not all uses are analyzed. Other studies (e.g. Dincer et al. (2004) and Utlu and Hepbasli (2007)) were not included because of similar reasons, with either no comprehensive data for all uses in a sector, or too low a resolution in terms of energy carriers.

Table 1: Data sources of technological final to useful energy efficiencies used in this study.

Source	Region	Time	Fuels	Processes
Ministério de Minas e Energia, Brazil (2005)	Brazil	1984, 1994, 2004	18	111
Eurostat (1978; 1980; 1983; 1988)	Belgium, Denmark, Federal Republic of Germany, France, Greece, Ireland, Italy, Luxemburg, Netherlands, Portugal, Spain, United Kingdom	1975 (only FRD and France), 1978 (except for Greece, Spain and Portugal), 1980 (except for Spain and Portugal), 1985	20	45
Bundesministerium für Handel und Wiederaufbau, Austria. (1955; 1958)	Austria	1953, 1956	8	26
Putnam (1953)	United States of America	1947	18	9
Nakićenović et al. (1996)	European OECD ^a countries, World	1990	6	22
Guyol (1971)	Netherlands	1960 - 1967	14	7
Ramain (1977)	France	1950, 1955, 1960, 1965, 1970, 1974 ^b	5	4
Laading (1960)	OEEC ^c	1957	4	4
Department of Energy, United Kingdom (1978)	United Kingdom	1950, 1954-1976	11	9
Masera and Dutt (1991)	Cheranatzicurin (Mexican village)	1989	11	26
Rosen (1992)	Canada	1986	1	1 ^d

^aOrganisation for Economic Co-operation and Development

^bprojections for 1985 in source not used

^cOrganisation for European Economic Co-operation, precursor to the OECD

^dOnly electricity use in industry could be included in this study.

2.2.2 Economic indicators

Gross Domestic Product per capita was used as an indicator for the level of economic development. The source used for these data is the database assembled by Maddison (2010) because it offers consistency across time and countries. The unit in which the values are expressed is the International Geary-Khamis dollar (per person) with 1990 as the benchmark year, with a value similar to the United States dollar. GDP values for countries other than the U.S.A. are converted into GK\$-denomination at purchasing power parities (PPP) using the Geary-Khamis method.²

2.3 Aggregation

In this section the aggregation method for the final and useful energy data used to derive efficiencies (to obtain comparability across sources) is discussed. This aggregation takes place on a sector and end-use level as well as on an energy carrier level.

2.3.1 Sectoral aggregation

One can subdivide energy users in modern society in several ways. Most commonly, the division is into the sectors industry, transport, residential, commercial, public or government, and agriculture. Not all of the data sources present the data in this way, but a three sector division can be applied to all of them. That division is industry; transport; and residential and commercial grouped as one category (including energy use by public administrations and government, and agriculture)³.

It should be noted that these categories are not defined very precisely, and some identical types of energy use might be put under different categories by different sources.⁴ The guiding definitions of the aggregating categories in this study are as follows.

- **Industry:** all end uses in the direct or indirect manufacturing of goods. Examples include the production of cement and steel but also the heating of factories.
- **Residential and commercial:** end uses in residences, and in commercial, public and agricultural facilities. Examples include residential lighting and office heating.
- **Transport:** all energy end use for propulsion of vehicles, e.g. trains, airplanes, subways, cars, tractors, ships, as well as pipeline operation.

²There are two exceptions to this. The first is Luxemburg: the Maddison data set only provides values for "14 small Western European countries" (including Luxemburg) grouped together. For the sake of consistency the GDP per capita series of the 14 small countries was used as a proxy for Luxemburg's. The second exception relates to the Mexican village study, the results of which are used as representative for a region with very low development. Therefore, GDP of the nation of Mexico in 1950 was chosen for the village study by Masera and Dutt (1991), even though it was performed in 1989.

³This follows the 'domestic' sector classification by the Smith et al. (2011).

⁴For example, fuel used for tractors could be categorized as transport, but also as agriculture. Where it was possible to single out this transport share, it was done. An example is energy use for non-public transportation in the Austrian energy balance (Bundesministerium für Handel und Wiederaufbau, Austria. (1955; 1958)) which is spread over the sectors "Households", "Trade and Industry", "Agriculture" and "Public Services". Across these sectors, the end use "Speed engines" was therefore assigned to transport. Finally, space heating in transport in the European useful energy balance sheets, was labeled as residential and commercial sector.

2.3.2 End use aggregation

Within each of the sectors, processes are aggregated according to the nature of the useful energy output. Lighting purposes are categorized as radiant energy, mechanical and motive purposes as kinetic energy, and heating or cooling as thermal energy. Unspecified uses are tagged as "other" uses. These are the uses appearing as "other" in the data sources, but include also electrolysis and other specific process applications. Cases where only a sector level aggregate was reported without further details on use, were not taken into account, nor were non-energy uses (e.g. feedstocks).

2.3.3 Energy carrier aggregation

Each energy carrier was assigned to one of three categories: coal products and (solid) biomass, electricity, other. This is a relatively easy task because the categories have distinct physical properties so that there are no ambiguities as in the case of the sectoral categorization. The chosen division is all-comprehensive and mutually exclusive by design. The categorical labels are congruent with solid fuels (including fodder for draft animals), electricity (including heat as final energy⁵), and all other energy carriers (including e.g. natural gas, hydrogen, gasoline, kerosene, etc.) respectively. It was possible to unambiguously tag each of the energy carriers in each of the sources with one of the three labels, with the exception of unspecified fuels or energy carriers. These were assigned to the category "Other". Gas produced from coal (coke oven gas, blast furnace gas, ...) was categorized as a coal product in this study.

2.4 Correlation between level of economic development and aggregate end-use efficiency per sector and carrier

The aggregate end-use efficiency was calculated by dividing the aggregate useful energy by the aggregate estimated final energy, per set of sectoral category, energy carrier category and end-use, and per region and year (from table 1). Then, region and time were eliminated through translation into a GDP (PPP) per capita value. The scatter plot in figure 1 shows all the points thus obtained. Although at first sight there is a rather large dispersion within each of the groups, in part due to the variety of data sources and corresponding assumptions, it is possible to discern a significant trend in increasing conversion efficiency as a function of the level of economic development. The correlation between technical process efficiencies and level of economic development is reciprocal: income has grown over time as a result of technological innovation which has also resulted in increased process efficiencies. In turn, rising incomes also make more efficient technologies affordable to a wider segment of the population and firms, raising aggregate process efficiencies.

For each of the nine groups (three sectors, three energy carriers) and of the end-uses in them, a functional expression was derived for the respective process efficiency as a function of GDP (PPP) per capita. The chosen form of this expression is exponential, motivated by the requirements that the steepest increases in efficiency occur at low levels of development, and that efficiency level off at higher levels of economic development

⁵e.g. district heating steam

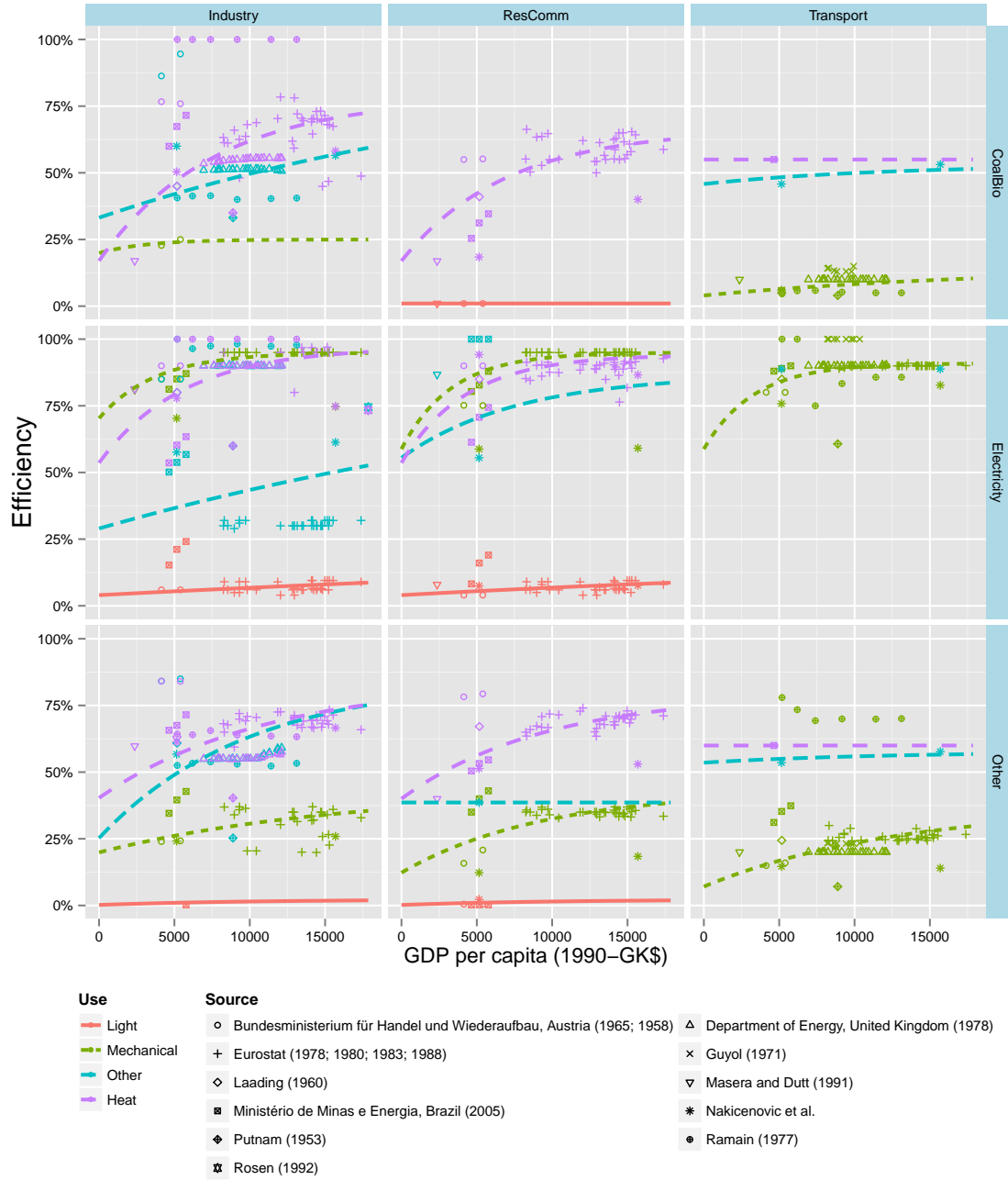


Figure 1: Aggregate final to useful energy conversion efficiencies for each of the three sectoral categories and for each of the three energy carrier categories, by end-use and by source reference. Relationships used in the efficiency model displayed as lines.

because it is bounded by a value less than or equal to 1:

$$\eta_{s,f,u}(g) = \eta_{min,s,f,u} + (\eta_{max,s,f,u} - \eta_{min,s,f,u}) \left(1 - e^{-g/\Gamma_{s,f,u}}\right) \quad (1)$$

where η is the final to useful energy conversion efficiency, g is GDP per capita, Γ is the

scaling GDP per capita⁶, and the indices s , f and u indicate sector, energy carrier, and end-use, respectively.

The minimum and maximum efficiencies η_{min} and η_{max} are generally determined by the minimum and maximum observed values over the relevant data. Adjustments were made to cases where the order of the minimum and maximum efficiencies within energy carriers and sectors is inconsistent with the general trends that can be seen: efficiencies must be in increasing order along the sectors transport, residential / commercial / other and industry, and along the energy carriers solid fuels, fluid fuels, and electricity/heat. 'Other' uses are not constrained by this rule.

That order in the efficiencies is intuitive. Applications in transport are for variable loads and are limited by constraints of having to be mobile, and thus are generally lower than in industry or in the residential/commercial sector where applications are rather more stationary with less variable loads. Industry can reap scale effects, and is therefore generally a more efficient sector in terms of final-to-useful energy conversion efficiency than the residential and commercial sectors.

On the energy carrier side, electricity is the most versatile in terms of conversion: electric motors are highly efficient, and electric energy can easily be converted almost completely into usable heat with a simple resistor. Electric lighting is also much more efficient than using other fuels like biomass or kerosene. Among fuels, fluid fuels (oil, gas) are more efficient than solid (coal, wood, ...) because of their greater energy density and generally greater reaction surface. The latter is important because less excess air is needed for complete combustion.

The parameter Γ is fitted to the data.⁷ The decision was made to treat each combination of region and data source equally and therefore the weight of each point in each group of sector, use and energy carrier is the inverse of the number of data points that are in that group that represent its data source and its region. The fit was not constrained to respect the aforementioned rule, which only applies to the lower and upper bounds of final to useful energy conversion efficiencies.

Six data points were dropped from the regression. These are the points in the lower right panel of figure 1 above 50% and correspond to "other" energy carriers in transport. These figures result from assumptions made in the source studies: there are 'specific' uses (in Raiman (1977)) for which no substitute is available and therefore for part of the final energy a conversion efficiency of 100% was assumed. The resulting high aggregate conversion efficiencies do not even exist for stationary heat engines, with the possible exception of combined cycle gas turbines. Figure 1 shows the parametrized expressions (equation 1) as the curves overlaying the scatterplot. The parameters are summarized in table 2. For non-energy uses (feedstocks), a conversion efficiency of 100% was assumed for this study.

The model deviates from these parameters for solid biomass in the residential / commercial sector, as this is supposed to be non-commercial biomass (not traded on official markets but e.g. fuel wood gathered from the environment and used for burning) which is in most applications used for cooking and direct heating, with much lower efficiencies than e.g. a coal stove. For this category, the efficiency obtained with expression 1 is halved.

⁶The equivalent of the exponential time constant in exponential decay.

⁷An exception was made for radiant energy from fluid ("other") energy carriers in industry, where the value is taken from the residential/commercial sector.

Sector	En. carrier	η_{min} (%)				η_{max} (%)				Γ (US\$-1990)			
		Heat	Light	Mech.	Other	Heat	Light	Mech.	Other	Heat	Light	Mech.	Other
Industry	Coal/Biom.	17.0	-	19.9	33.2	78.4	-	25.0	94.6	7597	-	3183	32089
	Electricity	53.6	4.0	70.3	29.0	97.0	24.1	95.0	98.2	5605	67445	3768	42757
	Other	40.3	0.2	19.9	25.3	84.1	2.3	43.0	85.0	11116	10383	15933	9894
ResComm	Coal/Biom.	16.9	1.0	-	-	66.3	1.0	-	-	6956	-	-	-
	Electricity	53.6	4.0	58.8	55.5	94.2	19.0	95.0	86.8	4297	47964	3329	7766
	Other	40.0	0.2	12.3	-	79.3	2.3	43.0	-	9439	10383	9328	-
Transport	Coal/Biom.	-	-	4.0	45.8	-	-	15.0	53.1	-	-	20458	12075
	Electricity	-	-	58.8	-	-	-	90.9	-	-	-	3296	-
	Other	-	-	7.1	53.5	-	-	37.4	57.7	-	-	12939	12075

Table 2: Parameters for final-to-useful energy conversion efficiency in function of GDP (PPP) per capita

3 Energy balances

The expressions for final-to-useful energy conversion efficiencies obtained in section 2.4 above can now be used to construct estimates of historical useful energy balances. However, this is only possible for regions and times for which a final energy balance is available that matches our system of energy carrier and sectoral categories. The International Energy Agency (IEA) publishes final energy balances for most countries after 1970 and for OECD member countries starting in 1960 with sufficient detail for our purposes (International Energy Agency, 2012b). In the longer run, e.g. the entire 20th century, for most countries and regions there are no data available in terms of final energy broken up by sector and/or energy carrier, and hence final energy balances were constructed for the period prior to IEA final energy balances as well.

For this study, the world was divided into a group of key countries and complementing regions. A country is included if, according to IEA statistics in 1971 (when statistics for most countries are available), its total final energy consumption minus international bunker fuels and non-energy uses is so large that including it into our sample countries achieves 80% of the world total final energy use in 1971 (with the least amount of countries). South Africa was also included. It does not satisfy the inclusion criterion but has much higher commercial energy use in the earlier decades of the 20th century than Nigeria which was in the initial selection. Together, this yields a sample of 15 countries, to which 5 "other" regions were added, such that aggregation to the 5 regions of the Global Energy Assessment (GEA, 2012) is possible.

The 20 countries and regions which are considered in this study are therefore:

- **OECD member states in 1990:** Australia, Canada, France⁸, Germany^{8,9}, Italy, Japan¹⁰, United Kingdom, United States, other OECD-90
- **Reforming economies:** Former Soviet Union¹¹, Poland⁸, other REF
- **Latin America and the Caribbean:** Brazil, other LAM

⁸The boundaries shift slightly over time as geographical areas belong to France, Germany or Poland. The boundaries to which the data series apply, are those corresponding to the data source reporting.

⁹Germany includes the German Democratic Republic, 'East Germany'.

¹⁰Including Ryukyu Islands.

¹¹Referred to as a country in this study. Before 1917 the data apply to the Russian Empire.

- **Asia:** China¹², India, other ASIA
- **Middle East and Africa:** Nigeria, South Africa, other MEA

First, a detailed final energy balance will be presented for one country (the United States). Then, the methodology for the reconstruction of final and useful energy balances for all countries and regions considered is explained. Finally, the data and the online database are introduced.

3.1 The United States energy system (1800-2010)

For the United States of America, historical energy statistics exist that allow for an approximation with reasonable detail of primary and final energy use starting in the year 1800. In this section, a final energy balance is created from several data sources, which will be compared with the final energy balance reconstructed with the simplified method (section 3.2, and used in the other countries/regions of this study) requiring less detailed data sources.

3.1.1 Data sources

The data sources used per energy carrier and per period are summarized in figure 2. The Energy Information Administration (IEA) of the U.S. Department of Energy (U.S. DOE) publishes energy data for four sectors (industry, transportation, residential and commercial) from 1949 onwards. For the years since 1960 however, the IEA statistics are used (International Energy Agency, 2012b) which also include explicit data on non-energy uses. Bunker fuels are included in transportation. Before 1950, Putnam (1953) reports primary energy for combustible fuels, and Dewhurst et al. (1955) for renewable energy such as wind and direct hydropower, as well as animate power. Edison Electric Institute (1970) reports time series for electricity production and sales. Finally, final energy per fuel and sector can be found in Schurr et al. (1983) for selected years.

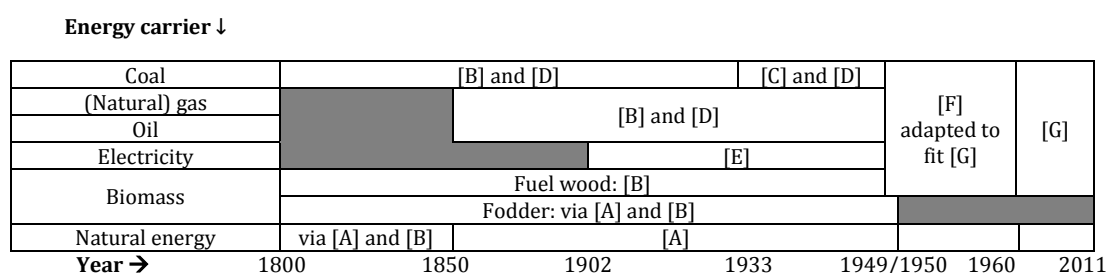


Figure 2: Overview of sources used for the historical final energy series in the United States of America.

