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A country-level primary-final-useful (CL-PFU) energy and exergy database: overview of its construction and 1971–2020 world-level efficiency results

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Abstract

Societal exergy analysis examines the flows of energy and exergy through societies, from primary (e.g. oil) to final (e.g. gasoline) to useful (e.g. propulsion) energy stages. By extending the study of energy to the useful stage, new insights into the under-represented role of energy in economic growth have been made. However, currently (a) country coverage is patchy and incomplete, (b) available data are based on varying methods and assumptions including efficiencies based on economic rather than engineering data, and (c) datasets are constructed using piecemeal computational approaches. To address these gaps, we construct a country-level primary-final-useful (CL-PFU) energy and exergy database for the period 1960–2020, containing country-level data created by a consistent physical approach, covering 152 individual countries and 3 rest of world regions, 7 aggregate and 46 detailed sub-sectors, 68 final energy products, and 85 final-to-useful (FU) energy conversion devices. This paper (a) provides details of CL-PFU database construction and its input datasets and (b) gives world-level primary-final-useful energy, exergy, and efficiency results for 1971–2020. We find that whilst world efficiency (including animal and human muscle work) has decreased over primary-to-final stages from 79% to 72% for energy and from 79% to 70% for exergy, there has been a much larger increase in world FU efficiency, which has grown from 37% to 65% in energy terms and from 15% to 23% in exergy terms. This large rise in FU efficiency leads to much larger gains in useful energy (3.71 × 1971 value) and useful exergy (3.20 × 1971 value) than at primary (2.33 × 1971 value) or final (2.10 × 1971 value) stages. Muscle work contributes only a small (less than 10%, and declining) share at primary, final, and useful energy stages.

1. Introduction

1.1. Societal exergy analysis suggests a significant, underplayed role of energy in economic growth

Among other things, the field of societal exergy analysis (SEA) examines energy flows at a macro scale (e.g. sector, country, or global level), from primary (e.g. oil) to final (e.g. gasoline) to useful (e.g. propulsion)

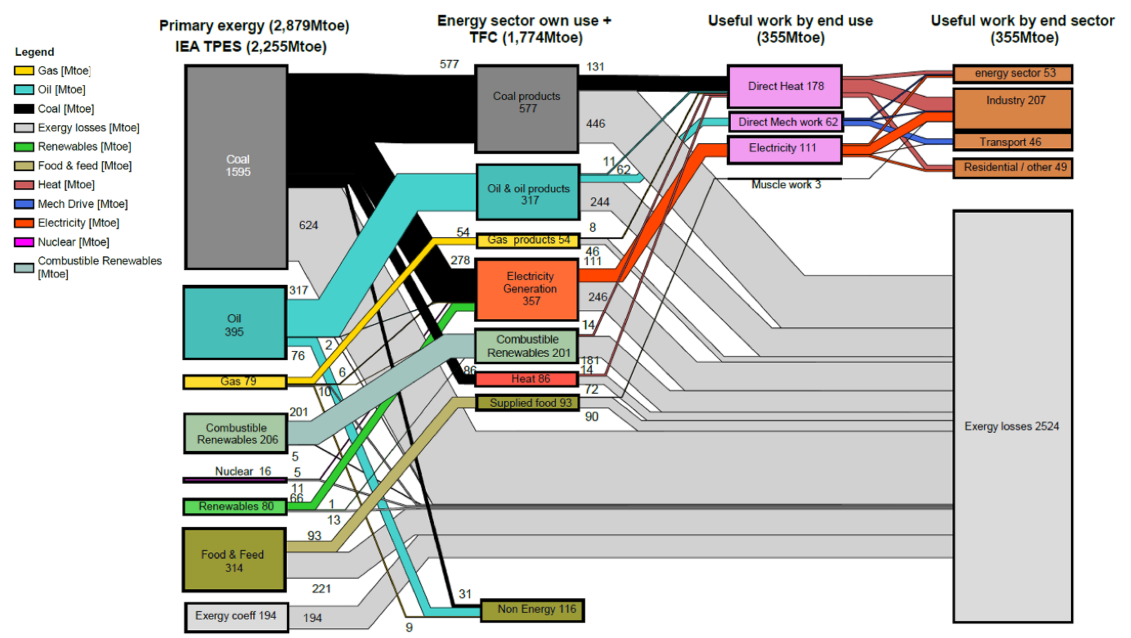

Figure 1. China Sankey diagram showing primary, final, and useful energy stages in 2010 with energy conversion losses (Brockway *et al* 2015). Reproduced from Brockway *et al* (2015). CC BY 4.0.

energy stages. SEA can quantify energy flows in energy terms (i.e. the heat content of energy carriers) or in exergy terms, which is defined as 'the maximum amount of work that a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly' (Ayres 1998, p. 392).

From SEA's early origin with a USA study (Reistad 1975), a wide set of country-level analyses have been completed. Efforts in the 1980s and 1990s were led by Wall and colleagues, producing country-level papers on Sweden (Wall 1987), Japan (Wall 1990), and Italy (Wall 1994). In the 2000s, Ayres and co-authors completed analyses of the USA, Japan, Austria, and the UK (Ayres 2003, Warr *et al* 2008, 2010, Williams *et al* 2008). Country-level studies often yield data that can be presented in the form of a Sankey diagram like figure 1, which shows the energy conversion chain (ECC) for China in 2010. In the example, which is typical for country-level analyses, only about 15% of China's primary exergy is delivered to society as useful exergy, with most exergy losses occurring during final-to-useful (FU) conversion.

Since 2014, analyses have been conducted for the UK and the USA (Brockway *et al* 2014), China (Brockway *et al* 2015), Portugal (Serrenho *et al* 2016), Mexico (Guevara *et al* 2016), and Ghana (Heun and Brockway 2019). With time, calculation robustness has improved and granularity has increased at sector and sub-sector levels. The recent status of the SEA field is well described by Miller *et al* (2016) and Sousa *et al* (2017). Important advances include the move to an International Energy Agency (IEA)-based energy accounting framework (Serrenho 2014) and improvements to key machine efficiencies for transport (Brockway *et al* 2014), muscle work (Steenwyk *et al* 2022), and lighting (Heun *et al* 2020). Commonly, SEA studies focus on exergy analysis (i.e. primary, final, and useful exergy), but this is not always the case. SEA research can also consider energy analysis (i.e. primary, final, and useful energy), an example being Cullen and Allwood (2010).

Key new insights have followed from these country-level SEA studies. For example, exergy efficiency gains in some highly developed countries are slowing down, due to 'efficiency dilution' from expanding use of low-exergy-efficiency technologies such as air-conditioning (Williams *et al* 2008, Brockway *et al* 2014). In developing economies, country-level exergy efficiencies are lower and therefore further from practical efficiency limits, leaving efficiency 'headroom' for future rapid economic growth (Heun and Brockway 2019). Going further, recent studies have suggested that efficiency gains are both (a) a key part of economic growth (Sakai *et al* 2019) and (b) a possible explanation for total factor productivity (TFP) in conventional economic growth models (Santos *et al* 2021).

1.2. Developing a country-level PFU database

Three issues drive our ambition to develop a country-level primary-final-useful (CL-PFU) database. The first issue is that although SEA has broadened over time to include more countries and sectors, coverage remains patchy and incomplete, limiting comparability and precluding country panel data studies. Indeed, only two studies include more than 4 countries: Serrenho *et al* (2014) studied the EU-15 countries and the

International Institute for Applied Systems Analysis (IIASA) database (De Stercke 2014) covered 15 countries and 5 rest of world (RoW) regions. The main reason for patchy and incomplete country coverage is that estimating useful stage data for even a single country requires significant investment of researcher time, typically many months to years. A way to speed the development of country-level analyses is needed.

The second issue is that existing datasets have been created by different researchers, using varying methods and assumptions, including some (De Stercke 2014) that derive efficiency estimates from economic (rather than engineering) data. Thus, analyses to date remain broadly comparable in terms of trends and overall insights but would benefit from greater consistency. Standardization using engineering-based input data built in a robust and consistent calculation framework is needed.

The third issue is that SEA practitioners have typically analyzed the ECCs of individual countries using linked spreadsheets in varying and inconsistent formats. The spreadsheet approach to SEA is not scalable to analyse over 150 countries at a world level. A new calculation approach to SEA is needed, one that scales across all countries and many decades.

To address these needs, we have developed, over the last 5 years, a CL-PFU database covering the period 1960–2020. This paper reports on the database construction process and key results, with three aims: (a) to describe the scalable process that we used to create a standardized, CL-PFU energy and exergy timeseries database that can be aggregated to regional and world levels, (b) to describe the CL-PFU database itself, and (c) to present, for the first time, aggregate sector-, region-, and world-level results for 1971–2020 derived from the CL-PFU database.