[A] Dewhurst et al. (1955), [B] Putnam (1953), [C] Schurr et al. (1960), [D] Schurr et al. (1983), [E] Edison Electric Institute (1970), [F] Energy Information Administration (2012), [G] International Energy Agency (2012b)

¹²Includes Hong Kong.

3.1.2 Method

Reconstructing historical final energy use is done by putting together the data from the various data sources. As of 1960, data from the IEA are used directly to assure maximum consistency and comparability with other countries and regions. In order to reconcile non-IEA and IEA statistical differences in the year 1960 where both data sets overlap, the data from EIA were multiplied with a factor, specific per sector and per energy carrier¹³, according to the 1960 relation between the US data sources (see figure 2) to the IEA data. The ratio of energy in "non-energy" to energy in industry from IEA in 1960 was applied to determine the non-energy share of industry as reported by EIA (EIA does not have a non-energy category - this is assumed to be subsumed under the EIA category 'Industry'). A factor of 1 was used for electricity. The resulting series were used from 1949 through 1959.

Before 1949, the reference for final energy is the energy balance published by Schurr et al. (1983) for selected years, providing values for 3 sectors (industry, combined residential and commercial, and transportation) and for different energy carriers. The distribution among sectors is interpolated linearly in between the selected years, and for each energy carrier. The split by energy carrier between the commercial and the residential sector was kept constant at the value in 1949 in the EIA statistics.

Schurr et al. (1960) have a detailed breakup of bituminous coal from 1933 through 1956 that is used through 1948. The same sectoral breakup is applied to anthracite for which the end-uses are not reported. Coke ovens and beehive coke plants, as well as electricity generation, were excluded as end-uses. The ratio in 1937 of the coal used in industry excluding coke ovens and plants, to all coal used in industry as reported in Schurr et al. (1983), about 0.77, was applied to all coal consumption in industry before 1933. Heating values used were 26.2 MMBtu per net ton¹⁴ for bituminous coal and 25.4 MMBtu per net ton for anthracite (from Schurr et al. (1960)). Primary energy values for fuel wood, natural gas, coal (before 1933) and oil were taken from Putnam (1953). After subtracting coal used for electricity generation (from Schurr et al. (1983))¹⁵, the following factors were applied as primary-to-final energy conversion efficiencies: 0.95 for solid fuels (coal and biomass), 0.9 for oil, and 0.85 for natural gas.¹⁶

Electric final energy before 1949 is taken from Edison Electric Institute (1970). Back to 1926, the sectoral break follows from the reported sales, where the residential sector was taken to include rural and residential customers as well as street and highway lighting; the commercial sector corresponds to small light and power, other public authorities and interdepartmental sales; industry to large light and power; and transportation to railroads and railways. Non-utility generation was not considered because of a lack of data, and the energy used for it is assumed to be a part of the final energy. Before 1926, the sectoral split in 1926 was applied, together with the implied system efficiency in that year, to the generation back to 1902 (with interpolations for missing years).

Fodder is included in biomass, together with fuelwood, up to 1950. The energy is calculated from an estimate of animate power in Dewhurst et al. (1955), with an assumed metabolic efficiency (calories into work) of 5%. Together with fodder, direct uses of wind

¹³Here, the same fuel mapping as for the calibration of the MESSAGE model was used. The main characteristic is that 'gas' encompasses all gases, including e.g. town gas.

¹⁴One net or short ton is equal to a mass of 2,000 lb or about 907.2 kg

¹⁵Before 1949, coal is the main energy carrier used for thermal electricity generation in the United States.

¹⁶These factors are estimated by Grubler and Cleveland (2008).

and water power are categorized as industry, and before 1850 they are scaled with the fuel wood data from Putnam.

3.1.3 Long-term final energy balance of the United States (1800-2010)

The resulting final energy balance can be visualized in a number of ways. Figure 3 shows total final energy consumption (including non-energy uses) and by energy carrier over time. It shows a clear transition from biomass to electricity as a final energy carrier over the course of the past centuries, passing through other energy carriers. Since the 1960s a slowing down of these substitutions can be observed though the increase in the share of electricity persists. The share of gas decreased but in recent years increased again (not shown in graph) because of the boom in shale gas extraction in the United States.

The dips in total final energy consumption (line in figures 3 and 4) correspond to events of economic importance: the wake of the First World War, the Great Depression around 1930, the end of the Second World War, the oil crisis in the beginning of the 1970s, the energy crisis at the end of the 1970s, the collapse of the Soviet World around 1990 and the most recent global economic crisis starting in 2008. During the twentieth century, final energy consumption increased by a factor 7, the growth slowing in the last decades.

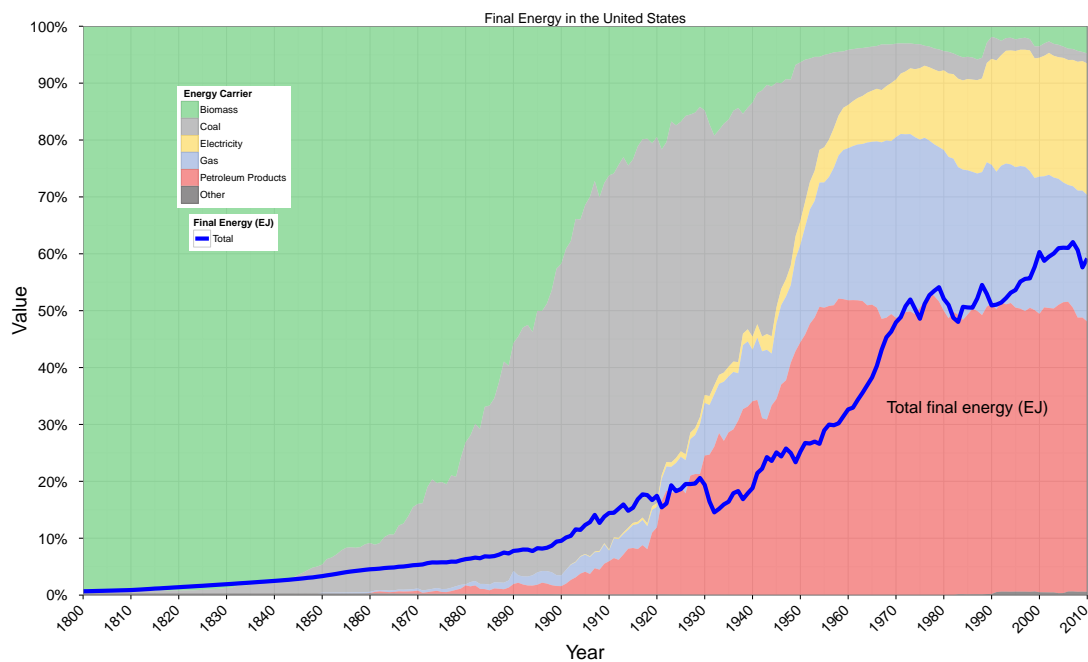


Figure 3: Final Energy in the United States, 1800-2010. Shares of energy carriers, and total final energy (EJ instead of %).

Figure 4 shows the breakdown of all fuels among sectors over time. Non-energy final consumption comes into the picture in 1949 because of a lack of historical data for all energy carriers. Both industry as well as the transportation sector grow in share during the 19th century. For the transportation sector, this growth is consistent and continues during the 20th century. The industry share decreases after the First World War. Growth picks up again with the Second World War, and the sector share starts a persistent decline after the mid-1960s as manufacturing is increasingly relocated to low-wage countries.

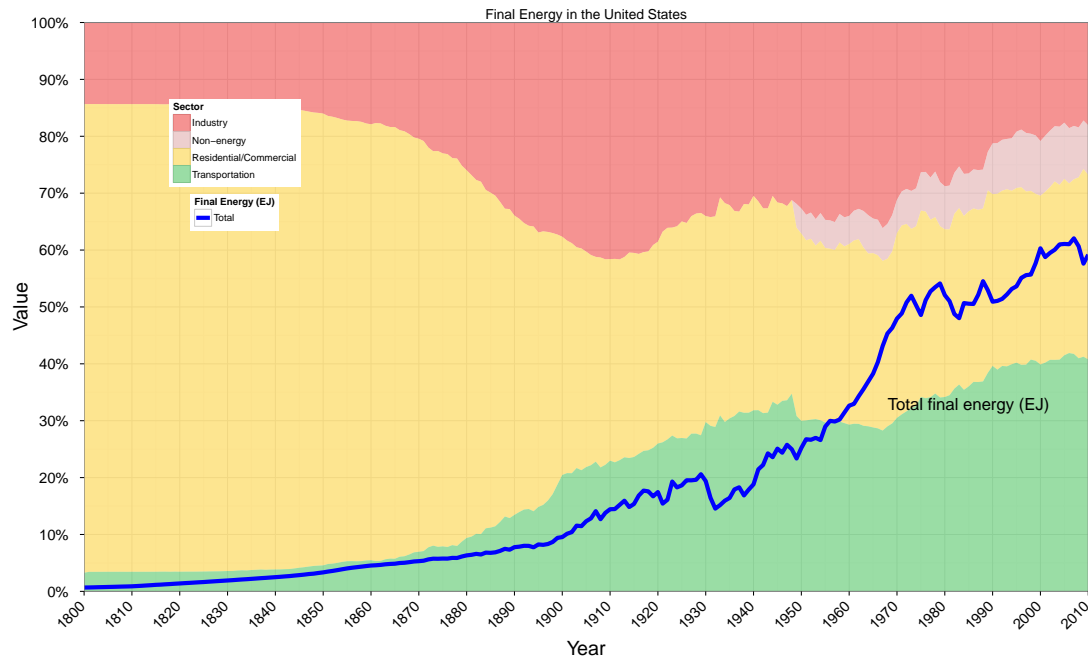


Figure 4: Final Energy in the United States, 1800-2010. Shares of sectors, and total final energy (EJ instead of %).

The non-energy uses in figure 4 are mainly petroleum products, and since 1990 about one tenth is natural gas, mainly for fertilizer production. The non-energy uses reported here do not include coal products employed in coke ovens or plants.

3.2 Construction of historical final energy balances

From 1960 (OECD member countries) or 1971 (non-OECD countries) on, the International Energy Agency publishes final energy statistics for all the countries/regions which are used in this study (International Energy Agency, 2012b). Data on final energy consumption before 1960 are very sparse. However, the statistics of some countries contain enough information for a (partial) final energy balance by sector and by energy carrier, for a number of years before the start of the IEA data. This is the case for the United States (section 3.1) and the United Kingdom. Fouquet (2008) calculated the final energy balance of the latter from several indicators and statistics, and it spans several centuries.¹⁷ For some other countries (e.g. Japan, the Former Soviet Union) statistics on certain sectors and energy carriers exist but not all and not for the entire period. A calculation of the missing pieces of final energy data in the way Fouquet did for the United Kingdom was beyond the scope of this study and hence for all countries/regions a simplified method of reconstructing final energy balances from primary energy statistics was adopted in this study.

Primary energy is generally well-documented for most countries since 1900, although there are gaps in data during socio-economically turbulent periods, the most prominent

¹⁷The book volume does not contain all of the final energy data series. These were obtained from Fouquet himself. The book does contain series for services provided (e.g. lighting in lumen-hours).

one being the Second World War (1939-1945). This is also the case for electricity generation data. A simple mechanism was devised to calculate historical final energy in the three sector framework based on historical primary energy data on the one hand, and on the very detailed IEA energy statistics on the other hand. For the countries with final energy data available before the start of IEA reporting, generally the same mechanism was used in order to have a consistent approach across countries and regions. Figure 5 shows the scheme for the reconstruction of the final energy consumption as well as of the allocation of energy among sectors. The steps are explained in detail in the next sections and paragraphs.

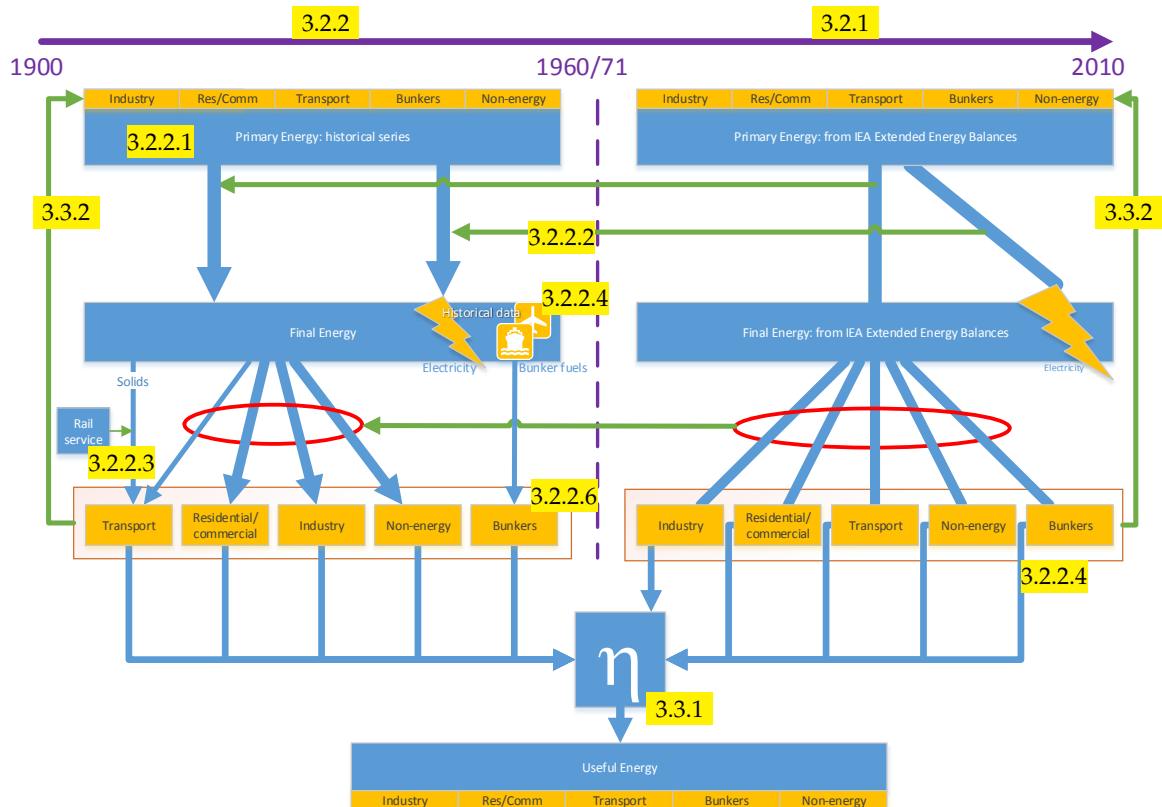


Figure 5: Scheme of the reconstruction of final and useful energy time series and of the allocation among sectors. Yellow boxes refer to the relevant section or paragraph. The box titled η symbolizes the final-to-useful energy conversion efficiency model.

3.2.1 IEA statistics

The IEA statistics form the most recent part of the historical final energy balances. The sectoral division of final energy adopted here is almost the same as employed by the International Energy Agency, with 'other sectors' grouped into residential/commercial, with the exception of the IEA 'fishing' flow, which is assigned to transport. The latter follows the sectoral division from Smith et al. (2011), but there are some differences with the classification in this study: aviation is included with transport here; non-energy uses are a separate category; non-ferrous materials and non-metallic minerals are included

with industry; heat pumps are not included in final energy,¹⁸ and international bunker fuels (aviation and marine) are a separate category.

The International Energy Agency reports 63 different energy products. Consistency with primary energy data required that these be grouped into 12 energy carrier groups according to their origin:

1. **Coal products:** all products originating from coal or peat, including manufactured gases
2. **Biomass:** both solid and liquid, includes charcoal and waste¹⁹
3. **Natural Gas:** natural gas, excluding natural gas liquids
4. **Petroleum products:** crude oil and refined petroleum products, including liquified petroleum gases. Also includes natural gas liquids.
5. **Nuclear**
6. **Solar:** photovoltaic and thermal
7. **Geothermal**
8. **Wind**
9. **Heat**
10. **Electricity**
11. **Hydro:** includes tide, wave and ocean energy
12. **Other**

Some of these energy carriers, such as nuclear energy and hydropower, are insignificant if not absent in the final energy flows. However, they are important for the allocation of the secondary energy forms (heat and electricity) to primary energy.

3.2.2 Methodology for historical final energy reconstruction

The reconstruction of final energy use is based mainly on the detailed IEA statistics, historical primary energy series, historical electricity generation series, international marine bunker fuel data and railway transportation service data. A cascading model was used to derive final energy from primary energy and some indicators. The first cascade is electricity generation. There is a second cascade for coal into transport. Third, the energy contained in international bunker fuels, and in non-energy uses, is subtracted. What is left from the primary energy flows is distributed among the three sectors (and losses). Selected ratios between final energy and part of the primary energy are fixed at the corresponding values in the earliest available IEA statistics, and applied to the primary energy data back to the year 1900 on a year-by-year basis.

¹⁸Referring to the 'heat pumps' flow which is part of the transformation sector in the IEA balances.

¹⁹Including municipal and other waste, as was done by Nakićenović et al. (1996).

3.2.2.1 Primary Energy The primary energy carriers of importance before the IEA statistics timeline are coal products, solid biomass, petroleum, natural gas, hydropower and geothermal (into electricity). Direct use of wind power (e.g. in windpumps) and water power (e.g. in water mills) are assumed to be negligible on a national and regional level, and animate power is not taken into account because of a lack of data. Nuclear energy for electricity generation is not taken into account because of its very small contribution before the availability of IEA energy statistics which start in 1960.

For the countries under consideration, statistics by Mitchell (1992; 1993; 1995) were used for coal products, petroleum products and natural gas. The time series are taken at face-value and for details and notes the reader is referred to the original sources²⁰. Where two values were reported for the same year, the value consistent with the following years was generally chosen. The apparent consumption of primary energy was calculated as [production] plus [imports] minus [exports] and thus includes international bunker fuels.²¹ The corresponding series for the IEA-based balances therefore also include international bunker fuels. The Mitchell statistics are reported in tonnage or volume. To calculate their energy content, the following approach was taken. Because coal heat content varies enormously according to the nature and provenance of the coal, coal products were converted from tons to energy content using the implied conversion factors following from a comparison of the tonnage from the Mitchell statistics and the heat content reported in the earliest available IEA statistics for the country/region in question. The petroleum products were converted using the ton of oil equivalent (41.868 GJ/ton) when reported in weight, and 6.119 GJ/barrel when reported in volume. The conversion factor for natural gas, always reported in cubic meters if not in energy content, is 38.2 MJ/m³.²²

Statistics from other sources complemented the Mitchell statistics in some cases. For example, Nigeria produced a lot of crude oil in the period since 1960 but exported most of it. Because Mitchell (1995) reports tonnages/volumes and not energy content, net exports exceed production, leading to a negative apparent consumption of primary energy. Therefore, statistics from Darmstadter et al. (1970) were used instead, as Darmstadter et al. report the produced and traded quantities in tons of coal equivalent for selected years.