1.3. Structure of the paper

The rest of the paper is structured as follows. In section 2, we describe features of the CL-PFU database and the method of its construction. Energy, exergy, and efficiency results from the database are shown in section 3 at world and regional levels, by sector, by energy stage, and by energy product. In section 4, we (a) discuss overall efficiency trends, (b) compare our world-level results to other PFU studies, (c) set out the limitations of the database, (d) discuss future improvements to the database, and (e) consider future applications. Section 5 concludes.

2. Methods: Construction of the CL-PFU energy and exergy database

Building upon the solid foundations of recent country-level analyses and advances in SEA methodologies, we developed the CL-PFU database, a granular, country-level energy and exergy database that we believe is the most comprehensive SEA resource constructed to date. The CL-PFU database contains country-level data for the period 1960–2020 and was created using a single, common analysis approach, covering 152 countries and 3 Rest of World (RoW) regions, 7 aggregate sectors (e.g. transport) and 46 detailed subsectors (e.g. road transport), and 68 final energy products (e.g. gasoline) that flow through 85 FU energy converting devices (that we call 'machines') to create 32 useful energy products (e.g. road propulsion).

The construction of the CL-PFU database is a detailed process that involves hundreds of input files and many hours of automated computer calculations and checks. The construction steps follow a SEA process, shown in figure 2. Broadly speaking, four steps are involved. First, primary- and final-stage energy data are gathered from the IEA. These data provide energy information at primary and final stages and therefore must be extended to the useful stage. (See section 2.1.) Second, data are gathered from the UN's Food and Agriculture Organization (FAO) and the International Labour Organization (ILO). These data provide final-stage energy data for muscle work (MW) and must be extended to the primary and useful stages. (See section 2.2.) Third, energy data from all sources (IEA, ILO, and FAO) and at all stages (primary, final, and useful) must be converted to exergy as described in section 2.3. Finally, data are aggregated in various ways, and efficiencies are calculated as discussed in section 2.4. Section 2.5 provides a discussion of the computational environment and analytical advances that enable construction of the CL-PFU database. Additional details are available in the Supplementary Information (SI) and two data repositories - refer to the Data Availability Statement.

2.1. Incorporate IEA Extended World Energy Balances (EWEB) data

We gather and collate primary, final, and useful stage energy from IEA data in four steps, set out below.

2.1.1. Step 1: Gather and organise IEA EWEB data

The starting point for constructing the CL-PFU database is the 2022 release of the IEA's EWEB dataset (International Energy Agency 2023a). Initially, in 1960, the IEA's EWEB data comprised just 26 OECD nations. By 1971, EWEB data had expanded to 116 countries and included RoW regions. The year 1971 also

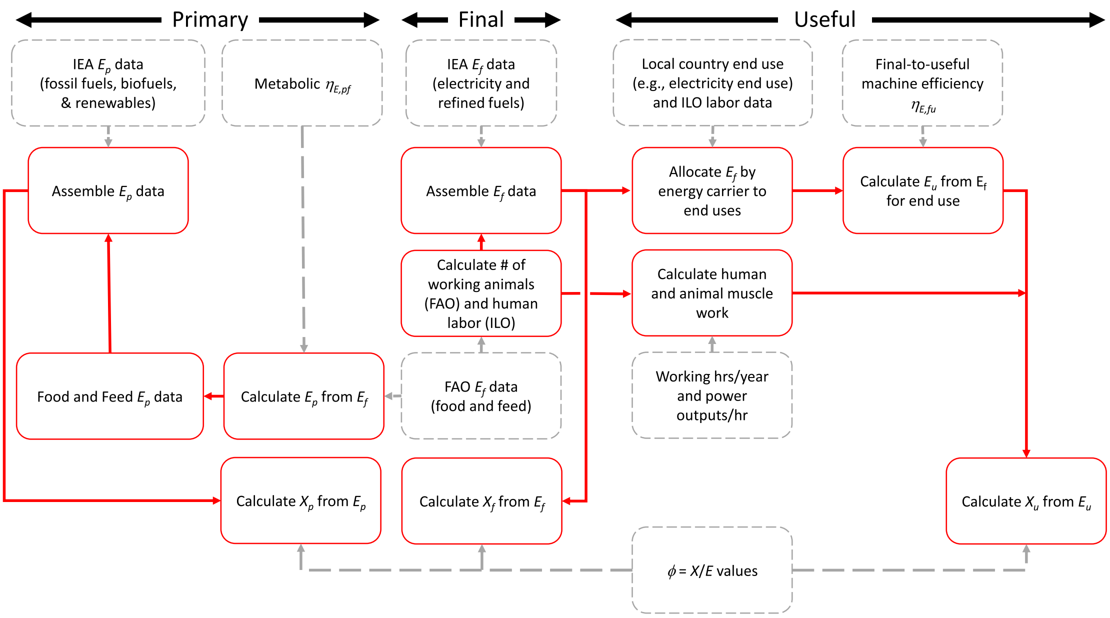

Figure 2. Societal exergy analysis process diagram. Gray boxes and dashed lines indicate externally-sourced data. Red boxes indicate analysis steps. Symbols denote primary, final, and useful energy (E_p, E_f, and E_u) and exergy (X_p, X_f, and X_u), primary-to-final energy efficiency (η_{pf}), final-to-useful energy efficiency (η_{fu}), and exergy-to-energy ratio (ϕ). Reproduced from Heun and Brockway (2019).

marks the start of the IEA's reporting aggregate world-level primary and final energy totals in the EWEB data, which is why the CL-PFU global dataset starts in 1971. By 2020, the IEA data comprises 156 current and former countries, 3 RoW regions, and 2 bunker regions[10]. Total energy supply and final energy use (known as total final consumption) are included.

The IEA's EWEB energy data, comprising over 4000 rows of data per country (years are in columns), are reported annually for each country and include 66 energy products, which fall into 7 broad categories: 18 coal and coal products, 24 oil and oil products, natural gas, 8 biofuels, 7 electricity products, 5 heat products, and 3 waste products. The IEA's EWEB energy data are available in ktoe (kilotonnes of oil equivalent) or TJ (terajoules). The CL-PFU database uses IEA EWEB data in TJ exclusively.

In the IEA's EWEB energy dataset, the final energy stage is divided into energy consumption in 7 main IEA sectors[11]: (1) energy industry own use (EIOU), (2) industry, (3) transport, (4) residential, (5) commercial and public services, (6) agriculture, forestry, and fishing, and (7) non-energy use (NEU). Within the 7 main sectors, energy data are provided for 46 sub-sectors, such as road, rail, air, boat, and pipeline transport within the transport sector.

The IEA's EWEB data includes primary energy constituents in terms of production, imports, exports, and stock and bunker changes, whose signed sum is total energy supply for each country. We take total energy supply to be equal to primary energy for each country. Total energy supply can be consumed within each country in two ways. One way is directly in final energy consumption (e.g. primary solid biofuels), in which case the primary energy passes straight through the ECC to be recorded as final energy consumption. The other, more common, way is to transform the primary energy (e.g. oil) into a final energy product (e.g. gasoline), which is consumed at the final energy stage. There are two types of processes reported by the IEA: (a) primary-to-final transformation processes (21 in total, e.g. oil refineries), wherein primary energy (e.g. crude oil) is used as feedstock for production of various final-stage energy products (e.g. gasoline) and (b) energy industry own use (EIOU, 17 in total), wherein the energy is consumed in energy extraction (e.g. coal mines) and energy transformation (e.g. oil refineries).

For combustion-related electricity and heat production (examples of primary-to-final transformation processes), the primary energy content (in TJ) of the energy product (e.g. coal or natural gas) is known and

[10] The 3 RoW regions are Other Africa, Other Americas, and Other Asia. The 2 bunker regions are World Marine Bunkers and World Aviation Bunkers, which we treat as separate countries.

[11] Different terms are commonly used to describe the places where final energy is purchased by end-users and converted to useful energy, depending on the background and preferences of researchers, including final demand sectors, energy-consuming sectors, or economic sectors. For simplicity, we use 'sectors.'

recorded for each transformation process. However, for electricity and heat produced from non-combustible sources, such as nuclear and renewables, the amount of electricity and heat produced is known, but the primary energy consumed is not. For such cases, the IEA (International Energy Agency 2023b, p. 615) estimates 'primary energy equivalent' inputs by dividing final energy values (in TJ) by assumed conversion efficiencies as follows: geothermal electricity (10%), solar thermal electricity (33%), nuclear electricity (33%), geothermal heat (50%), combined heat and power heat (100%), and renewable electricity from hydro, solar photovoltaics (PV), wind, wave, ocean, and tidal sources (100%).

Thus, we implicitly follow the IEA's physical content method (PCM), which assumes 100% primary-to-final energy efficiency ($\eta_{\mathrm{pf,E}}$) when calculating the primary energy equivalent of renewables-based electricity (except geothermal and solar thermal). There are two other ways of accounting for the primary energy equivalent of renewable electricity generation: the partial substitution method (PSM) and the resource content method (RCM). Refer to Sousa *et al* (2017) for a longer discussion and review of previous SEA studies, which have used the full range of PCM, RCM, and PSM methods for the primary-stage equivalent of renewable electricity. Other methods (PSM and RCM) could be incorporated in future versions of the CL-PFU database. At low (historical) penetrations of renewables-based electricity generation, overall results are indistinguishable among PCM, PSM, and RCM. However, differences will become apparent in the future as the transition to modern renewables-based electricity (mainly from solar PV and wind turbines) gathers pace.