Mitchell does not report biomass data. These were taken from a number of different sources that report estimates, and for those countries or regions with no estimates in the literature, the per capita biomass primary energy use was held fixed at the value resulting from the earliest available IEA statistics. Biomass primary energy data for Germany, France, Italy and the United Kingdom come from Kander et al. (2013).²³ Putnam (1953) reports numbers for India, Japan and the United States. The biomass series for Japan were interpolated between 1947 (from Putnam (1953)) to 1982 (from International Energy Agency (2012b)) as the absence of biomass in the IEA statistics before 1982 is assumed to be due to a lack of information rather than no biomass being consumed in that period. For biomass in France and Italy a similar correction was made. Lewytkyj (1979) provides

²⁰Time series might include discontinuities e.g. certain fuels or areas are included or excluded, or the generated electricity only includes production by public utilities. This is documented in the source but not repeated in this report.

²¹Consistency required that the flows 'statistical differences' and 'transfers' be added to this apparent consumption of primary energy for the years when IEA statistics are available.

²²In this study, a ton indicates a metric ton unless otherwise specified.

²³Attributions within book: Italy from Malanima (2006), England and Wales from Warde (2007), France from Gales' original series and Germany from Gales' and Warde's original series.

numbers for the Soviet Union - the biomass primary energy use in the first year of that series determines the consumption in the years before.

Instead of aggregating all the statistics from Mitchell into the 'other' regions, they were calculated from the national carbon emissions time series from the Carbon Dioxide Information Analysis Center (CDIAC) (Boden et al., 2009), which are based on the Mitchell series according to the same calculation method for apparent consumption of primary energy as employed in this study. The primary energy use of the complement regions was calculated by aggregating the data for solid, liquid and gaseous fuels across all countries composing those regions, and converted into the energy content of the fuels using the factors reported in Boden et al. (1995):

(from 10 ⁶ metric tons of carbon)	Solid fuels	Liquid fuels	Gaseous fuels
CDIAC factor (to unit)	$(0.982 \times 0.746)^{-1} (10^6 \text{ t})$	$(0.985 \times 0.85)^{-1} (10^6 \text{ t})$	$(0.98 \times 0.0137)^{-1} (\text{TJ})$
Factor to TJ	29.308	41.868	1

Table 3: Factors to convert from CDIAC carbon emission series

3.2.2.2 Electricity and heat The first step in the calculation of final energy data is to subtract the primary energy that is consumed to generate electricity and centralized heat. For most of the regions under consideration, detailed historical data on the generation mix are not available. However, Mitchell (1993) reports historical electricity production time series, and Etemad and Luciani (1991) report time series, starting in 1900²⁴, for electricity generated from hydropower as well as total electricity generated for countries covering most of the world.²⁵ The difference between total generation and generation from hydropower is taken to be generation from fossil fuels. Before the IEA timeline, nuclear energy does not play a significant role and geothermal is only important in Italy.

The increasing efficiency of electricity generation over time needs to be incorporated in the analysis. Two sources that report average efficiency time series are Edison Electric Institute (1970) for the United States (average heat rate) and Schilling et al. (1977). Figure 6 shows the series that run from 1925 to 1971²⁶. A regression on the Schilling et al. (1977) data yields, with a high coefficient of determination, a positive slope of 0.5% per year.

The procedure to reconstruct fuel use for electricity generation is based on the earliest available IEA statistics and combines two processes. On the one hand, for each of the fuel groups of coal products, petroleum products, biomass and natural gas, the implied electricity generation efficiency is calculated as the ratio of electricity output from each to the energy going into both main activity as well as autoproducer, electricity and CHP (combined heat and power) plants. Going back in time, each year 0.5% is taken off of the efficiency in each of the group down to a minimum of 12% at which it is held constant for earlier years.

On the other hand, the detailed historical statistics offered by Edison Electric Institute (1970) indicate that around 1925 and before, most fossil fuel-based electricity was generated using coal as a fuel. Therefore the shares of other fuel groups are brought gradually and linearly to zero (backwards in time) by a year depending on the specific country but

²⁴The series for Italy and Switzerland start earlier.

²⁵These data often include only electricity production from (public) utilities, but the electricity from auto-producers was estimated to have little effect on the analysis.

²⁶The 1971 point of the EEI series is an interpolation between the 1970 point of EEI and the 1975 data of the Energy Information Administration (2013).

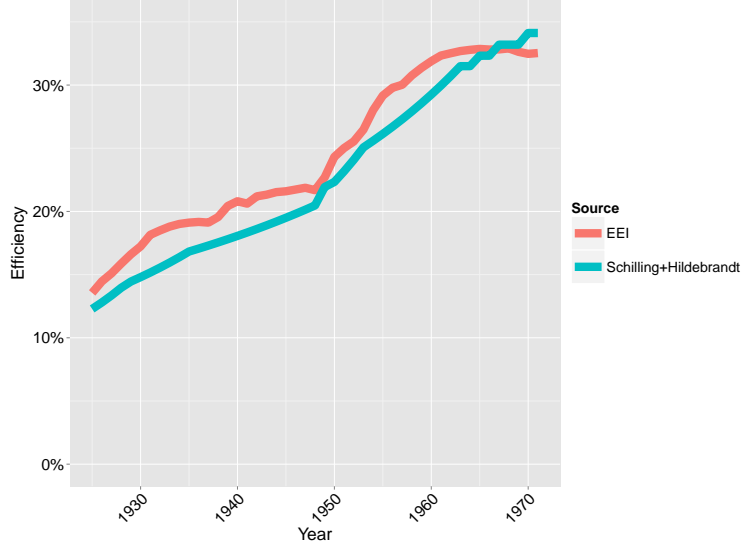


Figure 6: Historical average efficiency of electricity generation from fossil fuels, for the US (Edison Electric Institute, 1970) and World (Schilling et al., 1977)

most often 1925, with some exceptions (see appendix A.1 with country/region notes). The anchoring point for the shares is the earliest year of IEA statistics, and a fuel group is only considered if it makes up at least 10% of thermal electricity generation in that year.

3.2.2.3 Railway transport There is little historical data on the split of final energy among the industrial, transport, and residential / commercial sectors. Proxy indicators related to one energy carrier and one sector are few, but one of them is railway transport. Railway transport is generally well documented in terms of service output: statistics have been kept and published on persons or tons of freight transported, and on what total distance they traveled. In the beginning of the 20th century, locomotives were primarily propelled by steam power from the burning of coal (or biomass in some cases such as the United States (Schurr et al., 1960) and Brazil (Inspectoria Federal das Estradas, Ministerio da Viação e Obras Publicas, 1920)). If we regard international bunker fuels separately, and neglect national waterway transport, coal as final energy in the transport sector is only used for railroad transport and an estimate of that quantity adds significant accuracy to the historical reconstruction of overall final energy.

The amount of solid fuel in (railway) transport C_T is given by expression 2:

$$C_T = \alpha(t) (\beta_p s_p + \beta_f s_f) \quad (2)$$

where β_p and β_f are the inverse service efficiencies for passenger transport and freight transport, s_p and s_f are the services, and $\alpha(t)$ is a time-dependent multiplier.

s_p and s_f (in terms of unit of energy per passenger-km and ton-km) were calculated for railway transport on solid fuel using data from the United Kingdom. Apart from data availability, the rationale for benchmarking service efficiencies on the United Kingdom for solid fuels in rail transport is that the UK was a pioneer in steam locomotion and exported its technology to other regions of the world, for example to its former colony,

current India. Mitchell (1988) reports data for coal used by railways, and Fouquet²⁷ possesses series for passenger and freight transport service (number/weight times distance traveled). After applying the coal heat content as calculated from IEA statistics and Mitchell (1992) in 1960 (24.17 GJ/ton, assuming quality of coal used in the United Kingdom to be constant), a linear regression of energy use (TJ) against passenger-kilometers and ton-kilometers leads to the result in table 4. The intercept has been forced to zero.

Service	Coefficient	Standard Error	t-value	Significance
Passenger (passenger-km)	$\beta_p = 5.939 \times 10^{-6}$	3.40×10^{-7}	17.49	$< 2 \times 10^{-16}$
Freight (ton-km)	$\beta_f = 4.747 \times 10^{-6}$	3.47×10^{-7}	13.66	2.04×10^{-14}
Adjusted R-squared			0.9987	

Table 4: Results of regression of energy (TJ) from coal in railways against passenger and freight services

Because of the importance of biomass alongside coal in railway transport (such as in the United States and Brazil), the expression thus obtained was taken to be valid for solid fuels in general (regarding coal and wood as equivalent in service efficiency terms). Expression 2 estimates final energy use from solid fuels in transport in the beginning of the 20th century. In order to fit the historical final energy mix in railways to that as reported in the IEA statistics, the multiplier $\alpha(t)$ was introduced. The expression is assumed to explain railway solid fuel use completely ($\alpha = 1$) up to a certain year (1940 unless otherwise specified in appendix A.1), after which other energy carriers such as electricity and petroleum products start substituting coal and wood. From that year on, $\alpha(t)$ decreases linearly over time from 1 to the value implied by actual final energy in transport from solid fuels in the earliest IEA statistics.

For countries in which locomotives use a significant amount of wood alongside coal, it is assumed that the solid fuel used for railway transport is coal up to the point where coal supply, after accounting for the coal used in electricity generation, is insufficient. In that case, the remainder of the solid fuel is biomass. This rests on the assumption that coal is used as a fuel for prime movers in transportation with priority over other uses (apart from electricity production). Figure 5 shows this separate treatment of solid fuels in transport.

Data on railway services in passenger volume \times distance and freight tonnage \times distance are not always available. Where this is the case, numbers are determined through interpolation with passenger volume and freight tonnage as a proxy or using Gross Domestic Product (PPP) as a proxy. The country/region notes (appendix A.1) specify the exact method. An example is given for Australia in that section.

3.2.2.4 Bunkers Data on bunker fuel consumption for international aviation and marine traffic is available from the IEA since 1960 or 1971, depending on the country. United Nations Statistics Division (2007) statistics were used to complement them for earlier years. For even farther back, estimates by Darmstadter et al. (1970) were used (only marine bunker fuels). Since the latter only report data for selected years, back to 1925, the ratio to the remainder of primary energy (after subtraction of energy used for electricity/heat generation and for transport in the case of coal) was interpolated for the missing

²⁷Data underlying those published in the book, obtained through personal request.

years, holding the ratio constant before 1925 and with an upper bound equal to the ratio of all final energy (including bunkers and non-energy uses) to that remainder of primary energy in the first year for which IEA statistics are available.

3.2.2.5 Non-energy uses For each energy carrier, the amount going into non-energy uses such as fertilizer for natural gas, and plastics for petroleum products, is published in the energy balances of the IEA. For earlier years, a simple estimation method was adopted: the non-energy use share of the primary energy after subtraction of energy used for electricity/heat generation, solid fuels for transport, and international bunker fuels, decreases linearly from its value in the earliest year of IEA statistics, to zero back in 1940. The choice for 1940 is motivated by the fact that the two main industries relying on fossil fuels for non-energy uses - the fertilizer industry and the petrochemical industry - only really took off after the Second World War (Soh, 2001; Brydson, 1999). The value for the share is constrained in cases where non-energy uses would be greater than the remaining energy after subtraction from primary energy of the aforementioned uses.

3.2.2.6 Final energy series After subtracting from the primary energy data the energy used for electricity generation and the solid fuel used in railway transport, as well as the energy going into bunker fuels and non-energy uses (see sections 3.2.2.4 and 3.2.2.5), the remainder is divided among the sectors industry, transport and residential / commercial / other, and a virtual sector representing the primary-to-final energy conversion losses. Ratios are taken from the earliest IEA balance available for the specific country or region: for each energy carrier with the exception of solid fuels, the fraction of primary energy - after subtracting the amount used for electricity generation - going into each sector is determined, where the minimum threshold for a sector to be assigned energy is 10%. The sum of the fractions of the three real sectors is distributed proportionally to their fractions among the sectors for which the fraction is above the 10% threshold. The fractions are kept fixed and applied back in time to the reduced primary energy series to come to an estimate of historical final energy use. A shortcoming of this method is that the relative shares of the sectors in final energy are a function only of the changing shares of different energy carriers in the (total) final energy mix.

For solid fuels this method is adapted. In the case of coal in transport, the absolute amount is determined according to the procedure detailed in section 3.2.2.3. As the transport share of biomass in transport in the earliest IEA energy balance is less than 10% for all countries and regions in this study, the only biomass in historical transport is the amount required due to a lack of coal for the algorithm to satisfy the transport energy demand (see section 3.2.2.3).

For some regions the specific approach taken to reconstruct the historical final energy balance is a variation on the general approach explained above. This is necessary because of differences in data availability and quality. Detailed information on the reconstruction of the final energy series can be found in appendix A.1.

3.2.2.7 Method verification The data obtained with the method explained above can be compared against final energy balances constructed with more detailed data for the United States (from section 3.1) and for the United Kingdom (from Fouquet (2008)). Both

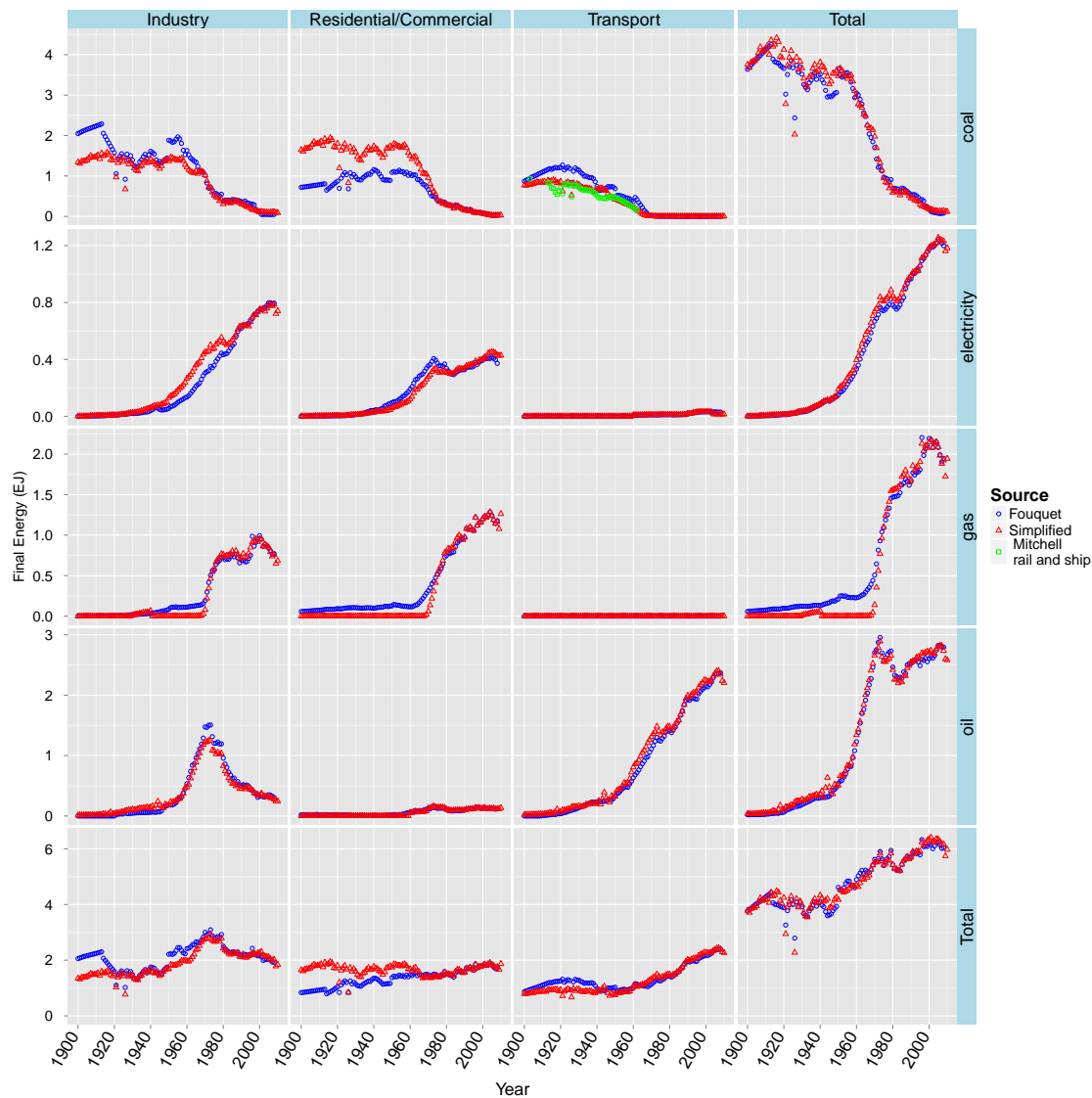


Figure 7: Comparison of the final energy balance for the United Kingdom obtained from Fouquet (2008), versus that obtained through applying the 'simplified' methodology, 1900-2010. Also shown is a series from Mitchell (1988) for coal in the transport sector. Transport includes bunker fuels.

time series for final energy consumption are shown in figures 8 (US) and 7 (UK²⁸) for different sectors (horizontal) and for main energy carriers (vertical)²⁹. International bunker fuels for shipping and aviation are included with the transport sector. Generally, the data are in good agreement.

²⁸The original fuel consumption series from Fouquet (2008) are expressed in higher heating values. Correction factors were applied to make them consistent with the LHV accounting in this study: 0.94 for liquid fuels, 0.95 for solid fuels and 0.9 for gaseous fuels (International Energy Agency, 2005).

²⁹Vertical axes are scaled differently for each row to fit the data.

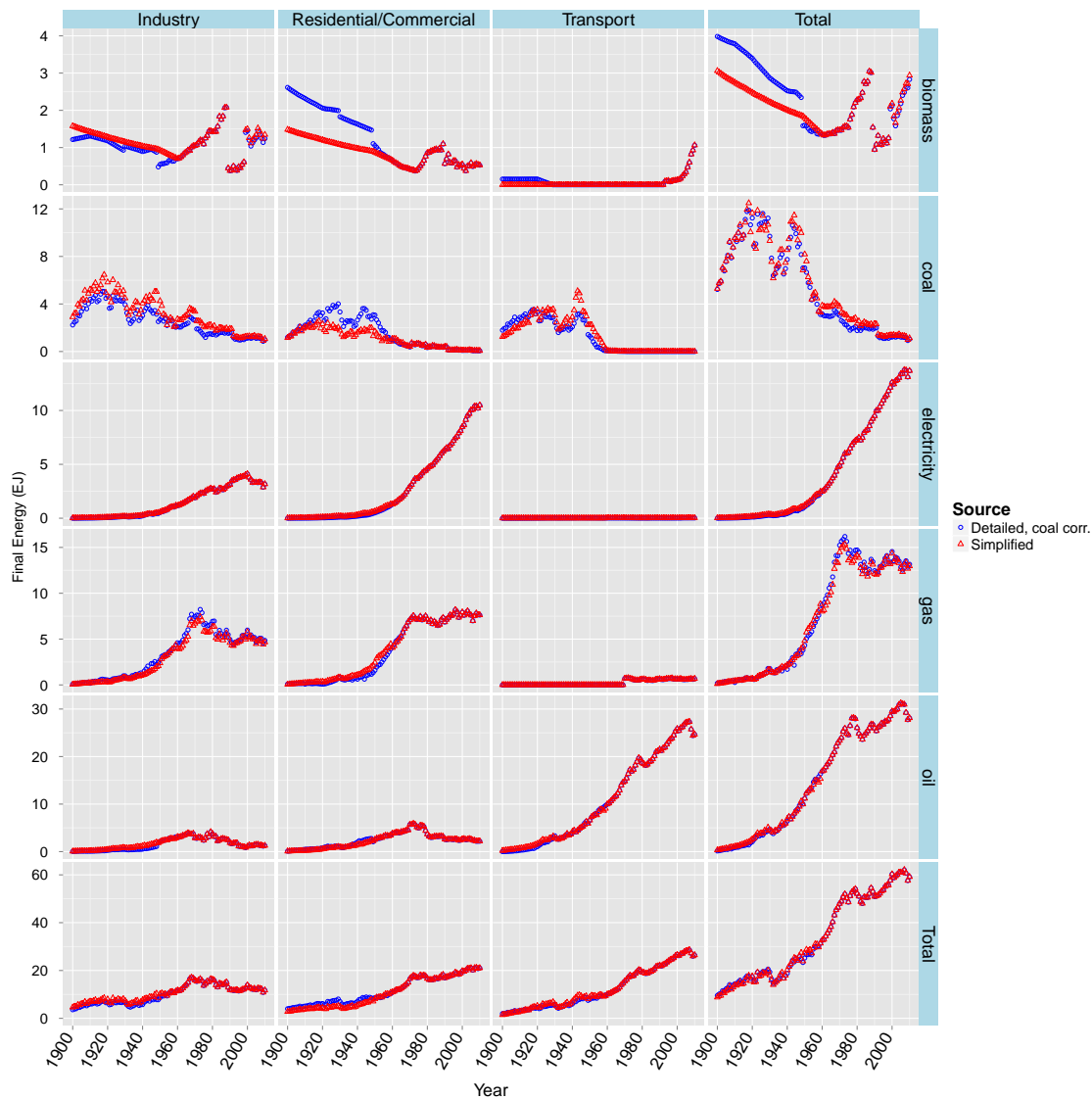


Figure 8: Comparison of the final energy balances for the United States obtained from several sources, versus that obtained through applying the 'simplified' methodology, 1900-2010. Transport includes bunker fuels.

The major differences for the United Kingdom with the Fouquet (2008) data are found in the 'gas' energy carrier category, as well as in the sectoral split³⁰ for coal and electricity, which are also reflected in the total over all energy carriers.³¹ Biomass is not shown because its contribution in the United Kingdom is marginal in the twentieth century (as opposed to the United States where it still played an important role). The discrepancy for gas is largely a consequence of the categorization of gases from coal (town gas from gas works and in smaller quantities coke oven gas and blast furnace gas), which is a part of 'gas' in the Fouquet (2008) series instead of 'coal' in the categorization of this study. These quantities are relatively small compared to the 'coal' category, where the totals

³⁰The sectoral split from the simplified method was adapted for harmonization purposes: the residential/commercial category here comprises only residential use. The remainder was assigned to industry, as Fouquet (2008) groups industry with 'other' uses.

³¹This includes energy carriers which are not shown. Their contributions are small, however.

across sectors align quite well. Differences in this total fall within the uncertainty range in terms of heating value of the coal. Transport appears the sector where the Fouquet (2008) coal series differ significantly and most from the series constructed with the simplified method. However, the latter corresponds well with the sum of the coal going into shipping and rail as reported by Mitchell (1988) when applying a heating value of 24.17 GJ/ton (following from the IEA energy statistics, see appendix A.1). Particularly here, differences in heating values to convert from coal mass units help explain the difference, as for transport uses higher quality coal would have been selected. In the residential sector, the series shown are in close agreement, except in the first decades of the twentieth century, where the simplified approach overestimates coal use. This goes together with an underestimation in industry for the first decade and (compared to the Fouquet (2008) data) transport up to the early 1920s. The split of electricity between industry and the residential sector differs between the 1940s and the 1980s, due to a different classification: uses for lighting were assigned to the residential sector for the Fouquet (2008) series. The electricity totals across sectors match closely. Fouquet's (2008) series exclude autoproduction of electricity, which is included in this study's data.

Overall, the series obtained with the simplified method thus approach estimates based on more detailed information quite well. What's more, since residential/commercial final-to-useful energy conversion efficiencies are similar to those in industry, on an aggregated useful energy level, the split between those two sectors will have only relatively small effects in terms of total quantity. However, this uncertainty should be kept in mind when dealing with quantities of high/medium temperature heat versus low temperature thermal uses as derived below.

The different series for the United States (figure 8) exhibit also a very good congruence. The only major differences occur in the solid energy carriers. The big discontinuity in total biomass consumption is due to the inclusion of estimates for fodder serving animal power before 1950, and the Putnam (1953) estimates for fuelwood which are larger than the EIA's. Coincidentally, the series for industry are very similar because the addition of fodder makes up for the non-aligned sectoral allocation in 1949. Conversely, however, in the first half of the twentieth century the difference between the totals across sectors can be found almost entirely in the residential/commercial sector.

The coal and gas series obtained with the generic reconstruction method differ from the ones following from the more carefully reconstructed series in the second half of the twentieth century because of the different allocation of gases from coal products as was the case for the United Kingdom. Overall, the totals for coal correspond quite well, with the most apparent difference being in the sectoral split between industry and residential/commercial. However, for the same reasons as the ones that applied to the United Kingdom, these sectoral split differences are not important for the final and useful energy aggregates. The peak of coal products in transport around 1944 obtained with the generic method is due to a peak in passenger volume (Mitchell, 1993).

These two examples give confidence in the applicability of the generic method proposed in this study for the reconstruction of historical final energy use for other countries and regions. In what follows, the thus obtained data will be used for all countries and regions, including the United States and the United Kingdom, for consistency.

3.3 Primary, Final and Useful energy balances

Applying the final-to-useful energy conversion efficiency model (section 2 above) to the final energy balances leads to the useful energy balances, and both are combined with the primary energy data to form a 7-dimensional dataset. These dimensions are time (1900-2010), space (countries/regions), sector (industry, residential/commercial, transport, non-energy and bunkers), energy carrier (see section 3.2.1), energy form (primary, final and useful energy), the nature of the energy use and quantity of energy.

3.3.1 Useful energy

The final energy balances constructed in section 3.2 are combined with the final-to-useful energy conversion efficiencies derived in section 2.4 to construct historical useful energy balances. For this, the end-uses of useful energy need to be determined. The basis for this is the database constructed for the purpose of estimating aggregate efficiencies, presented in section 2 above. The same 3 sectors were used, but this time the energy carriers were split into 5 categories: biomass, coal, electricity, (natural) gas and oil. A weighted average³² was taken of the share in useful energy of each of the 4 uses, per sector and energy carrier. The results were subsequently normalized per sector and per energy carrier group. The remaining 7 energy carriers (out of the 12 energy carrier categories used in this study) were assigned shares according to their most likely use. Hydro and wind energy are fully for kinetic energy purposes, and the others (direct heat, solar energy, nuclear energy, geothermal and 'other') are considered to be fully employed for thermal purposes, if present in final energy. The results of the useful energy shares are tabulated in table 5.

Sector	Energy carrier	Thermal	Light	Other	Kinetic
Industry	Biomass	84.2	-	15.8	-
	Coal Products	87	-	13	0.005
	Electricity	11.2	0.2	19.3	69.3
	Heat, nucl., geoth., other, solar	100	-	-	-
	Hydro, wind	-	-	-	100
	Natural Gas	87	-	10.8	2.2
	Petroleum Products	81.9	-	15.1	3
ResComm	Biomass	100	0.05	-	-
	Coal Products	100	-	-	-
	Electricity	50.4	3	0.6	46
	Heat, nucl., geoth., other, solar	100	-	-	-
	Hydro, wind	-	-	-	100
	Natural Gas	100	0.002	0.03	0.02
	Petroleum Products	91	0.01	-	9
Transport	Biomass	-	-	-	100
	Coal Products	-	-	-	100
	Electricity	-	-	-	100
	Heat, nucl., geoth., other, solar	-	-	-	100
	Hydro, wind	-	-	-	100
	Natural Gas	-	-	-	100
	Petroleum Products	-	-	-	100

Table 5: Shares of uses in useful energy, per sector and energy carrier, in percent

³²The weights are the same as the ones used for the regressions in section 2.

Although a clear correlation with degree of economic development or time, of these shares, is lacking, there are some boundary conditions which need to be respected. They mainly concern lighting uses. Before the advent of commercial electricity, the major source of (night time) lighting was the oil lamp, and this was the main residential purpose of oil. When electricity became first available it was overwhelmingly if not solely used for lighting. Because of these considerations, the shares obtained from the data are only used as a state to which the system evolves, and to determine the relative shares among uses that are not subject to particular initial boundary conditions. For electricity, the transition between the relative shares in the early years and the eventual shares is determined using national electrification as a proxy. The reasoning is that as an increasing share of the population gains access to electricity, the uses of this energy carrier in industry and in the residential/commercial sector shift from solely lighting to other uses (thermal, mechanical) as well.

This transition in electricity, from 100% light to the split by uses as deduced from the efficiencies database, is estimated as follows: (1) for the countries and regions in this present study, a logistic curve³³ (sigmoid function) was fitted to the level of electrification as in Banerjee et al. (2013) for the years 1990, 2000 and 2010;³⁴ (2) the complement of the function value was raised to the fourth power to incorporate the idea that at higher levels of electrification, the shift to multiple uses of electricity is disproportionately higher than at lower levels; (3) the complement of the resulting function is used for the shares of the uses of electricity, in industry and the residential/commercial sector, using appropriate offsets and scaling factors to satisfy the asymptotes for negative time (100% for light, 0% for the other uses) and for positive time (the shares as deduced from the efficiencies data set); (4) the values for the shares are set to the negative-time asymptotic values in the first year for which electricity generation is reported (from Etemad and Luciani (1991)), and in the following years were linearly interpolated to the value given by the function from step (3) in the tenth year, after which that function was used.

For petroleum in the residential/commercial sector, the exact same approach was used, based on electrification: for countries with low levels of electrification, a considerable amount of illumination is provided with oil lamps.

Since for a good part of the twentieth century, in countries relying on coal for their energy supply, coal-derived (town) gas was used for lighting purposes (e.g street lighting) as well, the share of light in coal products in the residential/commercial sector was set to 0.15% (in terms of useful energy) in the year 1900. The place of coal-derived gases in residential use was taken by natural gas towards the end of the twentieth century. Based on Fouquet's (2008) series, the share of light in residential/commercial coal products is therefore set to zero in 1970. Between 1900 and 1970, the share in terms of useful energy decreases linearly in this present study.

Finally, the share of light in biomass in the residential/commercial sector decreases from its previously determined value, in 1900, to zero in 1925. The latter year was determined

³³A logistic function of the form $f(x) = \frac{1}{1 - e^{-a(t-t_m)}}$ was used, following Fisher and Pry (1971), with t_m the year for which diffusion is 50% and a an inverse time constant ($\Delta t = \frac{\ln(81)}{a}$ with Δt the time to go from 10% to 90%). The fits were obtained by linear regression of the transformation $f(x) = x / (1 - x)$ versus time.

³⁴In cases where electrification is 100% for all three years, it was assumed that the electrification took place rapidly in the beginning of the twentieth century, and the parameters $\Delta t = 40$ and $t_m = 1920$ were chosen for those countries/regions.

based on the use of tallow candles in the United Kingdom (from Fouquet (2008)). Afterwards, light from e.g. wood fires is considered not functional as a lighting service.

The development indicators used for the final-to-useful energy conversion efficiency model come from the same dataset (Maddison, 2010; Bolt and van Zanden, 2013) that was used for the efficiencies in section 2.4.³⁵ However, since the update (Bolt and van Zanden, 2013) only reports GDP per capita numbers, no aggregates for the five 'other' regions could be calculated in a consistent way for the years 2009 and 2010. Their growth in GDP per capita was taken equal to the growth of representative countries in the world regions: Brazil, India, Nigeria, Poland and the United States. Population numbers for 2010 were scaled from 2009 using UN population data. GDP-PPP numbers for 2009 and 2010 (not used for the energy data but reported in the database) were calculated from the population and GDP (PPP) per capita values. Finally, for the regions 'Other Middle East and Africa' and 'Other Asia', the population and GDP (PPP) numbers before 1950 are such that they add up to the totals of the region or relevant sub-regions (as some countries have no data before 1950, with not even historical reference points to interpolate to).

Because biomass in transportation has been mainly liquid in recent decades,³⁶ the efficiency for 'other' (fluid) energy carriers is applied in the transport sector after a key year. For most countries 1959 turns out to be a good break point. For Brazil, the year 1970 was chosen.

The resulting total final and useful energy time series are compared with the data from Fouquet (2008) in figure 9, for the entire energy system of the United Kingdom, over the period 1900-2010. Both useful energy time series were determined using the final-to-useful energy conversion efficiency model from section 2. The two data sets are in general agreement, although not perfectly. The difference in final energy in light since the middle of the twentieth century is significant but within expected uncertainty, as the ranges of estimates of energy consumption for lighting are generally big: Mills (2002) mentions a difference of over 38% between two estimates of electricity for lighting in the United States. The difference in final (and useful) energy for mechanical uses in the first half of the twentieth century is in large part due to the differences in coal energy consumption between this study and Fouquet's (2008) series, previously ascribed to the difference in allocation among sectors, but also to differences in the assumed heat content of the coal products. Between 1960 and 1985, part of final energy is assigned to heat in Fouquet's (2008) data set but to mechanical uses in this study, However, this is a relatively small effect and again, within expected uncertainty.

3.3.2 Allocation of primary energy

Allocating primary energy inputs to the energy system by sector presents a number of problems. First, the energy from energy carriers that is lost in the transformation (on the level of the national/regional energy system) is not consumed in any end-use sector and so cannot be directly allocated. This is the case for electricity production, but e.g. also for refining where light fuel oil requires more distillation than heavy fuel oil but the

³⁵Where values for GDP per capita were missing, population numbers and GDP were linearly interpolated and the obtained values combined into an estimated GDP per capita.

³⁶In the final energy series, a phasing out and subsequent phasing in of biomass in transportation can be observed, corresponding to a cessation of railway and waterway transportation on solid biomass and the adoption of liquid biofuels such as ethanol.



Figure 9: Comparison of total final energy and useful energy per use for the United Kingdom, between Fouquet (2008) and this study. The useful energy series have been estimated using the final-to-useful energy conversion efficiency model developed for the present study. Feedstocks (non-energy uses) are not shown in this graph. The scale on the vertical axis varies across panels.

energy lost in refining processes is not broken up by final energy carrier. Second, for transformations with one input but more than one output, as is the case for cogeneration, there is no physical fraction of the primary energy to be assigned to one or the other. The allocation of primary energy to different sectors is therefore in many ways a question of accounting. For this database, primary energy was allocated, within each energy carrier category, proportionally to final energy use in each sector and for each service within that sector after accounting for electricity and heat. This is represented in figure 5 above by the outer green arrows.

Expression 3 was applied to the data to disaggregate primary energy by sector:

$$PE_{s,u,f} = \frac{FE_{s,u,f}}{FE_f} \times (PE_f - E_f - H_f) + \frac{FE_{s,u,electricity}}{FE_{electricity}} \times E_f + \frac{FE_{s,u,heat}}{FE_{heat}} \times H_f \quad (3)$$

where PE is primary energy, FE is final energy, E is energy used for electricity generation, H is energy used for heat generation, and the indices s , u and f indicate sector, end-use and energy carrier, respectively.³⁷ A missing index indicates the aggregate over that index. This expression is applied within each year and for each country/region.

The primary energy used for electricity and heat production (E and H in expression 3) was taken from the IEA balances for the available timespan. Primary energy going into cogeneration plants was split between heat and electricity using the system expansion allocation method³⁸: the fraction allocated to heat, for example, is the fraction of heat in the sum of the primary energy quantities that would have been required to generate the heat and the electricity separately in two dedicated plants. The reference efficiencies are those that follow from electricity and heat production from dedicated plants in the same year, for the same primary energy carrier and for the same country/region. When these cannot be determined, a reference efficiency of 80% was used for heat, and of 30% for electricity. If heat output from cogeneration was not reported by energy carrier, then a fraction from the total heat output from cogeneration from all energy carriers (always reported) is used, equal to the fraction of the inputs of the energy carrier in question to the total. In rare cases where inputs into cogeneration are reported but the outputs are zero, the inputs are not assigned to electricity nor heat, and simply not taken into account.

For the historical data, only primary energy for electricity, and not for heat, was calculated. The reference electricity generation efficiencies as discussed in section 3.2.2.2 are based on a denominator including both electricity plants and cogeneration plants, and therefore include some of the fuels used for heat generation. Hence, the heat in final energy before the availability of IEA statistics, is not used to calculate primary energy. As there is little to no historical data on heat in final energy such as district heating steam, heat has been estimated as proportional to electricity generation in those countries/regions where heat in final energy is nonzero in the first available year of IEA statistics, and assuming a decreasing proportionality factor going back in time (see section A.1). This approach ensures that the data are consistent, and the error in subsequent analyses can be considered small.

This allocation procedure by sector is consistent with the allocation of carbon emissions from fuel combustion among sectors as reported by the International Energy Agency (2012a). This can be seen from figure 10, which shows the carbon emissions for the world according to the method explained above, with the non-electricity/heat transformation sector separated (lines) as well as the emissions by sector in 2010 from the International Energy Agency (dots). The emission factors used in this study are in table 6. Here, bunkers were included in transport, and biomass in the residential/commercial sector was singled out because it is assumed to be largely non-commercial and therefore not included in the International Energy Agency statistics for CO₂ emissions. The two sources are in good agreement in 2010 considering the limited degree of detail in e.g. transport fuels and associated carbon emission factors in the present study, with the transformation

³⁷Here, bunker fuels and non-energy uses are treated as separate sectors.

³⁸A term from the Life Cycle Assessment methodology.

Energy Carrier	Carbon emission factor (tC/TJ)
Biomass	29.9
Coal Products	25.8
Natural Gas	15.3
"other"	20.0
Petroleum Products	20.0
All other energy carriers	0

Table 6: Carbon emission factors (based on Eggleston et al. (2006))

sector being a notable exception. In the International Energy Agency data, this represents the energy sector's own use (about 2.2 GtCO₂), whereas the time series represent *all* losses between primary and final energy apart from electricity or (centralized) heat generation. This explains the time series being higher than the International Energy Agency data point, for the transformation sector.