2.1.2. Step 2: Allocate IEA final energy to FU machines

The IEA's EWEB data (which ends at the final energy stage) must be next extended to the useful energy stage by allocating the IEA's final energy consumption data in each of the 46 final demand subsectors (and EIOU subsectors) to useful stage end-uses and 83 associated FU energy-conversion 'machines.' We call this process 'FU machine allocation' or 'FU machine allocation' for short. Our approach follows the pioneering work of Serrenho (2014). Continuing the gasoline example now with end use in the transport sector, percentages of gasoline consumption (in TJ) are assigned to different vehicle types (light duty vehicles, motorcycles, trucks, etc), based on country-specific data. Each FU energy-converting machine also has a matching timeseries of FU efficiency (η_{fu}), which is later applied via multiplication to calculate energy at the useful stage (see section 2.1.3). We apply the FU machine allocation approach of Serrenho (2014) to all countries with known FU machine allocation data.

For the CL-PFU database, FU machine allocations are required in each of 46 detailed sectors and for up to 66 IEA energy products. Unfortunately, such data are not available for all countries. Thus, we develop a unique two-part approach. First, for numerous countries where FU machine allocation data are available (e.g. Denmark data via the Danish Energy Agency (2020)), we specify FU machine allocations directly. Note that some allocation datasets have gaps in coverage, especially in early years (i.e. back to start of IEA final energy for a given country). In those cases, we interpolate or extrapolate as needed. Second, for countries where FU machine allocations are lacking, we use an innovative 'exemplar' system, developed for the CL-PFU database, which pulls allocation data from an 'exemplar' country where allocations are known. Refer to section 2.1.5 for a more comprehensive description of the exemplar system.

The CL-PFU database benefits from the fruits of important efforts in recent years to improve FU machine allocations and mapping, such that we now have much better understanding than ever before of FU energy conversion processes in many sectors and countries. Countries and regions with new or enhanced FU machine allocations in the CL-PFU database include Hong Kong (Electrical and Mechanical Services Department, The Government of Hong Kong Special Administrative Region 2020), the USA (EIA 2015), Canada (Natural Resources Canada, Office of Energy Efficiency 2020), Denmark (Danish Energy Agency 2020), the UK (BEIS 2021), Europe (ODYSSEE-MURE 2015, Mantzos *et al* 2018), and the world (International Energy Agency 2023b).

Figure 3 illustrates the FU machine allocation shares for the example of residential electricity in the UK. Refer also to the SI, which contains a summary of the FU machine allocations (and associated reference sources) to end use categories (at the useful energy stage) for the 24 countries with own-country allocations.

2.1.3. Step 3: Estimate FU efficiencies for IEA-based energy FU machines

With the final energy data and FU machine allocations in hand, the next step in the database construction process is to obtain FU energy conversion device ('machine') efficiencies for our 83 FU machines which convert IEA-based final energy to useful energy. We estimate the FU efficiencies ($\eta_{\mathrm{fu,E,m}}$) for these machines for as many individual countries as possible. As with allocation data, available efficiency data may not cover all of the IEA years for that country, so we interpolate and extrapolate to fill gaps. When efficiency data are unavailable for a country-machine combination, the exemplar system is employed in a manner similar to FU

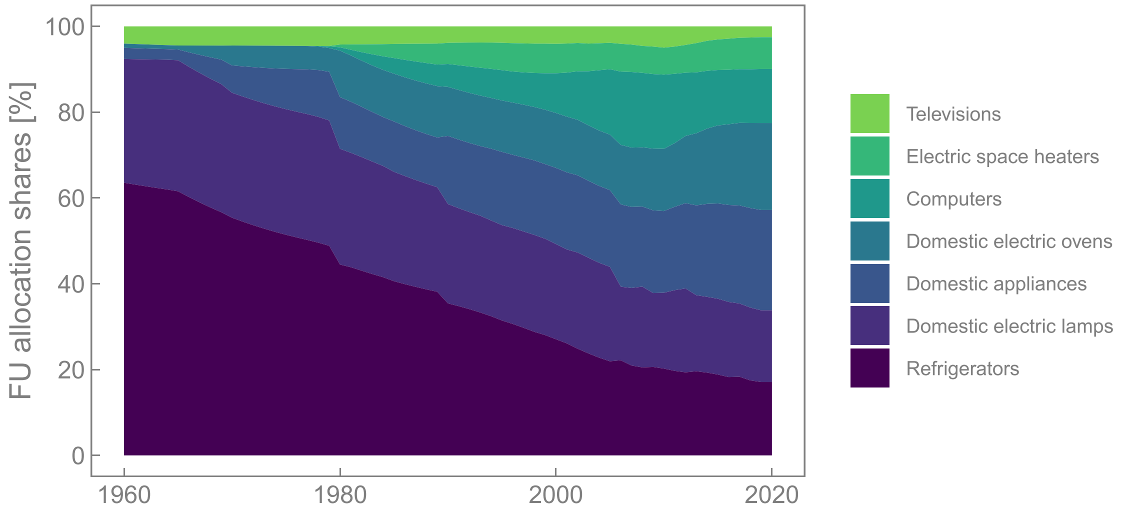

Figure 3. UK residential electricity allocation shares to final-to-useful energy conversion machines (BEIS 2021).

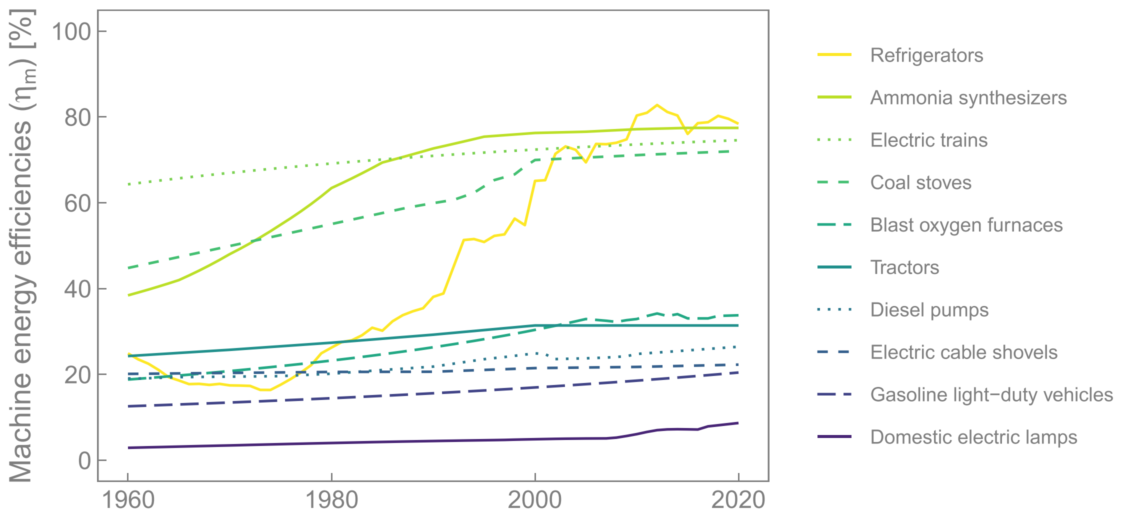

Figure 4. Energy efficiency (η_m) of common final-to-useful energy conversion machines for the World exemplar case.

machine allocations, as discussed in section 2.1.5. In figure 4 we provide FU energy efficiencies ($\eta_{fu,E,m}$) for the world exemplar (technically, a country named 'WRLD' in the CL-PFU database) for some of the most common machines. Refer also to the SI for a summary of the calculation basis and assumptions used for estimating the FU efficiencies for the 83 individual FU machines which convert IEA final energy to useful energy products.

2.1.4. Step 4: Calculate IEA-based useful energy

Last, we calculate useful energy for the IEA's EWEB energy data by the multiplying IEA final energy allocated to each FU machine (in each country and detailed subsector) by the calculated FU efficiencies for FU machines ($\eta_{fu,E,m}$).

2.1.5. Exemplar system

The IEA's EWEB dataset provides granular primary and final energy data for over 150 countries and 3 RoW regions which sum to produce world-level energy consumption from 1971. The previous sections (2.1.2–2.1.4) outline how we use FU machine allocations and FU machine efficiencies to calculate useful stage energy for each country. However, we do not have FU machine allocation or FU machine efficiency data for all IEA countries. In fact, we have FU machine allocations for 24 countries and FU machine efficiencies for 83 FU machines, with data coverage ranging from a single country (for diesel pumps in the USA) to 19 countries (for gasoline consumption by light duty vehicles).

To both solve this problem and to produce a modular database engine that allows for future improvements (see section 2.5), we developed and utilise an 'exemplar' system for missing FU machine allocations and efficiencies. The exemplar system works as follows. When FU machine allocations or efficiencies are missing for any given sector of a given country or machine in the sector, a list of exemplar countries and then regions are queried, in order, for available data. For example, the ordered list of Belgium's exemplars is France, then Europe, and then the WRLD exemplar. Exemplar countries are chosen based on three considerations: (a) Data availability: exemplars (in this example, France) must have own FU machine allocation and/or efficiency data. (b) Geography: France is a near neighbour of Belgium. (c) Economy: France has a similar economic profile compared to Belgium (e.g. GDP/capita).

Continuing the Belgian example, if France has FU machine allocation data but not for the required sector, then allocations and/or efficiencies for the region (Europe) are queried. Last, if the region lacks allocation or efficiency data, data for the WRLD exemplar are consulted. (The WRLD exemplar contains allocations and efficiencies for all energy uses and machines.) The exemplar system enables creation of the CL-PFU database for all IEA countries, despite missing FU allocations and/or machine efficiencies. As noted also in section 2.5, when missing FU machine allocations or efficiencies become available at a later date, they can be added to improve future versions of the database.

2.2. Incorporate muscle work energy data

In addition to primary, final, and useful data derived from IEA EWEB data, the CL-PFU database contains information on primary, final, and useful energy and exergy associated with two further FU machines that both deliver muscle work: human manual labourers and draft animals. By including muscle work only (from human and animal labor), we align with SEA accounting principles, which estimate energy and exergy content of input energy flows, as was set out for the IEA-based energy flows in section 2.1.

In the sections below, we set out 3 steps to calculate PFU muscle work energy for inclusion in the database, namely (1) estimate final-stage energy data on food and feed consumption based on both UN Food and Agriculture Organization (FAO) data and International Labour Organization (ILO) data (section 2.2.1), (2) generate primary stage energy data (section 2.2.2), and (3) generate useful stage energy data (section 2.2.3). Note also that we use only available country-level data and therefore do not employ the exemplar country system (section 2.1) for muscle work.

2.2.1. Step 1: Estimate food and feed consumption

The starting point for including muscle work in the CL-PFU database is estimates of annual food and feed energy consumed by draft animals and human manual workers. We follow the method of Steenwyk *et al* (2022), who completed a machine and muscle work study for world agriculture for 1800–2015.

First, we obtain the numbers and types of draft animals (oxen, horses, camels, etc) from the United Nations Food and Agricultural Organization (2022) and total labour force from employment data of the International Labour Organisation (2022a) for available countries and over the period 1960–2020. To estimate the number of draft animals, we convert the FAO total number of live animals to working animals based on percentage estimates of working animals by animal (e.g. Asses, Buffaloes) and region (e.g. Africa, China), following Steenwyk *et al* (2022). Then we partition the working animals into two sectors, agriculture and transport, using estimates derived from Steenwyk *et al* (2022). For humans, we estimate the fraction of reported manual workers in different classifications in each employment sector (services: 5%; industry: 25%; agriculture: 50%; mining: 75%), based on ILO data and classifications. For ILO data, we first check for the presence of data for the number of employed persons and yearly working hours for each combination of country, sector, and gender. If data exist for a given combination but years are missing, we linearly interpolate between data points and/or hold the first or last values constant until the first or last years (1960 or 2020 respectively).

Second, we gather the amount of feed and food required by draft animals and humans. For animals, we follow the approach of Steenwyk *et al* (2022). First, we estimate and sum working and non-working day feed consumption, calculated as the numbers of working and non-working days multiplied by the feed consumed on working and non-working days, for all working animals, by region and animal type. Total final energy is then calculated as total yearly feed (in TJ) multiplied by a gross energy-to-digestible energy ratio of 1.1636 from Wirsenius (2000) and by a trough waste factor $\left(\frac{1}{1-0.1} = 1.11\right)$ to account for 10% trough waste, also from Wirsenius (2000). Consumed feed intake for each type of animal is in the range of 6000–25 000 kcal d^{-1} (25–100 MJ d^{-1}) depending on animal type. For humans, male and female manual workers are assumed to consume 2500 kcal d^{-1} and 2000 kcal d^{-1}, respectively, of food. We assume that all food and feed consumed is final energy.

Third, we multiply numbers of draft animals and human labourers by their individual feed and food inputs to determine the aggregate annual final energy consumption by draft animals and human labourers in each country.

2.2.2. Step 2: Calculate muscle-work-based primary energy data

To move from the final energy stage to the primary energy stage for muscle work, we utilize wastage information from Wirsenius (2000) and the United Nations Food and Agricultural Organization (2022) for harvest losses of animal fodder (∼40%) and field-to-fork losses for humans (∼25%). Adding assumed wastage to food and feed consumption (i.e. final energy) enables estimation of primary energy required production for draft animal and human labourer muscle work.

2.2.3. Step 3: Calculate useful energy stage muscle work data

For both draft animals and manual human labourers, there is only one energy product at the useful stage: muscle work. Rather than moving from final to useful energy via an FU machine efficiency (as we did for the 83 machines that consume IEA final energy products), we calculate the muscle work directly following Steenwyk *et al* (2022). The calculation proceeds as follows. First, we obtain estimates for the power output (in watts, W) for draft animals and human manual workers from Steenwyk *et al* (2022). Power outputs for animals are typically 200–600 W, differing by animal type (e.g. oxen are more powerful than donkeys). Power outputs for manual worker classes average around 50 W but also vary by worker (miners have a higher power output than workers in manufacturing industries) and gender (males have 25% higher power output than females, but consume 25% more food). Second, we obtain estimates of annual working hours from Steenwyk *et al* (2022) for draft animals (typically 4–6 $\mathrm{h\,d^{-1}}$ for 200 $\mathrm{d\,yr^{-1}}$), and from the International Labour Organisation (2022b) for human labourers (typically 2000 hours/year). Third, we multiply power outputs by annual working hours per year to obtain useful-stage energy for each type of draft animal and human manual labourers. Fourth, we multiply useful-stage energy per animal and worker by the numbers of different types of animals (via FAO data) and workers (via ILO data) to obtain an estimate of manual work by draft animals and human labourers for all available countries.

After completing the above steps, we have in hand energy quantifications of ECCs for all available countries and years at primary, final, and useful stages with the highest available granularity for energy products, energy conversion machines, energy transformation processes, and sectors. The next step is to add exergy quantifications of the ECCs to the CL-PFU database.

2.3. Provide the ability to switch between energy to exergy

Converting energy to exergy involves a multiplication step wherein primary, final, and useful energy flows are multiplied by an exergy-to-energy ratio (ϕ) appropriate for each energy product. Table 1 gives the ϕ ratios adopted for all nine primary and final energy product types and eight useful stage energy products. (There are 31 energy products at the useful stage, with many more heating and cooling products at different temperatures. To indicate the range of ϕ values for heat, we show a selection of values at various temperatures, from −10 °C to 1600 °C.)

At the primary and final energy stage, following other SEA studies (e.g. Serrenho (2014) and Brockway *et al* (2014)), we adopt the exergy-to-energy ratios ratios (ϕ) for fossil fuels from Szargut *et al* (1988) (coal, oil, and gas products: 1.04–1.06; solid biomass: 1.15). For electricity at primary and final energy stages (including electricity derived from biofuels, waste, nuclear, and renewables), we assume the exergy-to-energy ratio is 1.00, as these products provide pure available work. At the useful energy stage, nearly all non-heat related energy carriers have exergy-to-energy ratios of 1.00, i.e. useful energy and useful exergy are equal. The exception is light for which $\phi = 0.953$ (Heun *et al* 2020).

For the exergy-to-energy ratio (ϕ) of heat-related end uses, we follow the standard protocol of SEA accounting and the second law of thermodynamics by adopting the Carnot temperature ratio as the exergy-to-energy ratio: $\phi = 1 - T_2/T_1$, where T_1 is the hot temperature, and T_2 is the cold temperature, typically the surroundings temperature (often 0 °C–20 °C), both quantified in absolute temperature units (in our case, Kelvin). Thus, ϕ values are based on an assessment of the temperature of the heat used in specific sectors. For example, most heat in the residential sector is allocated to space heating which is specified as low-temperature heat at 20 °C ($\phi = 0.05$). In industry, temperatures of heat (and thus ϕ) vary considerably, from medium temperature heat at 200 °C ($\phi = 0.38$) to high temperature heat at 1600 °C ($\phi = 0.85$).

To convert muscle work from energy to exergy, we assume ϕ values at primary and final energy stages are 1.00, following Serrenho (2014). Muscle work does not incur heat-to-work (i.e. Carnot) losses, so energy and exergy for muscle work are equal at the useful stage, too.

Table 1. Exergy-to-energy ratios (ϕ).