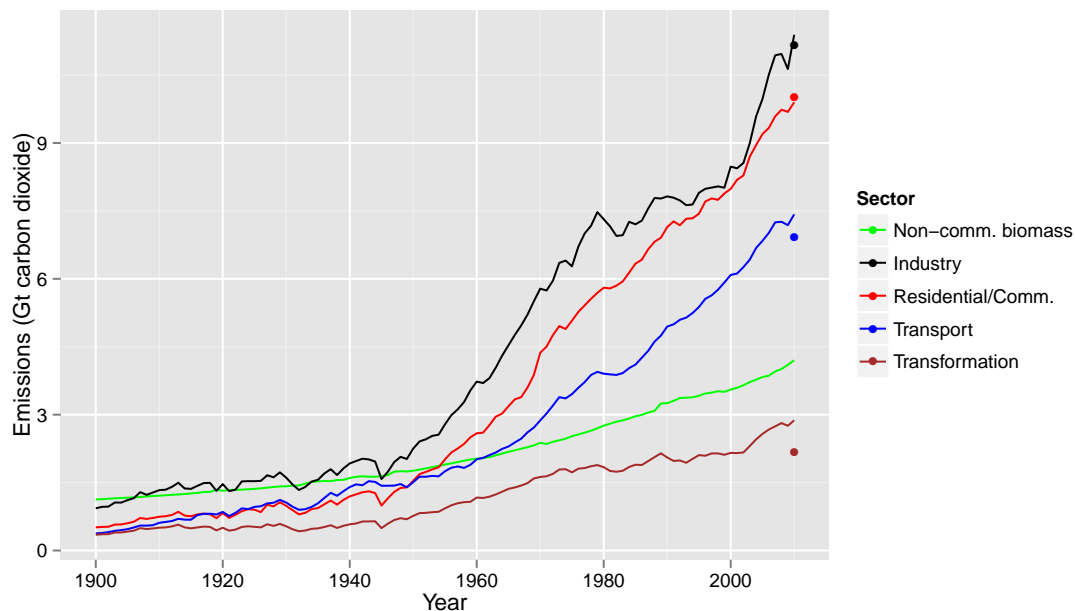


Figure 10: Carbon dioxide emissions from fuel combustion (non-energy uses not included), allocated per sector for the world by own allocation method (lines) and from International Energy Agency (2012a) (dots).

The primary energy from non-combustible energy sources is re-calculated using the equivalence method as adopted in the Global Energy Assessment (GEA, 2012). For the energy carriers hydroenergy, geothermal energy, nuclear energy, wind and solar energy, the primary energy equivalent is the energy required to produce the electricity from that source with an efficiency of 35% efficiency and heat with an efficiency of 85%. Direct uses as reported in the IEA database are translated into primary energy one-to-one. In what follows, whenever primary energy is reported, this will be the equivalent according to the GEA approach.

3.3.3 Global and regional balances

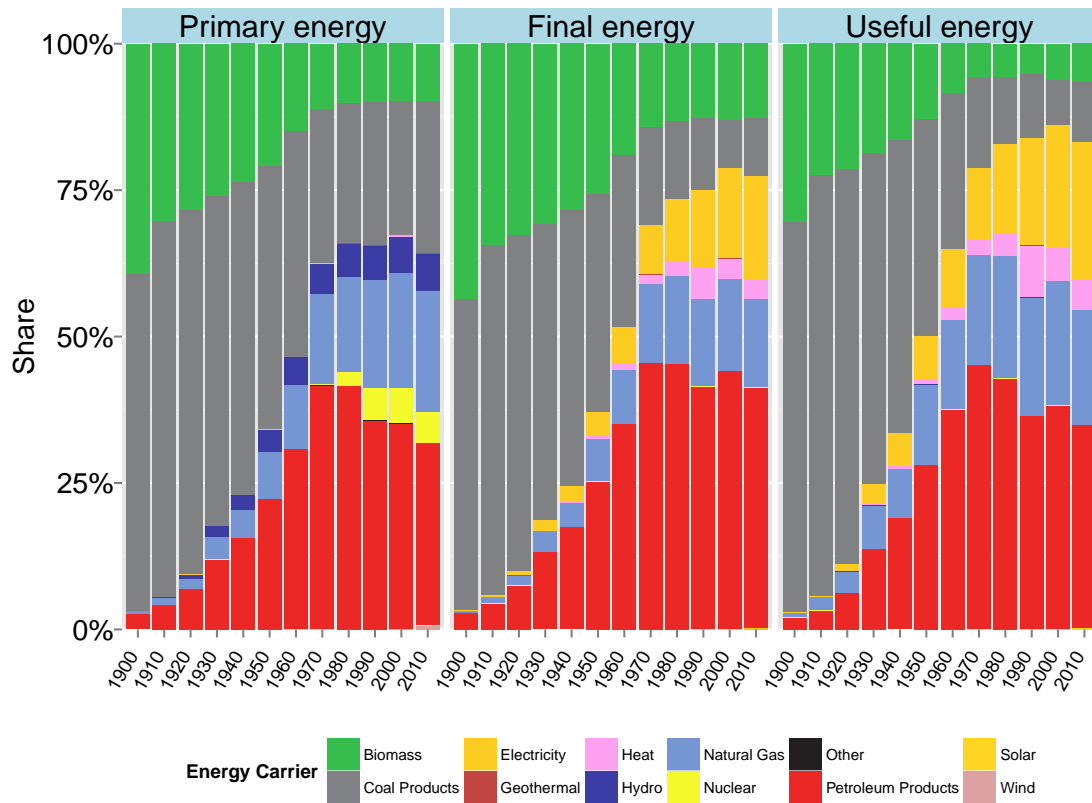


Figure 11: Primary energy, final energy, and useful energy (shares) for the world, selected (decadal) years. Non-energy uses are included. Negative values in primary energy due to electricity/heat imports excluded.

The balances thus constructed allow to visualize energy transitions over time on a primary (input), final and useful energy level, as well as by use. For selected years, figure 11 shows the global energy use by energy carrier share in terms of primary, final and useful energy. The system dynamics in terms of energy carrier substitution are immediately obvious. The share of biomass decreases over time on all levels, and while the share of coal products initially increases, it declines during the twentieth century with an increase in the last decade as countries like China satisfy their booming energy demand with cheap and plentiful coal. Natural gas and hydropower see a consistent increase on all levels, whereas nuclear, coming into the global primary energy picture in the 1960s, declines in share as less plants are constructed because of rising costs and opposition. The share of petroleum products peaks on all levels in 1970-1980 (of the selected years) because of the induced substitution that follows the oil crisis and the energy crisis in the 1970s. The share of petroleum products in useful energy is considerably lower than in final energy, because petroleum products are mainly used in transportation where the end-use converters are rather inefficient. In 2010, the share of petroleum products, while being much greater than that of electricity in final energy, is comparable to electricity's in useful energy because of the comparatively high aggregate efficiency of electric converters.

Figures 12, 13 and 14 show the evolution of primary, final and useful energy for the world and five world regions, by energy carrier, sector and end-use, respectively. The losses in the system moving from primary to useful energy are clearly visible. The consistent growth (accelerating everywhere up to 1970) in energy consumption on all levels over time can be observed, with notable exception the 'Reforming Economies' including the former Soviet Union which see a dramatic drop in energy use following the collapse of communist Europe at the end of the 1980s.³⁹ The energy use of the initial OECD member countries exhibits a dip after the energy crisis at the end of the 1970s. For this region, it is also important to point out the last decade as it shows the effectiveness of energy conservation and efficiency policies aimed at a number of issues such as energy security and climate change.

Petroleum products have come to dominate primary and final energy because of the increase in personal transport and air travel, both of which are overwhelmingly petroleum-powered. On the useful energy level, however, the shares of electricity and heat increase at the expense of petroleum's, because of their highly efficient conversion in end-use devices and applications.

The split by sectors in figure 13 reveals an increase in non-energy uses of energy carriers for all regions displayed. It is also obvious that the transport sector is the least efficient, with the share dwindling from primary to useful energy. For the reforming economies, the reason for the sharp decline in total energy use around 1990 is clearly a collapse of the industrial sector, whereas industry growth after the 1990s was responsible for most of the energy demand growth in the Asia region. In the OECD countries, transport is responsible for a considerable share of primary energy, as the prosperous population enjoys individual mobility and air travel.

The split by end-use in figure 14 was obtained using combinations of sectors with the end-uses as previously determined (thermal energy, kinetic energy, light and other uses). Thermal applications in industry were categorized as high (and medium) temperature uses, and in the residential/commercial sector as low-temperature. Mechanical uses of energy in both sectors are labeled as stationary power. The figure confirms the low conversion efficiency along the energy chain into light, and shows the increasing importance of it in upstream quantities. Low-temperature uses appear most important in the reforming economies and in the Middle East and Africa. In the former, this is because of considerable heating requirements, whereas in the latter region cooking is an important application in terms of shares of total energy.

3.4 Online database

The entire dataset, including the energy as well as exergy (section 5) series, is publicly available online, and can be reached through the Transitions to New Technologies (TNT) Program page on the IIASA website. Guests can log in using the **Guest Login** button. The **About** tab contains a brief explanation about the database and instructions on how to use it. At the top, the **Quick Balance** box allows to quickly generate a table or a graph with the time series on the chosen energy/exergy level, for the selected region and by selected variable (sector, energy carrier and/or end-use). More information on how to navigate the database can be found in appendix A.2.

³⁹The increase in final and useful energy from 1989 to 1990 is the consequence of an almost doubling of heat in final energy in the IEA statistics.

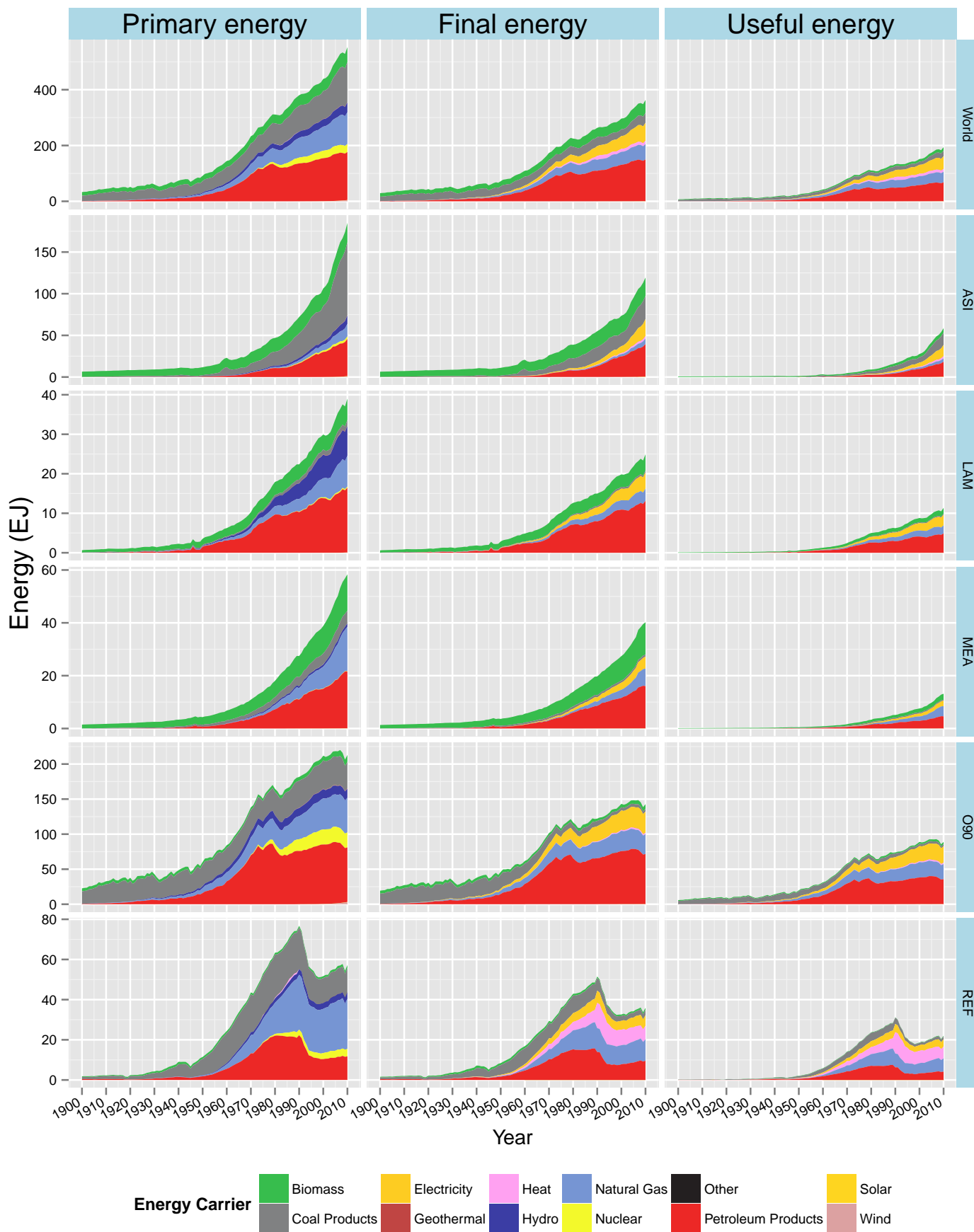


Figure 12: Primary energy, final energy and useful energy by energy carrier for the World and for 5 world regions, 1900-2010. The scale of the vertical axis varies across the regions.

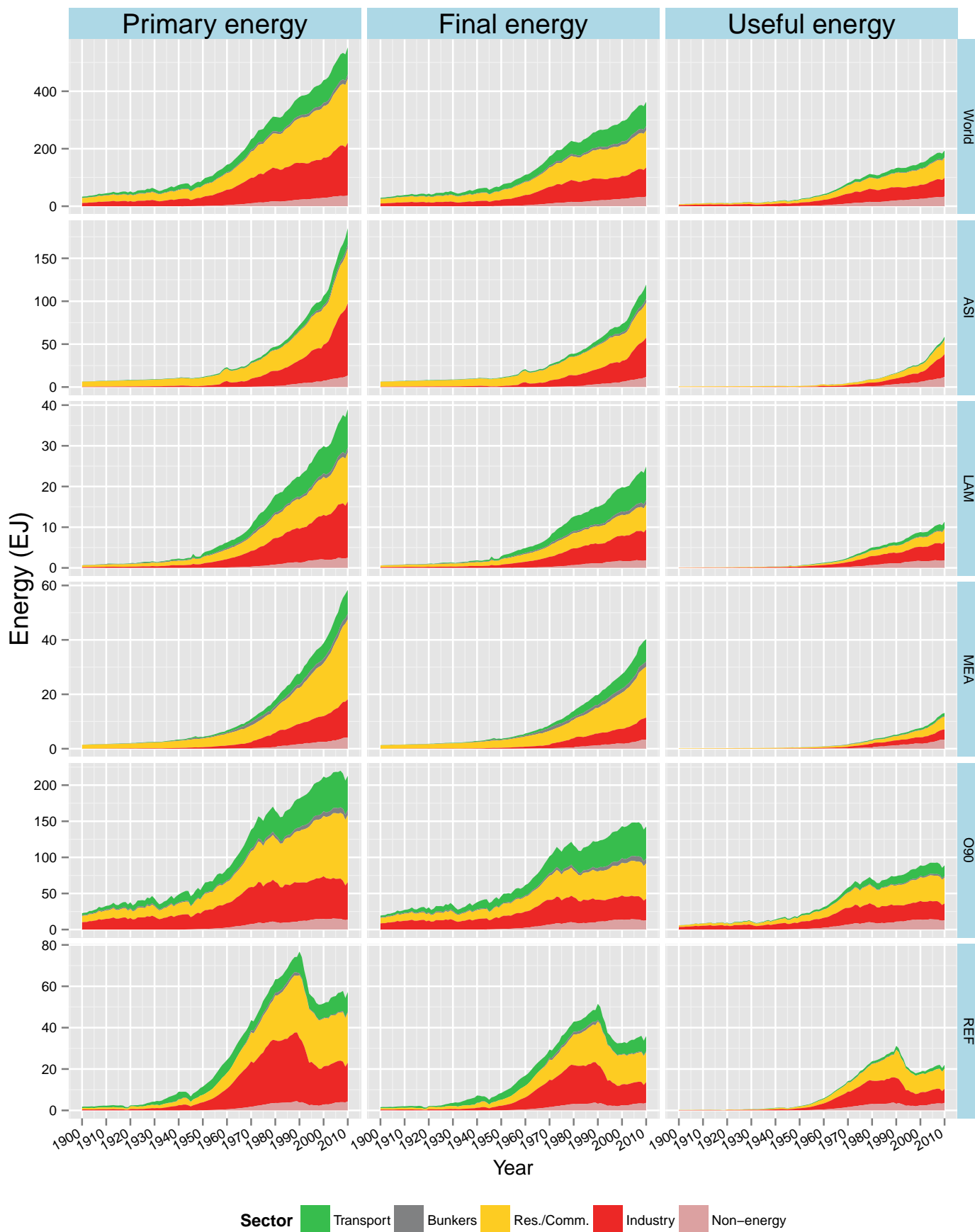


Figure 13: Primary energy, final energy and useful energy by sector for the World and for 5 world regions, 1900-2010. The scale of the vertical axis varies across the regions.

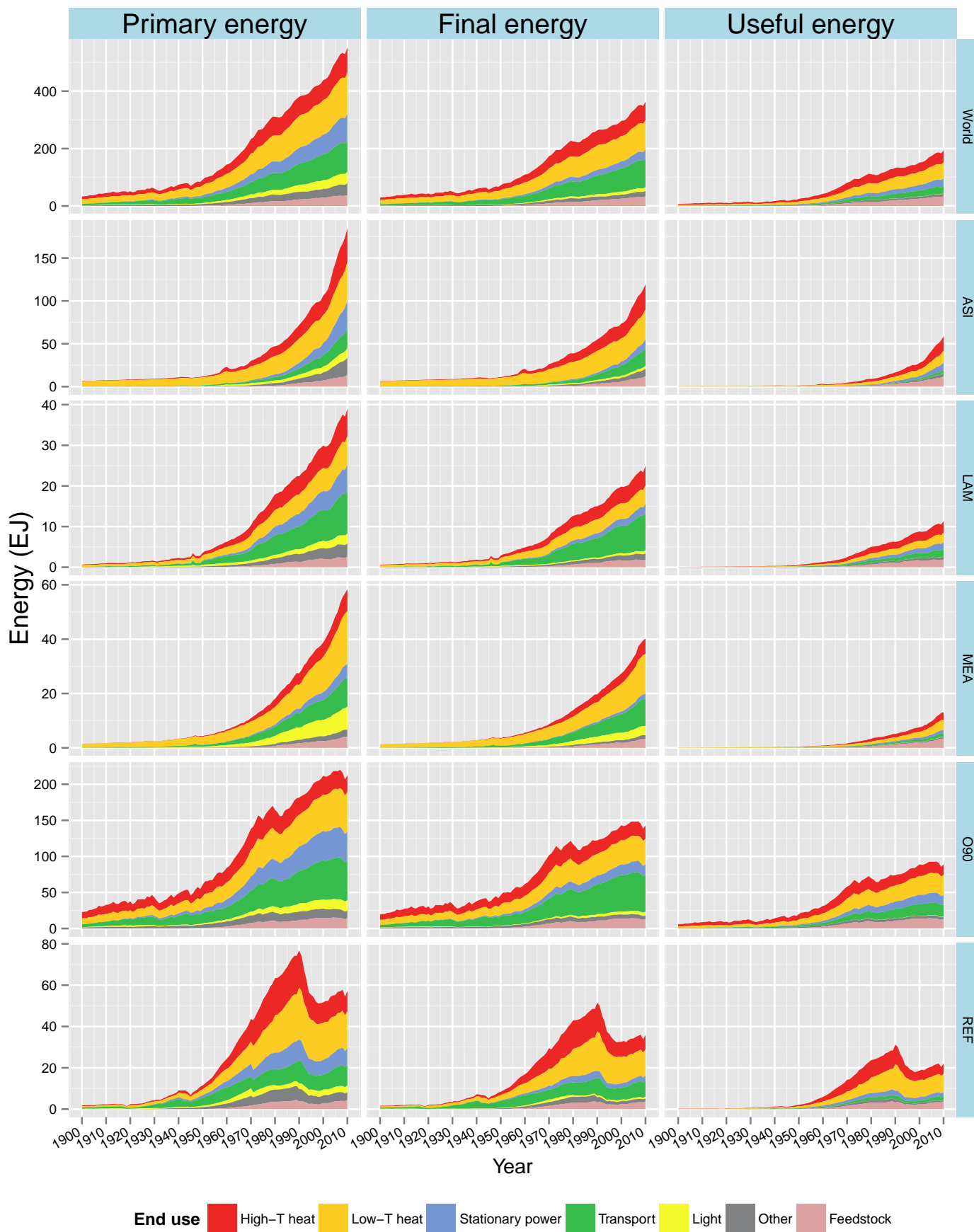


Figure 14: Primary energy, final energy and useful energy by end-use for the World and for 5 world regions, 1900-2010. The scale of the vertical axis varies across the regions.

4 Analyses

The constructed primary, final and useful energy balances are a base for global and regional analyses that were previously not available. Here, the system dynamics are studied in a variety of ways, comparing the input (primary / final energy) perspective to the output (useful energy) perspective.

4.1 Carbon Intensity

Carbon intensity is calculated from the data set using the standard carbon emission factors in table 6.^{40,41} Figure 15 shows several measures of carbon intensity for India, the United States and the world, by selected end-uses. The carbon intensity of primary energy, indicated by PPI, changes the least over time. The rate of decrease for the world of the carbon intensity of primary energy (for all uses) is about 0.33% per year over the period 1900-2010. This decarbonization of the energy system from an input perspective is due to the sequential substitution over time of less carbon-intensive energy carriers for more carbon-intensive ones: from fuel wood to coal to petroleum products to natural gas to an increasing amount of renewable energy supply, with nuclear energy's share in primary energy also increasing during the second half of the twentieth century. It is consistent with the 0.3% found by Grübler and Nakićenović (1996) for the period from 1850 to 1994.

The carbon intensity of the transformation sector⁴² has not changed drastically over time due to balancing effects, with an average annual decrease by about 0.1% from 1900 to 2010. On one hand, an increasing share of electricity and refined fuels in final energy: each unit of energy at the final energy level has at least as many units of energy (with associated carbon) upstream in the energy chain, which tends to increase the carbon intensity. On the other hand, the inputs to the transformation sector have been decarbonizing as discussed in the previous paragraph, tending to decrease the carbon intensity of the sector. For related reasons, the carbon intensity of final energy (expressed with final energy level carbon) has generally decreased over time, at an average rate of 0.44%/year: no carbon is associated with electricity or direct heat, and there is a transition to less carbon-intensive fuels.

The most dynamic intensity measure is the final energy level carbon intensity of useful energy (line indicated with FUI), which compounds three effects: the decarbonization of primary and final energy, the shift of carbon emissions to the transformation sector, and the increased energy conversion efficiency of the end-use. The rate of decrease for all uses combined over the entire period considered is 1.2% per year, globally. This faster dynamic is most pronounced for light, for which in all three regions considered the carbon intensity falls by orders of magnitude, with an average annual decrease of 3.7% for the world.⁴³ Note in particular the much higher numerical values of the carbon inten-

⁴⁰The carbon emissions do not necessarily correspond exactly to the ones reported by Boden et al.. This is partly explained by the use of different factors, but also by inventory uncertainty (discussed by Macknick (2011)).

⁴¹For some of the biomass the emission factor of petroleum products was used, with the approach from section 3.3.1, to more properly account for biofuels as e.g. used in transport.

⁴²Indicated by PFPFI in figure 15, equal to [primary energy level carbon **minus** final energy level carbon]/[Primary energy **minus** final energy].

⁴³The example of light was ideal to prove Nordhaus's (1996) point.

sity per unit of useful energy output (FUI) as a result of the significant conversion losses upstream in the energy chain.

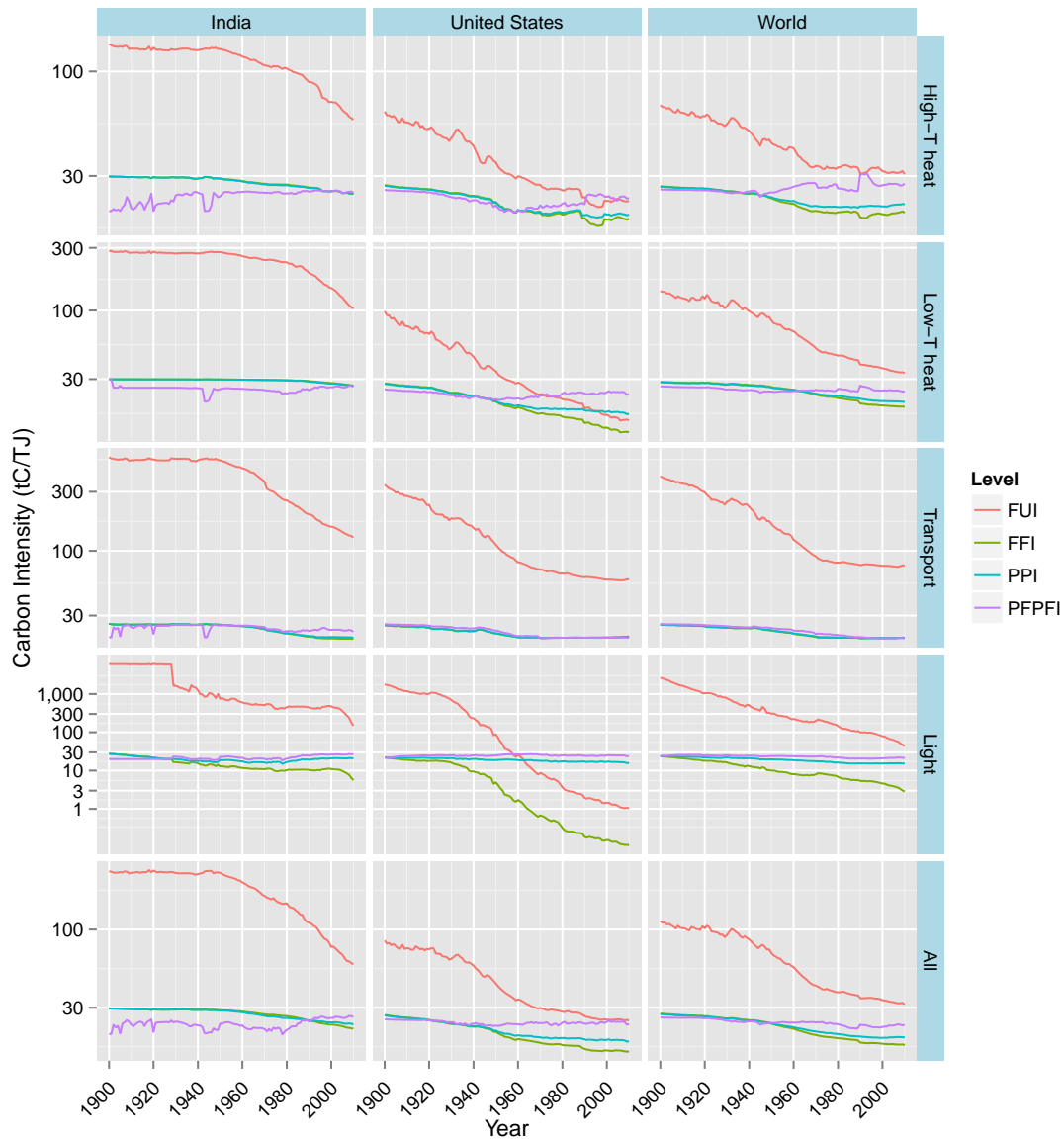


Figure 15: Carbon intensities (logarithmic scale) for India, the United States and the world, 1900-2010, by end-use. FUI is final energy level carbon per unit of useful energy, FFI is final energy level carbon per unit of final energy, PPI is primary carbon per unit of primary energy, and PFPFI is the intensity of the transformation sector, defined as the difference between primary energy level carbon and final energy level carbon, divided by the difference between primary energy and final energy.

4.2 Energy intensity of the economy

The database also allows to compare energy intensities of the different economies on the useful energy level in addition to final and primary energy. Figure 16 compares the

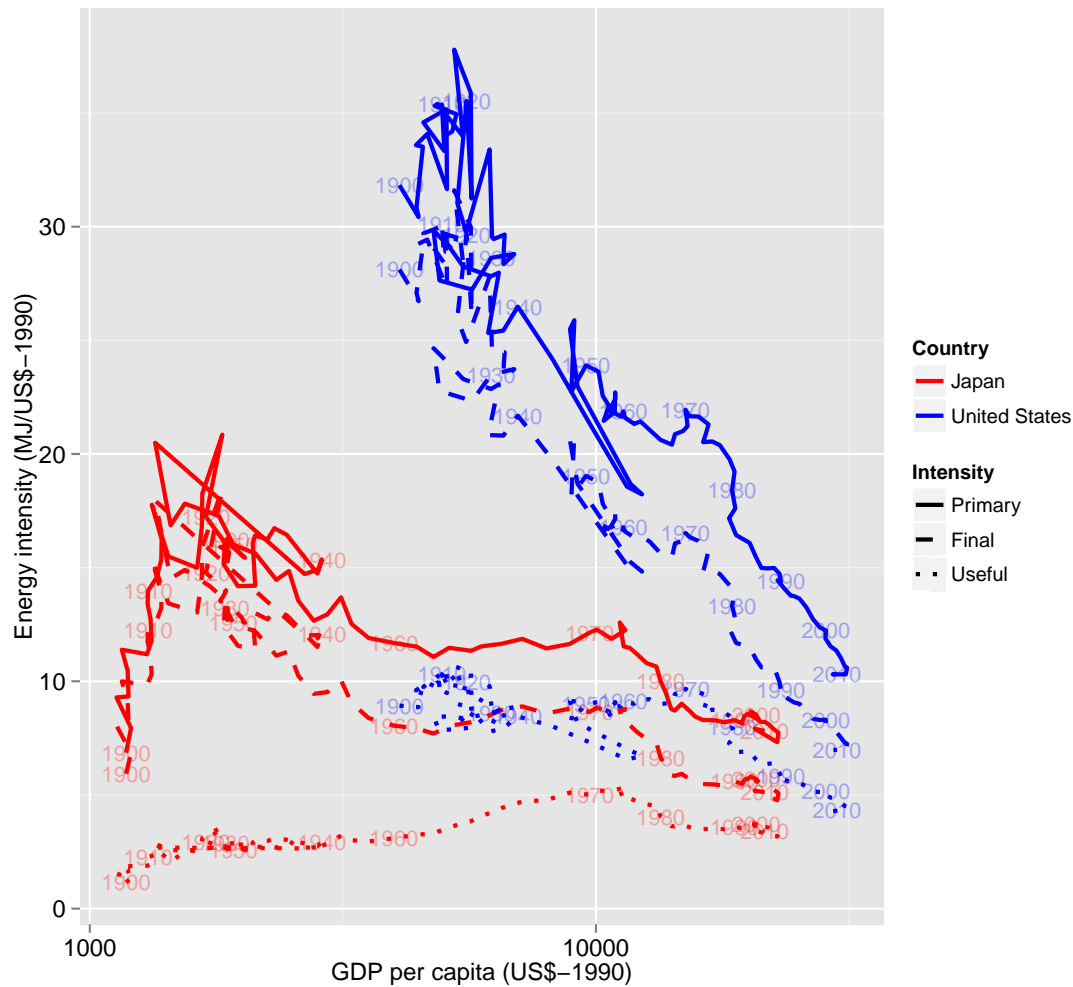


Figure 16: Energy intensity (MJ per unit of GDP) in function of GDP per capita (logarithmic scale) for Japan and the United States, 1900-2010. Years are indicated in the background. GDP (per capita) is expressed in US\$-1990 at PPP.

evolution of energy intensities over time, in function of per capita GDP between Japan and the United States. The Japanese energy system has been more efficient in economic terms over the entire time period considered, and this also illustrates a certain path dependence: although the United States have decreased their primary and final energy intensities more sharply, the intensities remain higher than their Japanese equivalents. For both countries, the useful energy intensity profile is flatter than the upstream intensities. This illustrates two important points. The first is that the evolution to more efficient end-use converters as well as to more efficiently converted energy carriers brought down the energy inputs (primary energy) required to fuel the economy. Second, the output of the energy system (useful energy) correlates better with economic output than input measures. This corroborates the notion that on one hand the system is driven by demands for energy outputs and not inputs, and on the other hand useful energy is a more directly related measure of economic activity.

5 Exergy

In this section, an exergy⁴⁴ layer is added to the dataset to illustrate the dynamics of energy systems in terms of exergy instead of energy.

5.1 A note on energy and exergy

The benefits of using exergy as a base quantity (instead of energy) to analyze energy systems have been proven in an extensive literature that is still very much alive, as exergy identifies a theoretical potential for improvement of energy conversion and energy utilization.⁴⁵ Useful exergy rather than useful energy has even been suggested as a third economic production factor, beside capital and labor, substituting largely for the 'total factor productivity' multiplier in a Cobb-Douglas production function (Ayres and Warr, 2010)⁴⁶. However, exergy analyses require an additional layer of data on top of an energy balance, i.e. an expression for describing the quality of energy forms, which necessarily requires additional assumptions. In this study, the interest was not so much in the potential for energy provision (where exergy is a useful concept), which is an input perspective, but as explained above, in the actual energy/exergy flows at the end use.

Analyzing energy and not exergy also ensures that the balances that are created in this Interim Report are directly comparable with published energy balances such as those by the International Energy Agency (2012b). Nonetheless, the importance of exergy as a concept is acknowledged by the author.

5.2 Methodology

The exergy to energy ratios used to estimate the exergy content of the energy flows are based on the estimate for the world in 1990 by Nakićenović et al. (1996). That contains fewer than the 12 energy carriers used in this study, and the missing values were taken equal to those of comparable energy carriers or energy carriers with comparable uses. The factors for nuclear, solar and geothermal are set equal to those of heat. Hydropower and wind were treated as electricity. Finally, "other" was assumed to correspond to petroleum products. The quality factors of the useful energy, by end-use⁴⁷ are the weighted average over all applications under the relevant uses as published by Nakićenović et al. (1996) for the world in 1990. All the factors are tabulated in table 7. The factor for primary and final energy is also known as the quality index (Wall, 1986).

The quality factors are applied as constant over time, in contrast to the final-to-useful energy conversion efficiencies which vary with time through economic growth. This is consistent: after all, technology has no impact on the actual quality of the useful energy demanded, which depends largely on the end-use. As an example, the quality of me-

⁴⁴Synonym to availability. Exergy is measured in energy units but incorporates the relative quality of the energy form by expressing the maximum work it can be used to produce, given the environment. For a comprehensive treatment, see e.g. Wall (1986), the title of which inspired the title of this Interim Report.

⁴⁵Exergy is used as a quantity beyond the energy systems discussed in this study, too, as it can apply to global environmental flows and stocks as well as to material flows and stocks. One such global quantification was done by Hermann (2006) and a database is published online by the Global Climate and Energy Project (2013).

⁴⁶Ayres and Warr (2010) use the term useful work for useful exergy.

⁴⁷Determined as detailed in section 3.3.3.

chanical energy is the same now as a century ago, as is the quality of the useful part of light and of cooking. This is because of the definition of *useful* energy: that energy which fulfills its purpose of movement, of a certain amount of lumen-hours, or of a temperature of 100°C or slightly above to boil potatoes; in other words, useful energy is the energy *at the quality at which we want it*.

Energy Carrier	Primary/final exergy factor	Useful exergy factor						
		Light	HiT heat	LoT heat	Stat. power	Trnsprt	Fdstck	Other
Coal Products	1.06	0.90	0.33	0.10	1.00	0.99	1.06	0.23
Biomass	1.19	0.90	0.26	0.14	1.00	0.99	1.19	0.23
Petroleum Products	1.04	0.90	0.43	0.23	1.00	0.99	1.04	0.23
Natural Gas	1.03	0.90	0.33	0.10	1.00	0.99	1.03	0.23
Nuclear	1.00	0.90	0.26	0.07	1.00	0.99	0.27	0.23
Hydro	1.00	0.90	0.52	0.15	1.00	0.99	1.00	0.23
Electricity	1.00	0.90	0.52	0.15	1.00	0.99	1.00	0.23
Heat	0.27	0.90	0.26	0.07	1.00	0.99	0.27	0.23
Other	1.04	0.90	0.52	0.15	1.00	0.99	1.04	0.23
Solar	1.00	0.90	0.26	0.07	1.00	0.99	0.27	0.23
Wind	1.00	0.90	0.52	0.15	1.00	0.99	1.00	0.23
Geothermal	1.00	0.90	0.26	0.07	1.00	0.99	0.27	0.23

Table 7: Exergy factors (exergy-to-energy ratio) based on Nakićenović et al. (1996).

By applying these factors to the primary, final and useful energy series, a new layer, that of exergy, is created.⁴⁸ This exergy balance for the world in 1990 differs somewhat from the balance reported by Nakićenović et al. (1996), due to different underlying statistical data sources and also partly due to the fact that the former was constructed "bottom-up" by adding together the balances of the 15 countries and 5 other regions that compose the world, each with a different level of final-to-useful energy conversion efficiency. However, the differences are relatively small, as can be seen from figure 17.⁴⁹ In primary exergy, the main observable difference apart from hydropower (Nakićenović et al. (1996) uses a direct equivalent of the electricity produced from this energy form) is in the amount of renewable fuel/biomass, with Nakićenović et al. (1996) on the higher side. This can also be found in final exergy, in addition to heat in final exergy being greater than that reported by Nakićenović et al. (1996). The latter is most likely due to a change in the treatment in the IEA balances of heat from cogeneration plants in the former Soviet Union and Eastern Europe. When looking at useful exergy, however, the differences between the two datasets are starker, with this study's about a quarter higher than Nakićenović et al.'s (1996) data. This is a direct consequence of the estimation procedure of the final-to-useful energy conversion efficiencies, with the datapoints stemming from the Nakićenović et al. (1996) data set being generally below the curve (see figure 1), most strongly for the energy carrier category encompassing oil and natural gas.