Energy product	ϕ	Source
Primary and final stages		
Solar thermal heat	0.25	Serrenho (2014)
Heat	0.60	Serrenho (2014)
Electricity	1.00	Serrenho (2014)
Food & feed	1.00	Serrenho (2014)
Natural gas	1.04	Serrenho (2014)
Coal & coal products	1.06	Serrenho (2014)
Oil & oil products	1.06	Serrenho (2014)
Waste & biofuels	1.11	Serrenho (2014)
Biomass	1.15	Brockway *et al* (2014)
Useful stage (selected)		
Low temperature cooling (−10 °C)	0.11	Own calculation using Carnot ratio
Low temperature heat (20 °C)	0.05	Own calculation using Carnot ratio
Medium temperature heat (300 °C)	0.50	Own calculation using Carnot ratio
High temperature heat (1600 °C)	0.85	Own calculation using Carnot ratio
Light	0.95	Heun *et al* (2020)
Machine mechanical work	1.00	Serrenho (2014)
Human mechanical work	1.00	Serrenho (2014)
Road Propulsion	1.00	Serrenho (2014)

When the above tasks are complete, we have added exergy quantifications of ECCs to the CL-PFU database. The next step is to aggregate the energy and exergy conversion chains into energy product groups; high-level sector groups; at primary, final, and useful stages; by region; and to the world level.

2.4. Calculate aggregated PFU energy and conversion efficiencies

Having summarised the CL-PFU database construction, we now describe the steps to aggregate PFU energy and conversion efficiencies. First, all countries and RoW regions are summed into world-level results for each year in the period 1971–2020. Second, to facilitate easier viewing and understanding of the results presented in section 3, grouping of results is undertaken by energy products and sectors at primary, final, and useful stages in the ECC. Two additional points are noteworthy. First, at primary and final stages, EIOU is aggregated to its own sector, thereby enabling reporting of energy consumption and efficiency results in both net (without EIOU) and gross (with EIOU) terms. Second, we complete an upstream swim[12] to remove primary, final, and useful energy carriers associated with NEUs, enabling reporting of energy consumption and efficiency at all ECC stages with NEUs included or excluded.

With energy stage aggregations in hand, we calculate primary-to-final (η_{pf}), FU (η_{fu}), and primary-to-useful (η_{pu}) efficiencies for every country, every region, and the world.

2.5. Computational environment and analytical advances

In this section, we discuss three important features of CL-PFU database construction, which together enabled completion of the database. (For further details and a working example, see Heun *et al* (2024), a companion paper covering the software used to create the CL-PFU database).

First, the data format for the CL-PFU database is the Physical Supply Use table (PSUT) framework (Heun *et al* 2018, Aramendia *et al* 2022), a method for succinctly describing ECCs with four matrices, together known as the **RUVY** matrices[13]. (See table 2.) The PSUT framework and its **RUVY** matrices enable calculation of important ECC metrics[14] via matrix equations that are independent of ECC granularity (i.e. the number of energy products, the number of energy conversion machines, and the number of sectors). Calculations are simplified because the **RUVY** matrices do much of the bookkeeping for the analyst.

[12] In an 'upstream swim,' we remove directly energy products put to NEUs (e.g. Naphtha as a feedstock, or Bitumen/Asphalt for tarmac road surfacing) *and* the primary and final energy associated with making those non-energy products. This process is accomplished via a matrix inversion calculation similar to the Leontief matrix from input-output analysis. This process is performed for the ECCs of every country in every year.

[13] The PSUT framework is inspired by economic input-output (IO) analysis. Energy and exergy analogues exist for typical IO concepts, such as the Leontief inverse matrix. Similar to how IO analysis simplifies economic analysis and enables new insights, the PSUT framework simplifies SEA and enables new insights.

[14] Metrics shown in this paper include (a) ECC stage, region, sector, and energy carrier aggregations; (b) sector and energy carrier efficiencies; and (c) machine and transformation process efficiencies. Other possible metrics include (d) energy return on investment (Aramendia *et al* 2024), (e) carbon emissions; and (f) embodied primary energy of final and useful energy carriers.

Table 2. The **RUVY** matrices.

Matrix	Name	Description
R	Resource	Contains exogeneous energy inputs to an ECC
U	Use	Describes how energy conversion devices use energy, 'feed' indicating feedstock and 'EIOU' indicating energy industry own use: $\mathbf{U} = \mathbf{U}_{\text{feed}} + \mathbf{U}_{\text{EIOU}}$
V	Make	Describes how each energy conversion device makes energy
Y	Final demand	Describes sectors in which energy products are consumed

Table 3. `R` packages to create the CL-PFU database.

Package	Purpose
Available on CRAN	
RCLabels (Heun 2023f)	Manipulates matrix row and column names in matsindf data frames
matsbyname (Heun 2023a)	Performs matrix mathematics that respects row and column names
matsindf (Heun 2023b)	Stores matrices in cells of data frames
Available on GitHub	
IEATools (Heun *et al* 2023)	Converts IEA data to **RUVY** matrices in matsindf data frames
MWTools (Marshall and Heun 2023)	Converts ILO and FAO data to **RUVY** matrices of human and animal muscle work in matsindf data frames
Recca (Heun and Aramendia 2023)	Performs `R` energy conversion chain analysis
PFUSetup (Heun 2023e)	Identifies input and output locations for the PFUPipeline and the PFUAggPipeline
PFUPipelineTools (Heun 2023d)	Provides basic functionality for all PFU pipelines
PFUPipeline (Heun and Marshall 2023)	Provides a targets pipeline to create a data frame of **RUVY** matrices
PFUAggPipeline (Heun 2023c)	Provides a targets pipeline to aggregate **RUVY** matrices

Second, we developed several `R` packages (available on CRAN and GitHub) that create and execute `targets` pipelines (Landau 2021) to construct the CL-PFU database via the steps discussed in sections 2.1–2.4. (See `R` package details in table 3.) The outputs of the pipelines are primary, final, and useful energy and exergy datasets and associated efficiencies, which together comprise the CL-PFU database. All energy, allocation, and efficiency input datasets (described in sections 2.1 and 2.2) are contained in Excel or .csv files. There are approximately 300 such input files for the CL-PFU database, using over 250 source data references covering FU machine allocations, machine efficiencies, country concordances, and aggregation mappings. The `R` packages in table 3 make the data processing for constructing the CL-PFU database both possible and repeatable.

Third, both the structure of CL-PFU database and the calculation pipelines that produce it are deliberately modular, meaning the input datasets and therefore the entire database are amenable to improvement over time. The exemplar systems described in sections 2.1 and 2.2 enable fine-grained data inclusion for FU machine allocations (for as little as one final energy product in one sector of one country in one year) and machine efficiencies (for as little as one machine in one sector of one country in one year). This design means that new information can be incorporated quickly and easily by adding data to input files.

In addition, we note that three validation checks are performed every time the calculation pipelines are executed. First, energy balances are checked in the source IEA EWEB data for each combination of country, year, sector, and energy carrier. These checks are necessary because the source IEA EWEB data have slight imbalances (with typical errors less than 1 TJ yr^{-1}). All energy product imbalances of less than 6 TJ yr^{-1} are corrected for each combination of country, year, sector, and energy carrier by modifying the IEA's 'Statistical differences' value[15] . Precise energy balances (to within machine precision) are important for minimizing propagation of numerical imprecision during some matrix operations. Second, when moving from final energy as the last stage (as provided by the IEA) to the useful energy as the last stage, all allocations of final energy carriers to FU machines are verified to sum to 100%. This verification step eliminates data-entry

[15] For one energy imbalance of more than 6 TJ/year, we reached out to the IEA for clarification and eventual correction.

errors in Excel and .csv allocation files. Finally, all energy products that are outputs of the resource (**R**) and make (**V**) matrices are verified to be consumed by machines in the use matrix (**U**) or by sectors in the final demand matrix (**Y**). This verification step ensures that energy balance is maintained both when extending from the final stage to the useful stage and when converting from energy to exergy.

3. Results: World-level energy and exergy consumption and efficiencies

The CL-PFU database contains detailed information at the country level, for some countries from 1960 and for most countries from 1971. As discussed in section 2, aggregated data (at continent and world levels) are also available from 1971, which therefore marks the start of our global, world-level PFU data. In the two sections below, we focus on aggregated world-level results covering 1971–2020: (a) primary, final, and useful stage aggregate energy and exergy data are shown in section 3.1, and (b) efficiencies are shown in section 3.2. In various figures, data are shown in both gross (solid lines) and net (dashed lines) terms. Gross includes the EIOU sector at all stages (primary, final, and useful). Net does not. In common with conventional SEA studies, we generally exclude NEUs from the results, except in figures 5 and 6 where we see that NEU makes up a small-but-not-insignificant (5–10%) share of energy consumption at primary and final energy stages. (The output data repository can be consulted for more detailed non-energy results - see Data Availablity Statement.) Several figures are faceted by energy and exergy (in columns) and designated in rows as 'IEA,' muscle work ('MW'), or their sum ('IEA + MW').