Cullen and Allwood (2010) performed an analysis of energy use and exergy flows in the world for the year 2005, based on detailed estimates of the characteristics of the converters in the entire energy system. Their value for total useful exergy in 2005 is 55EJ, which is about 20% below this study's estimate (without non-energy uses). Figure 18 shows a comparison of the useful exergy composition by end-use, between this present study and Cullen and Allwood's (2010). The estimates for heating, lighting and other appli-

⁴⁸These data are also available in the online database (section 3.4)

⁴⁹There were also differences on the final energy level - on which useful energy is based - because of differences in allocation into fuel categories, and because the IEA energy balances have undergone several revisions since the publication of the paper (Nakićenović et al., 1996).

cations correspond well, and the proportions of the three main uses (heat, motion and light) follow the same order. Motive useful exergy is larger in this present study, however, because of higher estimates of the final-to-useful energy conversion efficiencies for these applications.

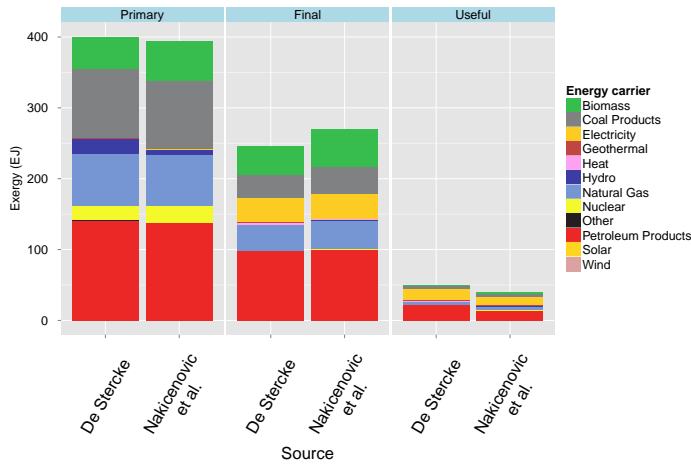


Figure 17: Comparison between the Nakićenović et al. (1996) exergy balance for the world in 1990, and the corresponding balance from this study. Negative values in primary energy due to electricity/heat imports excluded. Non-energy uses are excluded on the final and useful level.

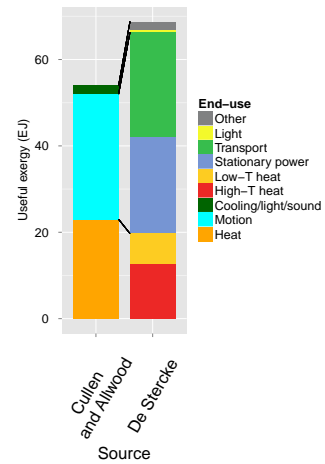


Figure 18: Comparison with the Cullen and Allwood (2010) useful exergy breakup by use for the world in 2005. Non-energy uses are excluded.

Figure 19 shows the energy and exergy balance for the world by end-use. Primary and final exergy are generally greater than primary and final energy, except for electricity (equal) and heat (smaller) (cf. table 7).⁵⁰ However, useful exergy is much smaller than useful energy for most applications (table 7) and hence also in the world aggregate (more than double in 2005 with 144 EJ of useful energy versus 69 EJ of useful exergy)⁵¹. This indicates that the energy flows obtained through conversion of energy carriers in end-use devices are of low quality relative to the quality of the energy carriers on the primary or final energy level. Essentially, exergy or availability, being high-quality energy, is to a large part wasted on demands for low-quality energy such as space and water heating to temperatures only slightly (in absolute terms) above the temperature of the environment, or only slightly below for household refrigeration purposes. Figure 19 thus demonstrates that the energy service needs could be satisfied, from a thermodynamic standpoint, with a much smaller system input. Because exergy takes quality into account, this is even more striking when looking at an exergy balance than at an energy balance. This is the point made by Cullen and Allwood (2010) and also illustrated by the results obtained in this study.

⁵⁰For electricity and heat, these are factors for thermomechanical availability. Electricity's is 1 because it is fully available, whereas heat is not fully available because of the finite temperature it is assumed at. For the fuels, the factor refers to chemical availability. It is higher than the heating value, as the latter measures the heat produced in the combustion process and the chemical availability also includes the availability that was destroyed due to irreversibilities in the combustion process. Moran and Shapiro (1998) elaborate on the distinction in a very clear way.

⁵¹Excluding non-energy uses such as feedstocks.

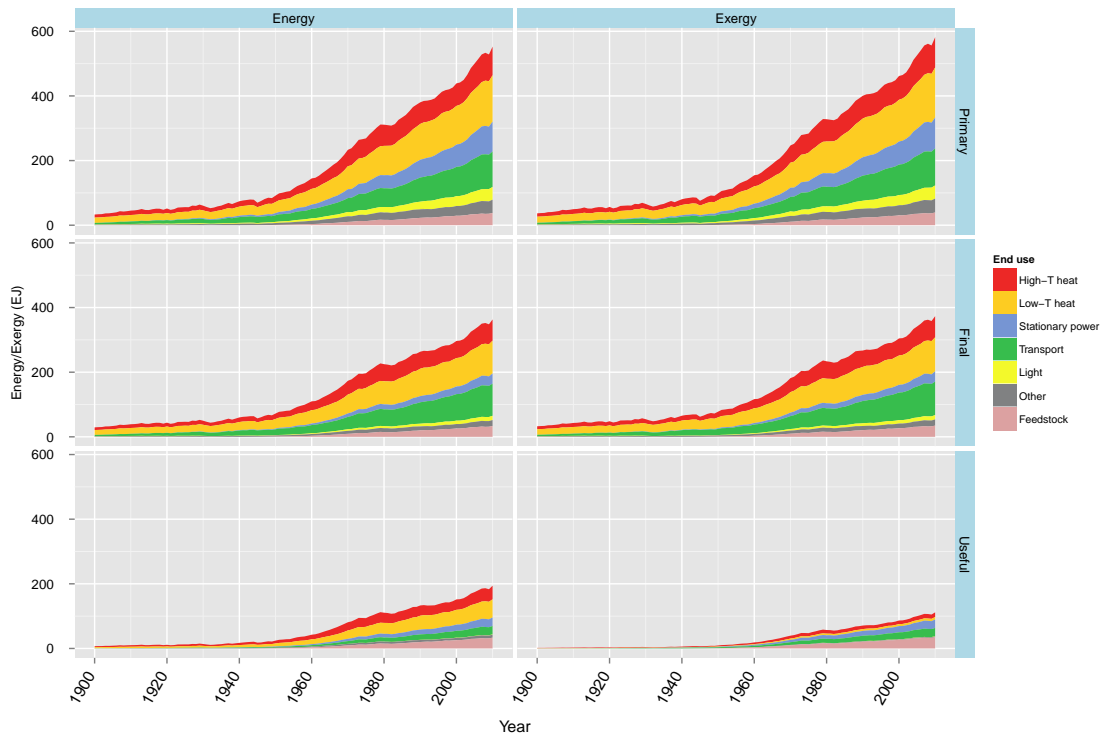


Figure 19: Primary, final and useful energy and exergy, by end use, for the world, 1900-2010.

6 Conclusion

This paper presents the data sources and methods for constructing historical energy end-use balances from an output (useful energy) perspective. For the period spanning the years 1900 to 2010, final energy use was estimated for the 15 countries which historically have dominated (80%) global final energy use, as well as for 5 residual regions that together with the 15 countries comprise the globe. Final-to-useful energy conversion efficiencies were derived as a function of sector, energy carrier type, and type of end-use; and a model of the evolution of final-to-useful energy conversion efficiencies as a function of degree of economic development was developed. As a result a unique and comprehensive historical energy data set with a focus on an energy output perspective was thus created, following energy from supply to service.

This study also presents some preliminary analyses based on the novel data set. A first important result is the illustration that the dynamics of change in energy systems depend very much on the perspective chosen for the analysis: an output or useful energy perspective shows trends and patterns very much distinct from the traditional input-oriented (primary energy) perspective that has traditionally dominated historical energy analyses. This is shown for instance by the measure of carbon intensity of energy use: across all sectors and places, the decrease has been faster in terms of output (useful energy) than in terms of input (primary energy). An output perspective on energy systems also changes our sectoral perspective: transport is a big share of input resources, but due to low end-use conversion efficiency, its share in terms of output is much smaller.

Second, useful energy is better correlated with economic development than supply side input measures of energy are. This is shown for instance by historical energy intensity trends, and corroborates the idea at the base of this study, i.e. that the energy system is driven by the demand for output and services. From these first two conclusions it follows that input perspectives and measures obscure the dynamics of the system, and that output measures are a most valuable complementary measure when looking at systems transformations and their rates of change.

Third, an exergy analysis based on the estimated end-uses of the energy flows reveals, as many studies have shown before, the importance of end-use converters in delivering energy services and the generally low overall efficiency of energy service provision. A lot of availability is destroyed in the process of providing energy services, and in light of the external constraints placed on energy supply (economics, resource limitations and environmental externalities, including climate change), policies should be aimed at better matching the *quality* of supply to the quality of demand. Heat pumps for low temperature applications and electric motors instead of internal combustion motors are examples of converters that can reduce upstream energy consumption considerably while maintaining quantity and quality of energy services provided.

Evidently, there is significant room for future research and improvements in the methods and results of constructing the historical energy balances presented here. The aggregate and simplified approach used here for the historical reconstruction of final energy balances for determination of final-to-useful energy conversion efficiencies - inevitable due to the lack of direct data availability and the enormous scope both in space and time - can be further refined and corresponding uncertainty estimates provided. The data set also invites further in-depth analysis of the dynamics of change of energy systems and of the different drivers of historical energy transitions using both input and output perspectives and a comparative context. Lastly, the new historical trends revealed by an output perspective should also be used to judge the feasibility of future transition pathways and inform energy scenarios, particularly within a climate change mitigation context.

7 References

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A Appendix

A.1 Country/region notes

For each country or region, the specific approach taken to reconstruct the historical final energy balance is a variation on the general approach explained in section 3.2.2. This is necessary because of differences in data availability and quality. The notes below give detailed information on the reconstruction of the final energy series. They also explain salient features in the data.

A.1.1 Australia

Coal is historically the dominant fuel in the Australian energy system. In 1960, more than 90% of electricity was generated from coal products. Therefore, all non-hydro electricity generation before 1960 is assigned to coal products. Coal in transport is determined completely by the rail transport equation through 1940. After 1940, the multiplier decreases linearly to about 0.56 in 1960, meaning that coal usage in transport is then 56% of what would be predicted from the equation. Because Mitchell (1995) only reports freight tonnage-distance numbers for Australia, the numbers for passenger volume-distance are scaled back from the 1971 number reported by the Australian Government Department of Infrastructure and Transport (2011) using the GDP-PPP series from Maddison (2010). The ton-km value for the year 1900 was taken to be the same as in 1901.

The heating values for coal are 26 GJ/ton for hard coal output and for output of unspecified coal, 8.97 GJ/ton for brown coal output and 18.49 GJ/ton for coal exports.

Linear interpolations: 1932 for imports of crude oil; 1932 for hydropower; 1938-1947 for fraction of hydropower in total electricity generated.

A.1.2 Brazil

The data for both passenger and freight services in rail transport go back to 1916. Before that, the 1916 values are scaled with GDP-PPP from Maddison (2010). The multiplier for the coal-in-transport expression is 1 through the year 1940. Biomass comes into transport for a lack of coal in the data in the periods 1900; 1917-1918; 1931; 1934-1964. This is consistent with the fact that the Brazilian energy system relies heavily on biomass, also in industry and the residential and commercial sectors, and has abundant supplies of it. Coal imports in 1900 are set at 360TJ as there are no data on production nor imports for that year but the model needs this amount of coal for electricity generation. The heating values are 15.78 GJ/ton for coal production, and 30.17 GJ/ton for coal imports.

There is a sharp drop in natural gas production in energy terms between 1965 and 1966 because the reporting changes to PJ instead of million cubic metres.

Before 1971, electricity is generated mainly from petroleum and coal. The share of petroleum is forced linearly to zero in 1925.

Linear interpolations: 1931 for coal output and coal imports, 1901-1909 and 1911-1927 for share of hydropower in electricity generation.

A.1.3 Canada

Railway transport numbers are scaled back proportionally to GDP-PPP: from 1910 for passengers, from 1907 for freight. The multiplier α in equation 2 is 1 through the year 1940.

The heating value for coal is uniformly 24.03 GJ/ton, following a comparison for hard coal production between the International Energy Agency (2012b) and Mitchell (1993). There are no electricity generation data before 1918 so electricity is set to zero through 1917. In the calibration year 1960, coal products, petroleum products and natural gas each have a significant share in thermal electricity generation. The shares of petroleum products and natural gas are forced linearly to zero in 1925.

A.1.4 China

China includes Hong Kong. Rail service data were scaled with GDP-PPP back from 1920 value for passengers and from 1912 value for freight. Other missing data were replaced by linearly interpolated values. The multiplier α in equation 2 is 1 through the year 1940. The data show no significant coal trade before 1971. The heating value for the output of coal is 20.57 GJ/ton. The production of coal in 1902, 50,000 tons, is taken from (Etemad and Luciani, 1991). The spike in coal output between 1957 and 1962 coincides with the Great Leap Forward and is consistent with historical events. Joseph (1986) mentions that a surge in steel demand at the end of the 1950s pushed up the demand for coal. The reconstruction algorithm in this study allocates the increased coal output among the three sectors, whereas in reality residential consumption of coal was likely lower during that period because of the associated spell of extreme poverty and famine.

Total electricity production comes from Mitchell (1995) and the gaps are filled up with data from Etemad and Luciani (1991). Only coal products and petroleum products are used for thermal electricity generation. The share of petroleum is forced linearly to zero in the year 1940. Linear interpolations: 1930 for ton-km; 1945-1948 for passenger-km and ton-km; 1950-1951 for crude oil output; 1934-1949 for share of hydropower in electricity generation.

A.1.5 Former Soviet Union

The Former Soviet Union covers the Soviet Union and the states it broke up into after the Soviet era, and the Russian Empire before the Soviet Era.

The coal in transport multiplier α in equation 2 is 1 through the year 1940. The heating value employed for hard coal production is 21.39 GJ/ton and 14.68 GJ/ton for brown coal output. Where this distinction in production is missing (before 1913), the heating value 21.13 GJ/ton is employed, which is the average of the hard coal and brown coal heating values weighted with their respective shares (in tons) in 1913. Coal imports and coal exports have heating values of 23.57 GJ/ton and 25.29 GJ/ton respectively. Time series for peat and shale from Lewytzkyj (1979) are included in coal. They are reported in energy units (tons of coal equivalent) but a factor of 0.786 is applied for the series to correspond to the value for peat in the year 1971 in the IEA statistics. As peat can contain a lot of moisture, and the IEA statistics report lower heating values or net calorific values, this factor is plausible as the ratio of lower to higher heating value for the peat. The peat and shale series reach back to the year 1913 but are only reported for selected years. The

values for other years between 1913 and 1971 are linear interpolations.

Biomass supply is taken from Lewytzkyj (1979) (fuelwood values) with no heating value correction because the value in 1971 is smaller than the corresponding value in the IEA statistics. Again, values for non-reported years are linear interpolations. Before 1913, the per capita fuelwood consumption is fixed at the 1913 value and multiplied by the population numbers from Maddison (2010).

The values for traded petroleum products from Mitchell (1995) from 1965 onwards were divided by 1000 because of an apparent error in the reported unit.

The shares of petroleum products and natural gas in thermal electricity generation are forced linearly to zero in the year 1950 because of a small apparent consumption of petroleum products and natural gas in the Soviet energy system before 1951. Heat in final energy is reported by the IEA, but no historical data could be found. Therefore, before 1971, in each sector heat has been calculated by multiplying the value for electricity consumption by a heat/electricity ratio varying linearly over time from 0 in the first year in which electricity is reported to the value for the sector in question in the year 1971 (earliest IEA statistic).

Other linear interpolations: 1941-1944 for rail passenger-km; 1911-1912 and 1914-1920 for the ratio of passenger-km to passengers in railway transport; 1911-1912 for ton-km; 1919, 1928 and 1936-1938 for coal imports (zero in 1939); 1941-1944 for output of hard coal, brown coal and crude oil; 1941-1945 for coal imports and exports (exports are zero in 1940), crude oil imports and refined petroleum product exports; 1940-1948 for crude oil exports; 1914-1921 for natural gas production; 1906-1912, 1914-1915, 1917-1918 and 1941-1944 for total electricity supply; 1914-1920 and 1941-1944 for hydropower.

A.1.6 France

The country of France as considered in this study covers the varying area that appertains to the French nation. The region of Alsace-Lorraine, belonging to Germany until the end of the First World War, is therefore excluded up to that point (as well as during German occupation in the Second World War). As the boundaries are only relevant with respect to the rail service, primary energy flows and electricity data, the reader is referred to the original sources for details (Mitchell, 1992; Etemad and Luciani, 1991). The great impact of the two World Wars are clearly visible in the data and the deduced energy balance.

Rail transport service data are complete for France. The coal in transport multiplier α in equation 2 is 1 through the year 1940 and coal is sufficient to cover rail transport as well as electricity generation for the time period considered.

The heating value applied to all coal data before 1960 is 26.29 GJ/ton. Biomass supply is taken from Gales' original series in Kander et al. (2013) up to 1960, followed by a linear increase to the value reported by the IEA in 1970.

Thermal electricity generation before 1960 is taken to be all coal except for some production from natural gas which increases linearly from zero in the year 1955 to its share in 1960 as reported by the IEA. The entrance of natural gas in electricity generation is so late because of the development in the late 1950s of the natural gas field of Lacq.

A.1.7 Germany

In this study, Germany is the country that has undergone most severe changes because of its central role in both World Wars and the periods surrounding them. The boundaries

of what this study considers Germany have changed considerably over the course of the 20th century, starting from the German Empire encompassing a large part of what is now Poland. As in the case of France, the definition of the boundaries is largely data driven. In this study, Germany encompasses both West and East Germany in which it was split between the Second World War and the end of the Cold War. Because data are reported for East and West Germany separately during that period, and because East Germany is excluded from the IEA statistics before the year 1970, both parts were treated separately up to then. However, the standard procedure as performed for the other countries was applied to West Germany as a continuation of the pre-WWII German state, and as a precursor to the 1970 German whole as reported by the IEA. East Germany was treated as a separate country between WWII and 1970, and the resulting energy balance was then added to the (West) German one. (West) German data from 1960 through 1969 come from the IEA statistics.

A heating value of 29.08 GJ/ton is applied to output of hard coal, and of 8.21 GJ/ton to output of brown coal. Values for Saarland (reported separately by Mitchell (1992)) are added to the output, with a heating value of 29.08 GJ/ton. Coal imports are converted using 24.28 GJ/ton and coal exports with 25.92 GJ/ton. The supply of biomass for the whole of Germany comes from Gales' and Warde's original series in Kander et al. (2013) through the year 1960. Since in 1960 the IEA reported no biomass, a choice for the allocation to the sectors had to be made. 90% was assigned to the residential and commercial sector, 10% to the industry sector. Between 1960 and 1970 (the earliest year with a nonzero value for biomass in final energy in the IEA statistics) a linear interpolation replaces the IEA data. Coal is used for all thermal electricity generation up to 1960. Electricity generated from 1960 up to 1970 was assigned to energy carriers using the total breakup of electricity of East and West Germany combined: for West Germany, the data come from the IEA statistics, for East Germany the data come from Nitzsche, G. and Institut für Energetik Leipzig (1990).