3.1. Aggregate World-level energy and exergy consumption

This section presents aggregate plots for primary-, final-, and useful-stage energy and exergy data. First, figure 5 shows that energy supply (at primary and final energy stages) is dominated by fossil fuels. Second, figure 6 presents final- and useful-stage energy and exergy consumption by sector. Industry is a large sector at both final (top row of figure 6) and useful (bottom row of figure 6) energy stages (measured in both energy and exergy terms) due to the high energy and exergy efficiencies of this sector, as seen later in figure 11. The residential sector is also a large sector at the final energy stage (top row of figure 6). However, at the useful stage (bottom row of figure 6) the residential sector is a large consumer only in energy terms. In useful exergy terms, the residential sector's share of consumption is much lower, due to the high proportion of low exergy efficiency end uses, such as low temperature heating and cooling. Transport is the third largest energy-consuming sector, significant at both the final and useful stages. However, in useful energy terms (as there are no losses from energy to exergy for propulsion), the relative share of transport is lower in energy compared to exergy terms (bottom row of figure 6).

Third, figure 7 shows useful stage energy and exergy consumption by useful energy product in absolute terms and as shares of the total in each year. Figure 7 contains some of the most novel results reported herein. For example, low-temperature heating and cooling are significant in terms of their share of useful energy (on average 43% across 1971–2020), but, due to very low (typically 5%–10%) FU exergy efficiencies ($\eta_{\text{fu,X}}$), their contribution to total useful exergy is small (on average 5.5% across 1971–2020). On the other hand, shares of useful exergy are higher for medium and high temperature heating (typically in industry, on average 36% across 1971–2020) and propulsion (for transport modes, on average 28% across 1971–2020), due to much higher (typically 30%–40%) FU exergy efficiencies ($\eta_{\text{fu,X}}$).

Next, we summarize the relative roles and contributions of IEA versus muscle work energy at primary, final, and useful stages in two figures. Figure 8 shows the primary, final, and useful energy and exergy aggregate totals to allow comparison. Figure 9 shows the fraction of muscle work inputs and outputs relative to total energy and exergy (i.e. IEA plus muscle work) at the primary, final, and useful stages. In figure 8, we see that muscle work inputs are relatively small, compared to IEA-based energy, and declining. In figure 9, we see that gross energy shares of muscle work at primary and final stages have declined from 9.1% and 5.6%, respectively, in 1971 to 3.4% and 2.4%, respectively, in 2020. Gross exergy shares at primary and final stages have declined from 8.6% and 5.3%, respectively, in 1971 to 3.2% and 2.3%, respectively, in 2020. The share of muscle work energy and exergy becomes progressively smaller with both time and as we move through the ECC, due to lower conversion efficiencies for muscle work compared to fossil fuels between primary and final stages ($\eta_{\text{pf,MW}} \approx 50\%$, $\eta_{\text{pf,FF}} \approx 70\%$) and between final and useful stages ($\eta_{\text{fu,MW}} \approx 10\%$, $\eta_{\text{fu,FF}} \approx 20\%$).

3.2. Aggregate world-level energy and exergy efficiency

Figure 10 shows world efficiencies split by IEA, muscle work, and both (the sum of IEA and muscle work). The 'IEA' and 'IEA + MW' efficiencies are virtually identical, because world muscle work energy and exergy inputs are small (figure 8), meaning that muscle work efficiency has little effect on overall efficiency. In fact, the muscle work efficiencies are very stable, as expected. Animal and human biology has changed little in the last 50 years. Muscle work efficiencies are identical for energy and exergy, as the useful-stage energy is

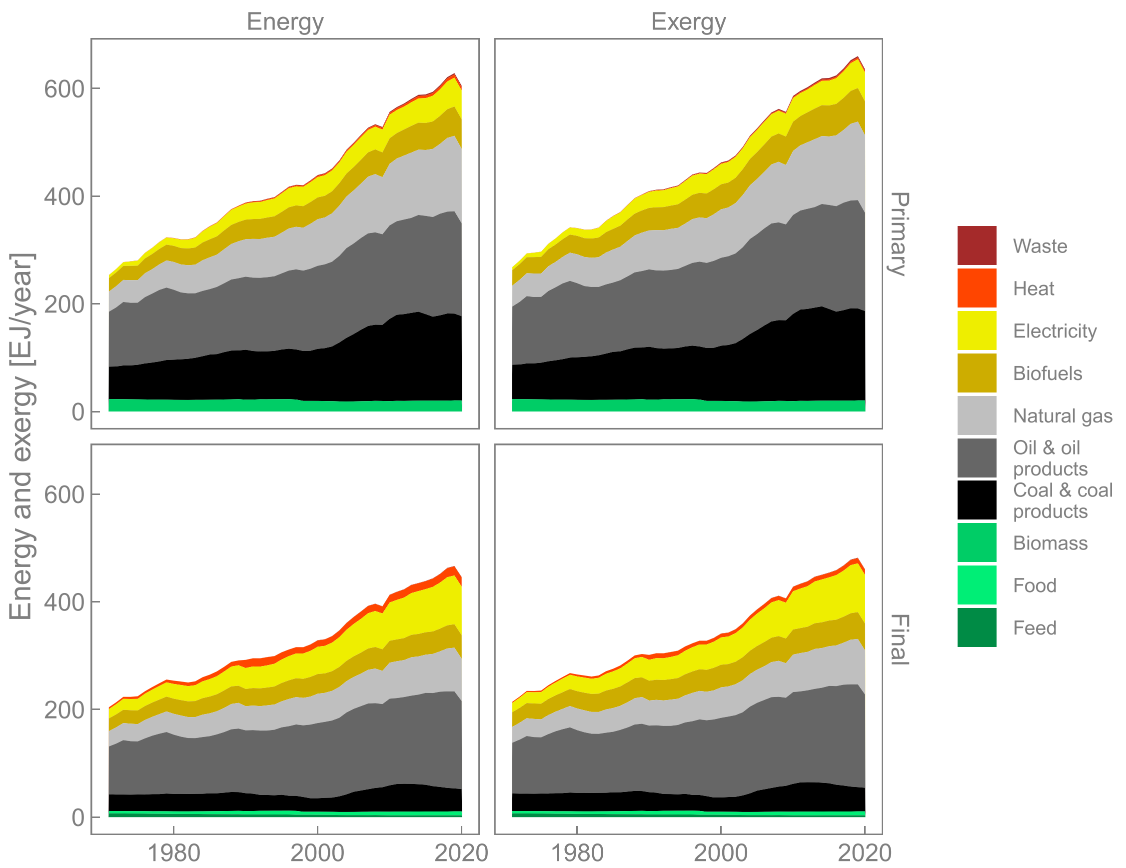

Figure 5. World gross primary and final energy and exergy consumption by energy product group. Non-energy uses are included.

mechanical work. Primary-to-final efficiencies (η_{pf}) for muscle work are around 50%, where $1 - \eta_{pf}$ indicates the combined field-to-mouth losses for food and feed. The average FU efficiency for muscle work ($\eta_{fu,MW}$) across 1971–2020 is 6.5% which, as expected, matches Steenwyk *et al* (2022), whose approach we followed. Our estimate of $\eta_{fu,MW}$ is also between previous estimates of 4% (Smil 1994) and 13% (Ayres and Warr 2010).

Notably world primary-to-final efficiency (η_{pf}) is decreasing (in both energy and exergy terms), due mainly to the growth in fossil-fuel-based electricity consumption worldwide, which has a much lower primary-to-final efficiency (typically 35%–40%). Table 4 and figure 10 show that gross FU energy efficiency ($\eta_{fu,E}$) for the sum of IEA and muscle work has increased from 37% (in 1971) to 65% (in 2020), and gross FU exergy efficiency ($\eta_{fu,X}$) for the sum of IEA and muscle work has grown from 15% (in 1971) to 23% (in 2020). These gains in η_{fu} are likely due to the growth in share of electricity use, because electricity end-uses tend to have higher efficiency, i.e. conversion losses occur between the primary and final stages, compared to non-electricity fossil fuels, where the losses mainly occur between the final and useful stages, as shown in figure 1. The growing proportion of low-temperature heating and cooling (see figure 7) means that growth of FU exergy efficiency ($\eta_{fu,X}$) is slower than growth in FU energy efficiency ($\eta_{fu,E}$).

Second, figure 11 shows the world-level FU (η_{fu}) efficiencies by sector. Industry is seen as a higher-than-world-average efficiency sector in both energy and exergy terms, due to its high efficiency processes, which operate at high temperatures (thus with smaller Carnot exergy penalties). Residential and commercial and public services sectors also have higher-than-world-average energy efficiencies ($\eta_{fu,E}$), due to their high share of low temperature heating and cooling, which have high energy efficiencies (η_E). However, these same technologies also have low exergy efficiencies (η_X), due to high Carnot penalties, which means these same sectors switch from highest efficiencies in energy terms ($\eta_{fu,E}$) to lowest efficiencies in exergy terms ($\eta_{fu,X}$). The banding (around the world average) is also seen to be much tighter at a sector level in exergy terms than energy terms, as shown in figure 11.

Third, figure 12 shows efficiencies for all continents and the world. We see that continent-level efficiencies have a wide range of values either side of world average efficiencies. High shares of fossil fuel based electricity (with low primary-to-final efficiency) is a key drag on primary-to-final efficiencies, which largely affects all

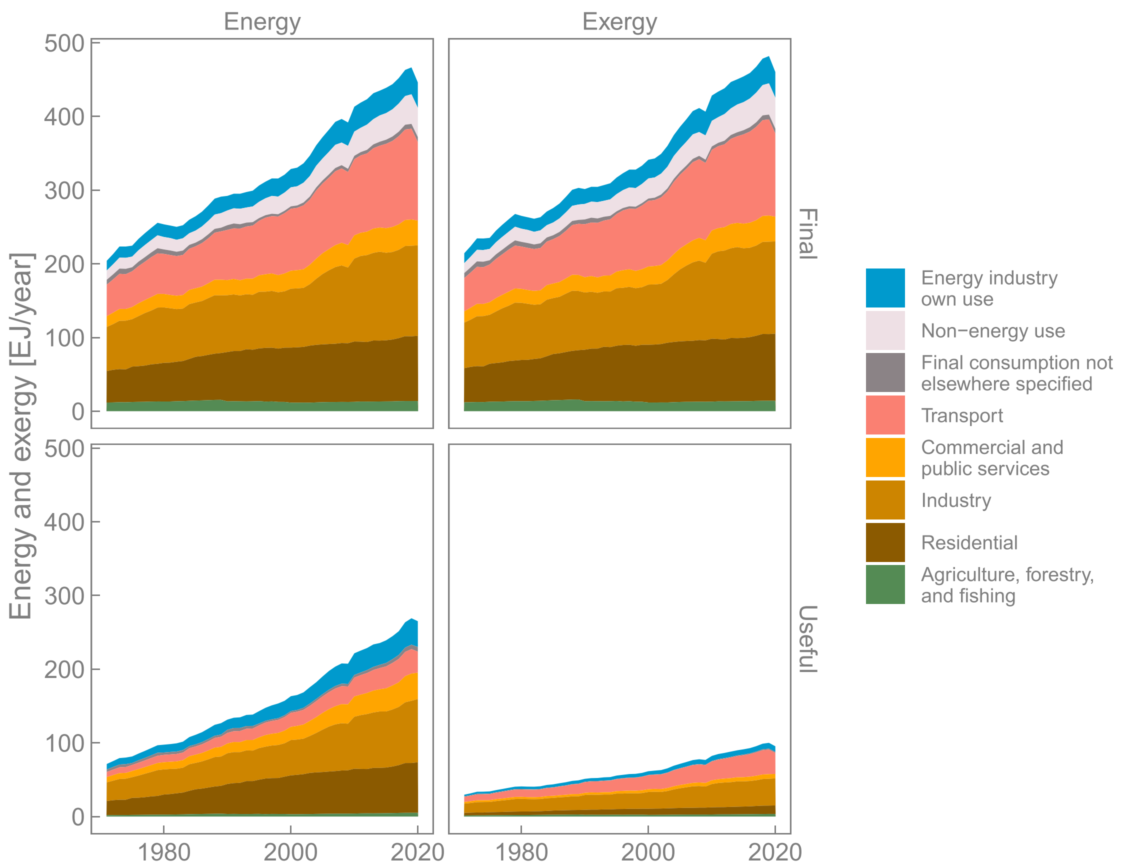

Figure 6. World gross final and useful energy and exergy consumption by sector. Non-energy uses are included at the final energy stage.

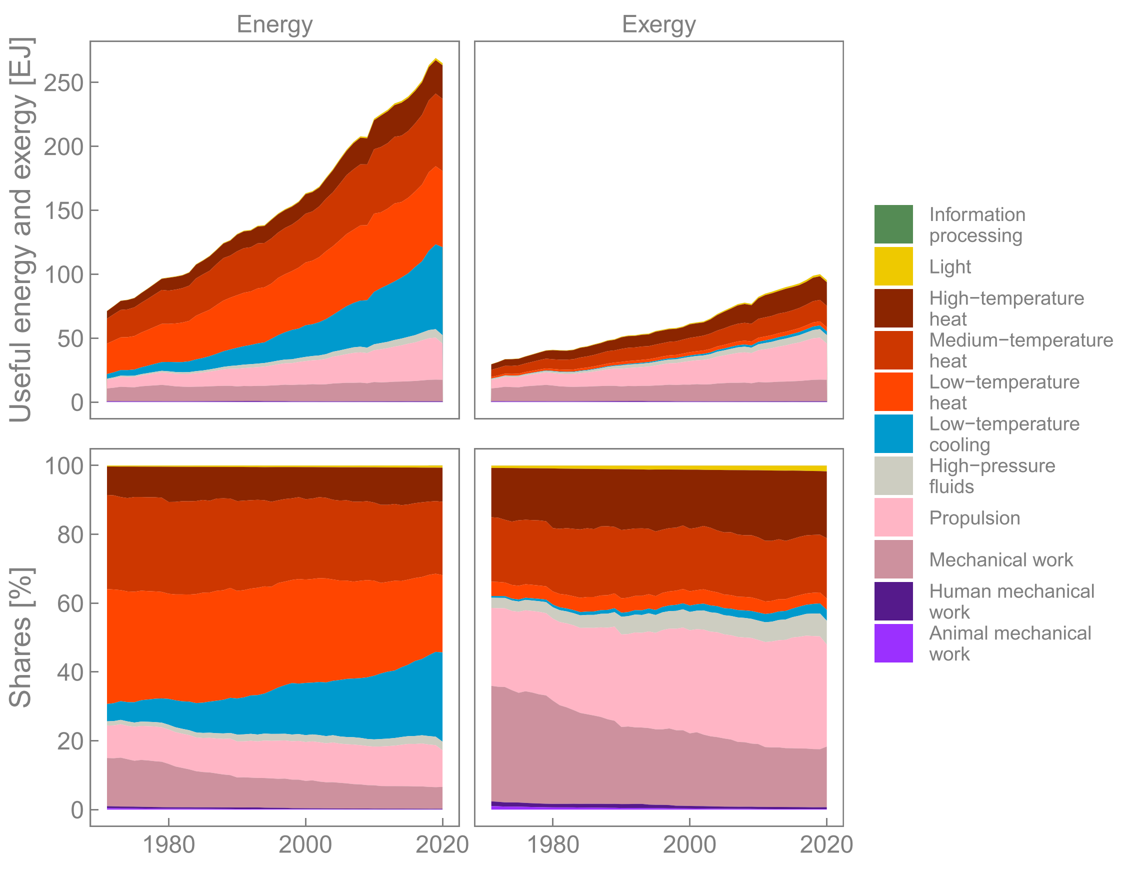

Figure 7. World gross useful energy and exergy consumption and shares by energy product group. Non-energy uses are excluded.

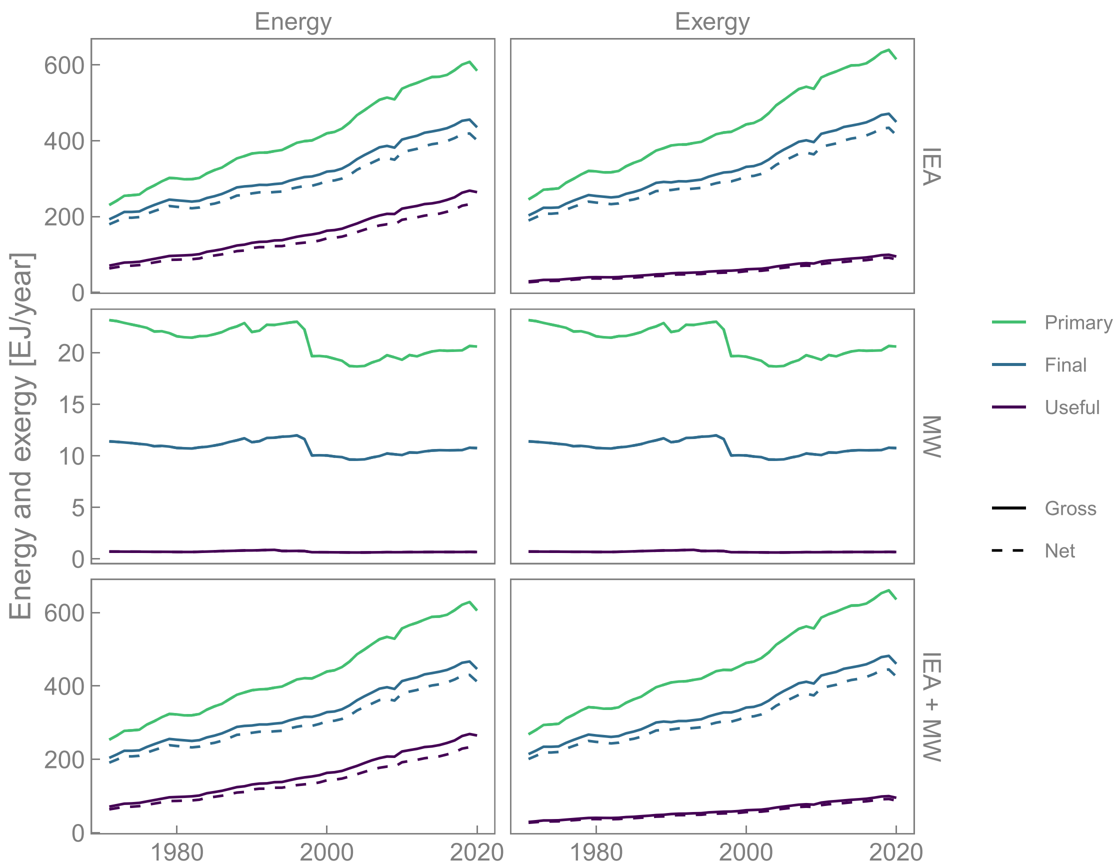

Figure 8. Gross and net world aggregate energy and exergy consumption including both IEA and muscle work (MW) energy data. Note energy and exergy are identical for muscle work, and the scale is different for the muscle work (MW) graphs. Non-energy uses are excluded.