Differences between (West) Germany and East Germany:

(1) *(West) Germany*. The multiplier α in equation 2 is 1 through the year 1940. The value is fixed in 1960 at 0.467 which follows from comparison with the IEA statistics.

(2) *East Germany*. The multiplier α in equation 2 is 1 through the year 1940. The value is fixed in 1960 at 0.59 which follows from comparison with the data set for East Germany (Nitzsche, G. and Institut für Energetik Leipzig, 1990). Values for fuels going into thermal electricity generation are taken from Nitzsche, G. and Institut für Energetik Leipzig (1990), grouping the 'other' category with the liquid fuels category into petroleum products and grouping gaseous fuels with solid fuels into coal products.⁵² The complete final energy balance for East Germany from 1960 through 1969 is taken from Nitzsche, G. and Institut für Energetik Leipzig (1990). Between the Second World War and 1960, final energy for East Germany was estimated using the general procedure, with relevant ratios (primary to final, sectoral) fixed at the values implied from the 1960 Nitzsche, G. and Institut für Energetik Leipzig (1990) data.

Heat in final energy is reported by the IEA, but no historical data could be found. Therefore, before 1960, in each sector heat has been calculated by multiplying the value for electricity consumption by the heat/electricity ratio for the sector in question in the year 1960.

The absence of data for petroleum products during the Second World War is consistent with the production of Ersatz fuels or synfuels through Fischer-Tropsch based gas-to-liquids transformations in Germany's strategy of self-reliance for energy resources for its

⁵²Assuming that gas is synthesized from coal in that period in East Germany

war machine. To capture this conversion in the energy balances requires a much more detailed energetic analysis of the Second World War and is beyond the scope of this study. Other linear interpolations: 1914-1921 and 1940-1945 for railway transport services; 1923 and 1946-1948 for passenger-km in railway transport; 1927 for Saarland coal output; 1942 and 1944-1945 for hydropower; 1947 for total electricity supplied in East Germany; 1947-1949 for hydropower in East Germany; 1961-1964 for final energy, fuels for thermal electricity generation, and thermal electricity generation from combustible fuels in East Germany.

A.1.8 India

Over the course of the 20th century the territory that this study considers India has decreased in area. From around 1937 on, Burma (presently Myanmar) is not included anymore, and from around 1947 on Pakistan is excluded. The effects in terms of total energy consumption are minimal, and in terms of shares almost imperceptible.

Passenger-km values are scaled with GDP-PPP back from 1904. The coal in transport multiplier α in equation 2 is 1 through the year 1940. In 1900, 1901 and 1944 coal is not sufficient for electricity generation and transport combined and a small amount of biomass is present in transport in those years as a result.

Coal produced in India is of low grade: the heating values are 19.91 GJ/ton and 9.7 GJ/ton for output of hard coal and brown coal, respectively. Values for coal imports and coal exports are zero.

The share of petroleum in thermal electricity generation is forced linearly to zero in the year 1925. Before 1925, electricity generation is set to zero for lack of data. The share in 1925 of final energy is negligible.

Linear interpolations: 1937-1939 for passenger-km in rail transport; 1940 for imports of petroleum products; 1950-1970 for biomass supply; 1930-1932, 1934-1936 and 1938 for total electricity supplied and for hydropower; 1938-1945 for hydropower.

A.1.9 Italy

Italy was also deeply involved in the two World Wars and therefore the data shows uncertainty and discontinuity in energy use around those periods. Where data was lacking, the value was set to zero if not linearly interpolated from adjacent values.⁵³

The coal in transport multiplier α in equation 2 is 1 through the year 1940. The heating value applied to all coal flows is 19.76 TJ/ton.

For the years in which the value for hydropower reported by Etemad and Luciani (1991) exceeds the total electricity supplied as reported by Mitchell (1992), the values from Etemad and Luciani (1991) are used. Because the share of hydropower in the early decades of the 20th century is considerable, thermal electricity generation was set to zero for some years in which numbers for total electricity supplied are missing. The shares of petroleum products, natural gas and geothermal heat in thermal electricity generation are forced linearly to zero in 1945.

The supply of biomass for the whole of Italy comes from Malanima (2006) in Kander

⁵³Linear interpolation in historical data is based on the assumption of continuity, which can be made in the case of production but less so in the case of trade of energy resources as war disrupts external trade flows. Therefore, values for e.g. coal in Italy are small during the Second World War because production is reported but trade is not. The latter was set to zero.

et al. (2013) through the year 1960. Since in 1960 the IEA reported no biomass, a choice for the allocation to the sectors had to be made. 90% was assigned to the residential and commercial sector, 10% to the industry sector. Between 1960 and 1974 (the earliest year with a nonzero value for biomass in final energy in the IEA statistics) a linear interpolation replaces the IEA data.

Other linear interpolations: 1904 for rail transport service; 1943-1944 for ton-km in rail transport.

A.1.10 Japan

The coal in transport multiplier α in equation 2 is 1 through the year 1940. Heating values for coal are: 33 GJ/ton for hard coal output, 16.18 GJ/ton for brown coal output and 30.75 GJ/ton for coal imports.

Crude oil imports were converted from million US gallons to 1000 tons by dividing by 0.3.

The supply of biomass is taken from Putnam (1953) (wood) for the period 1915-1947. Before, the implied per capita supply was kept constant using population data from Maddison (2010). Since in 1960 the IEA reported no biomass, a choice for the allocation to the sectors had to be made. 90% was assigned to the residential and commercial sector, 10% to the industry sector. Between 1947 and 1982 (the earliest year with a nonzero value for biomass in final energy in the IEA statistics) a linear interpolation replaces the IEA data.

The share of petroleum products in thermal electricity generation is forced linearly to zero in 1925. Before 1926, all thermal electricity generation comes from coal products.

Linear interpolations: 1908 for passenger-km; 1939 and 1946 for coal imports; 1936-1943 and 1949 for crude oil imports.

A.1.11 Nigeria

The energy system of the most populous country of the African continent⁵⁴ is historically very biomass-intensive. Since the country became an oil producer, most of the oil has been exported. Because the apparent consumption data during the Nigerian Civil War (1967-1970) exceed what would be required for reported electricity production, the supply numbers have been replaced by what would have been required. Petroleum product imports from Darmstadter et al. (1970) were included because the exports reported in Mitchell (1995) exceed reported production, without mention of imports.

The coal in transport multiplier α in equation 2 is 1 through the year 1940. Biomass is present in transport during 1968-1970. Biomass is scaled with population from the 1971 value reported by the IEA. Before the year 1950, Maddison (2010) does not report population data. Two anchor points were chosen and values in between were linear interpolations: 400,000 TJ of biomass in the year 1900 and 500,000 TJ of biomass in the year 1925.

Linear interpolations: 1968 for coal output; 1926-1928, 1930-1932, 1934-1936, 1939-1949, 1951-1952, 1954, 1956 and 1958-1959 for imports of refined petroleum products; 1930-1935 for total electricity supplied; 1939-1943 for hydropower.

⁵⁴'The Giant of Africa'

A.1.12 Poland

Poland only gained independence after the First World War, forming one country from parts of the former German Empire, Russian Empire and Austro-Hungarian Empire. The energy balance for Poland starts with the year 1920 as that is the first year for which data are reported. During its history, Poland underwent major territorial changes, leading to data variability.

The coal in transport multiplier α in equation 2 is 1 through the year 1940. Of the coal produced in Poland, hard coal has a heating value of 24.64 GJ/ton and brown coal one of 9.1 GJ/ton. A heating value of 23.36 GJ/ton was applied to traded coal.

Biomass is scaled with population, back from the 1960 value reported by the IEA.

Coal is used for all thermal electricity generation. Heat in final energy is reported by the IEA, but no historical data could be found. Therefore, before 1960, in each sector heat has been calculated by multiplying the value for electricity consumption by the heat/-electricity ratio varying linearly over time from 0 in the first year in which electricity is reported to the value for the sector in question in the year 1960 (earliest IEA statistic).

Linear interpolations: 1941-1945 for rail transport services; 1940-1945 for total electricity supplied.

A.1.13 South Africa

The coal in transport multiplier α in equation 2 is 1 through the year 1940. Passenger-km data are scaled with GDP-PPP from the 1981 value of 20,201 million passenger-km⁵⁵. Ton-km values are scaled with GDP-PPP before 1928. Biomass is used in transport in 1900. The heating value applied to coal output is 23.6 GJ/ton.

Data for imports of refined petroleum products are absent from Mitchell (1995) after 1944. Therefore, the series is continued with linearly interpolated data from Darmstadter et al. (1970).

Electricity supply data from Etemad and Luciani (1991) were used. All thermal electricity generation is from coal.

Linear interpolations: 1945-1949, 1951-1952, 1954, 1956 and 1958-1959 for imports of refined petroleum products.

A.1.14 United Kingdom

The coal in transport multiplier α in equation 2 is 1 through the year 1940. Passenger-km values in rail transport were scaled with GDP-PPP before 1939, and with ton-km values before 1920. All coal flows have a heating value of 24.17 GJ/ton. Biomass supply is zero following the implied per capita consumption in the IEA statistics in the year 1960, as well as Putnam (1953).

Electricity is mainly generated from coal products and petroleum products. The share of petroleum products is forced linearly to zero in the year 1925.

Linear interpolations: 1939-1941 for ton-km in rail transport; 1940-1942 for passenger-km in rail transport; 1908-1919 for total electricity supplied.

⁵⁵World Bank, World Development Indicators

A.1.15 United States

Although coal substituted for wood much later than in other developed countries such as the United Kingdom, around 1900 most wood had already been replaced by coal, especially for power uses (Schurr et al., 1960). The coal in transport multiplier α in equation 2 is 1 through the year 1940 but then decreases rapidly to just 0.0144 in 1960 because of diesel and electric locomotives. Heating values applied are: 25.96 GJ/ton for hard coal output, bituminous coal output (when no distinction between hard and brown coal is made) and traded coal; 14.99 GJ/ton for brown coal output; and 29.308 GJ/ton for anthracite output. Biomass supply is taken from Putnam (1953) through 1949.

Thermal electricity generation is from coal products and natural gas. The share of natural gas is forced linearly to zero in 1925.

Linear interpolations: 1950-1959 for biomass supply; 1903-1906, 1908-1911, 1913-1916, 1918-1919, 1946-1949, 1951-1952, 1954, 1956 and 1958-1959 for the ratio of hydropower to total electricity supplied; 1919 for hydropower.

A.1.16 Other regions

As in section 3.2.2.1, for the 5 'other' regions time series of apparent consumption were calculated from the CDIAC emission series. The algorithm used to reconstruct a historical final energy balance is largely the same as for the countries. The calculation of solid fuels in transport is different in that the service-dependent factor in expression 2 is not used. It is replaced by the solid fuels use in transport, scaled back from the earliest IEA statistic with GDP-PPP.⁵⁶ The factor α is calibrated in some years at values based on comparison with countries in the same region, and varies linearly in between. Biomass supply is scaled with population, back in time from the earliest IEA statistic.⁵⁶

- **Asia:** In the years 1946-1948 the supply of coal products and of petroleum products as reported is not sufficient for electricity generation and railway transport. What's more, the calculated value for the supply of petroleum products in 1949 is negative. Therefore, these seven values are replaced by what is required by solid fuel consumption in rail transport and thermal electricity generation. The share of petroleum in thermal electricity generation is forced linearly to zero in 1920. For GDP and population changes, only China (and not India) is used, because India exhibits a discontinuity when Pakistan becomes a separate country. This addition of the Pakistan GDP and population to the 'other Asia' region is assumed to be diluted in the region and not to lead to a big discontinuity in the aggregated numbers. $\alpha(1940) = 1, \alpha(1960) = 0.5, \alpha(1971) = 0.2$
- **Latin America and the Caribbean:** Petroleum supply, as calculated from the CDIAC data, would be negative in 1914. Therefore, the value was replaced with the average of the supply in petroleum products of the previous and the following year. Electricity is generated thermally from coal, petroleum products and natural gas. The shares of the latter two are forced linearly to zero in 1920. $\alpha(1940) = 1, \alpha(1960) = 0.4, \alpha(1971) = 0.05$
- **Middle East and Africa:** The supply of petroleum products in the year 1933 is too low to satisfy thermal electricity generation (from petroleum products and from

⁵⁶The evolutions in GDP-PPP and in population are assumed to be the same as for the ensemble of countries in the region that were studied in greater detail.

natural gas, the share of the latter being forced linearly to zero in 1955). Therefore, the supply has been substituted by what is required for thermal electricity generation in that year. $\alpha(1940) = 1$, $\alpha(1960) = 0.4$, $\alpha(1971) = 0.05$

- **OECD-1990:** The share of petroleum products in thermal electricity generation is forced linearly to zero in the year 1925. $\alpha(1940) = 1$, $\alpha(1960) = 0.25$
- **Reforming Economies:** The shares of petroleum products and natural gas in thermal electricity generation are forced linearly to zero in the year 1950. $\alpha(1940) = 1$, $\alpha(1960) = 0.5$, $\alpha(1971) = 0.1$. Heat in final energy is reported by the IEA, but no historical data could be found. Therefore, before 1971, in each sector heat has been calculated by multiplying the value for electricity consumption by a heat/electricity ratio varying linearly over time from 0 in the first year in which electricity is reported to the value for the sector in question in the year 1971 (earliest IEA statistic).

A.2 Online database manual

What follows is a short tutorial on the use of the database, which can be found through the IIASA website (www.iiasa.ac.at under the TNT program and then under 'Models and Databases'. This text is also on the website.

A.2.1 Navigation tabs

At the upper end of the browser window five navigation tabs can be found that provide different functionality of the web database. These five tabs are described in more detail in the following section. The data in the PFU database can be viewed online through two of the tabs shown on top of the screen, 'Sectors' and 'Series', all of which present the data from a slightly different perspective.

About tab The 'About' page provides information about the database as well as instructions on how to use the database.

Sectors tab The 'Sectors' view allows selecting multiple variables from a single region. This view is most useful for displaying a set of variables, for example all different energy carriers of industrial final energy consumption or of a specific use, in exergy terms. Again, if the variables can be added in a meaningful way (e.g. different energy carriers of one sector) a stacked area graph is shown. Please note that **it is necessary to mark a variable name (highlighted in blue) in addition to selecting variables for the graph on the right hand side to be updated** (see also under (3.) Variables below).

Series tab The 'Series' view allows selecting a single variable from multiple regions. The preview graph on the right is always a line graph and is most useful to compare trends across different pathways in one or multiple regions.

A.2.2 Database view structure

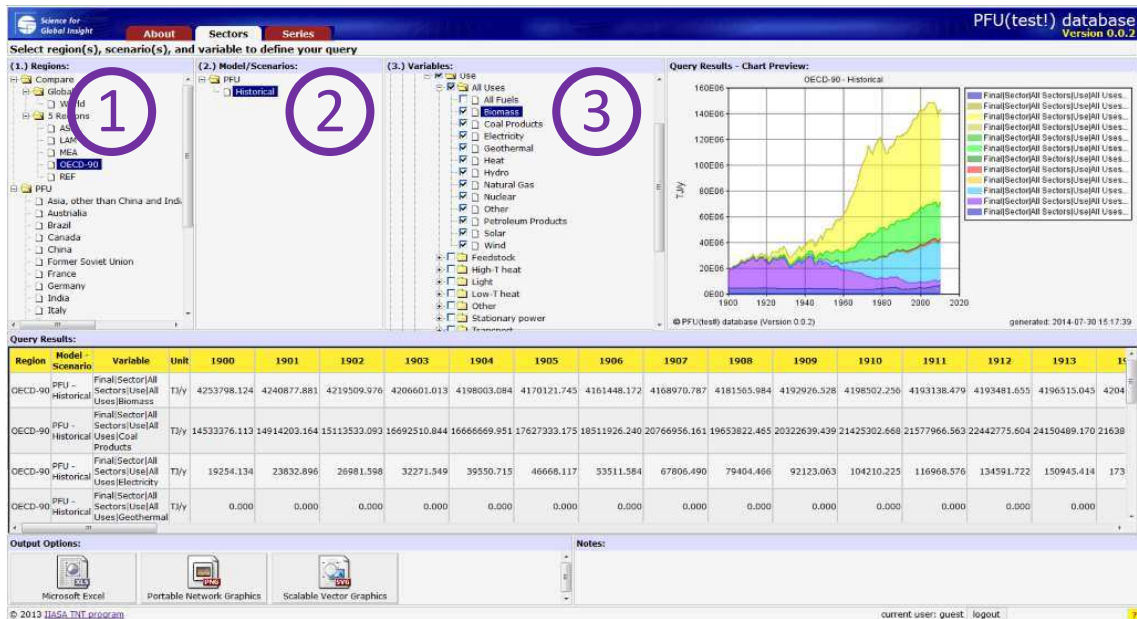


Figure 20: Screenshot of the online database interface.

When viewing the database through any of the two tabs indicating different aggregations of data (i.e. 'Sectors' or 'Series'), the following query fields are in the left upper middle of the screen (the numbering corresponds to the annotations on the screenshot in figure 20):

- 1. Regions:** In the upper left area of the screen is a field named 'Regions'. This field is used for choosing the region or regions for which the data is shown. If data is aggregated over sectors (i.e. data is accessed through the tab 'Sectors'), only single region can be chosen at a time.
- 2. Scenarios:** This field is used for choosing the scenario for which the data is shown. Multiple scenarios can be chosen simultaneously only if the aggregation method used is 'Series'. For now, the only scenario is historical.
- 3. Variables:** This field is used for choosing the variable or variables for which the data is shown. Note that if the aggregation used is 'Series', only a single variable can be presented at a time.

The desired variables are selected by ticking the box next to the desired variable in the Query Results field. This allows you to define the required aggregation freely - all variables marked will be included in the aggregation. If no tick box is shown only a single variable can be selected and you may want to change to a different view.

Note: you must tick at least one box or select a variable in each of the three input fields and click on any of the input options to generate (updated) figures and tables!

The output fields show a graphical and numerical view of the chosen data:

Query Results - Chart Preview Displays a graph of the chosen on the right of the screen. The graph is either a stacked coloured graph or line graph in the 'Sectors' views, and a line graph for the 'Series' views.

Query Results Shows the results in numerical format.

Output Options Allows exporting of the selected PFU data into MS Excel or to higher-resolution PNG or SVG graphical formats (graph open in a new window). Full time series will be included in the Excel file, even if only selected years are shown in the 'Query Results' frame.

Notes Shows any information that is relevant to interpreting the chosen variables. If you hover your pointer over the '?' box in the far bottom right, you will see information about the pathway and variable names that the database uses internally.