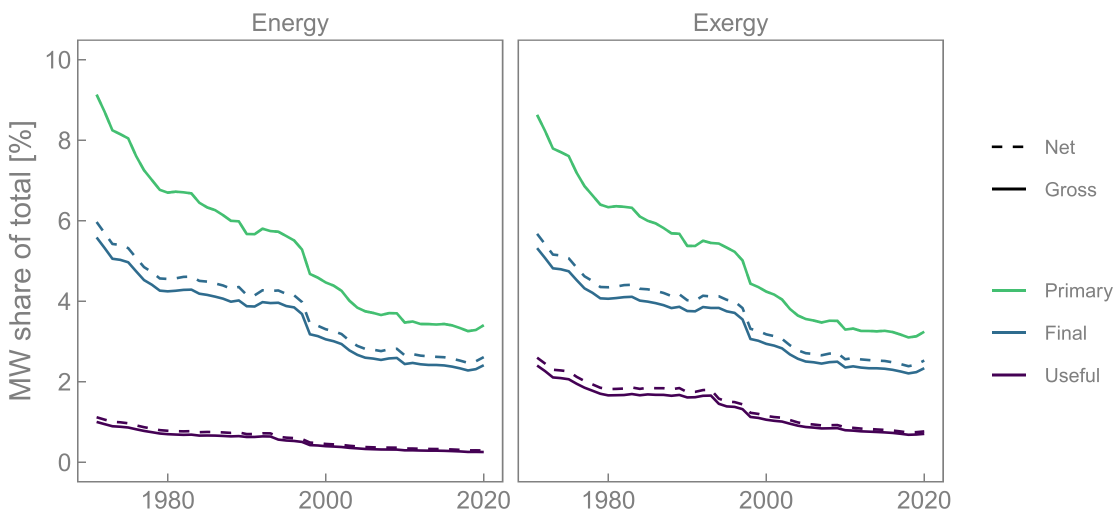

Figure 9. Muscle work share of total (i.e. 'IEA + MW' in figure 8) primary, final, and useful energy and exergy. Non-energy uses are excluded.

continents, except South and Central America (pink line), which has the highest primary-to-final continent efficiency (η_{pf}) but also features the highest use of hydroelectric electricity (with lower conversion losses).

Regarding continental FU energy efficiency (η_{fu}), we see that Europe (dark green line) generally has the highest efficiency, in both energy and exergy terms. A contributing factor is that Europe commonly features the highest FU efficiencies when comparing the same machines between continents (e.g. European light duty vehicles are the most efficient in the world). Africa (orange line) has among the lowest FU exergy efficiencies (η_{fu}). Contributing factors include having often the lowest FU machine efficiencies and higher shares of

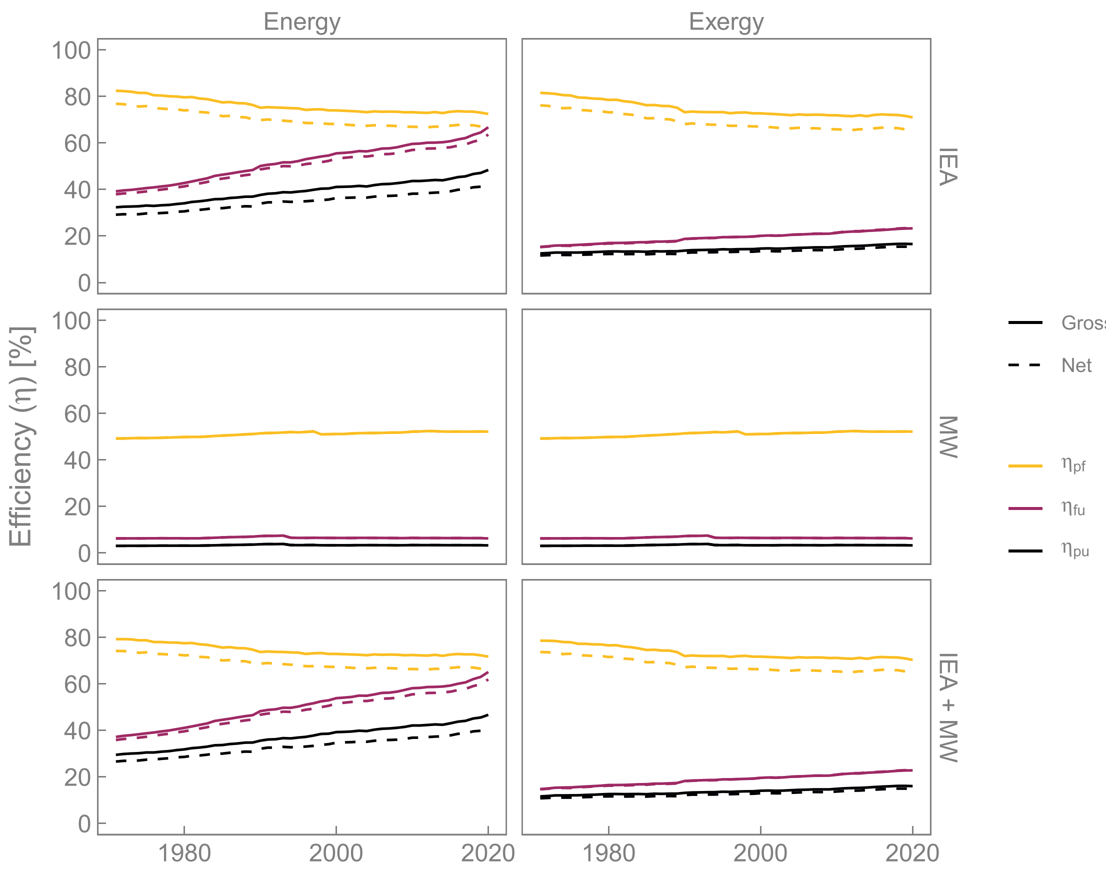

Figure 10. World gross and net aggregate efficiencies including both IEA and muscle work (MW) energy data. Non-energy uses are excluded. η_{pf} is primary-to-final efficiency; η_{fu} is FU efficiency; η_{pu} is primary-to-useful efficiency.

Table 4. Gross world efficiencies including both IEA and muscle work data. Non-energy uses are excluded.

	Energy		Exergy	
	1971	2020	1971	2020
η_{pf}	79%	72%	79%	70%
η_{fu}	37%	65%	15%	23%
η_{pu}	30%	47%	12%	16%

energy carriers (biomass, charcoal, wood, food, and feed) that lead to low efficiency end uses, such as cooking and muscle work.

We also observe in figure 12 that Europe (green line) has a step change in FU efficiency (η_{fu}) in 1990, caused by discontinuities in energy accounting across the dissolution of the Soviet Union and Yugoslavia. For example, the IEA's EWEB data show much higher heat usage in the Former Soviet Union (FSU) countries post-1990 compared to the Soviet Union pre-1990, especially in industry. These FSU heat uses cause a step change in (η_{fu}) for both Europe and the world because heat represents a large share of overall energy consumption and exhibits high energy and exergy efficiencies. (See appendix C for efficiencies of Soviet and Yugoslav states across the 1989–1990 accounting discontinuity.)

4. Discussion

4.1. Overall efficiency trends

First, bringing the aggregate data together in one place, figure 13 shows the primary, final, and useful energy and exergy data in indexed form (1971 = 1.00). As shown in table 5, gross, world-level primary energy and exergy values in 2020 are, on average, 2.33 × 1971 values, whilst world-level final energy and exergy values are, on average, 2.10 × 1971 values, corresponding to average annual growth rates of 1.71% yr^{-1} and 1.49% yr^{-1}, respectively. However, gross, world-level, useful stage energy and exergy have grown faster, increasing by 3.46 × in the same period, averaged between energy and exergy, corresponding to an average annual growth rate of 2.51% yr^{-1} (again, averaged between energy and exergy).

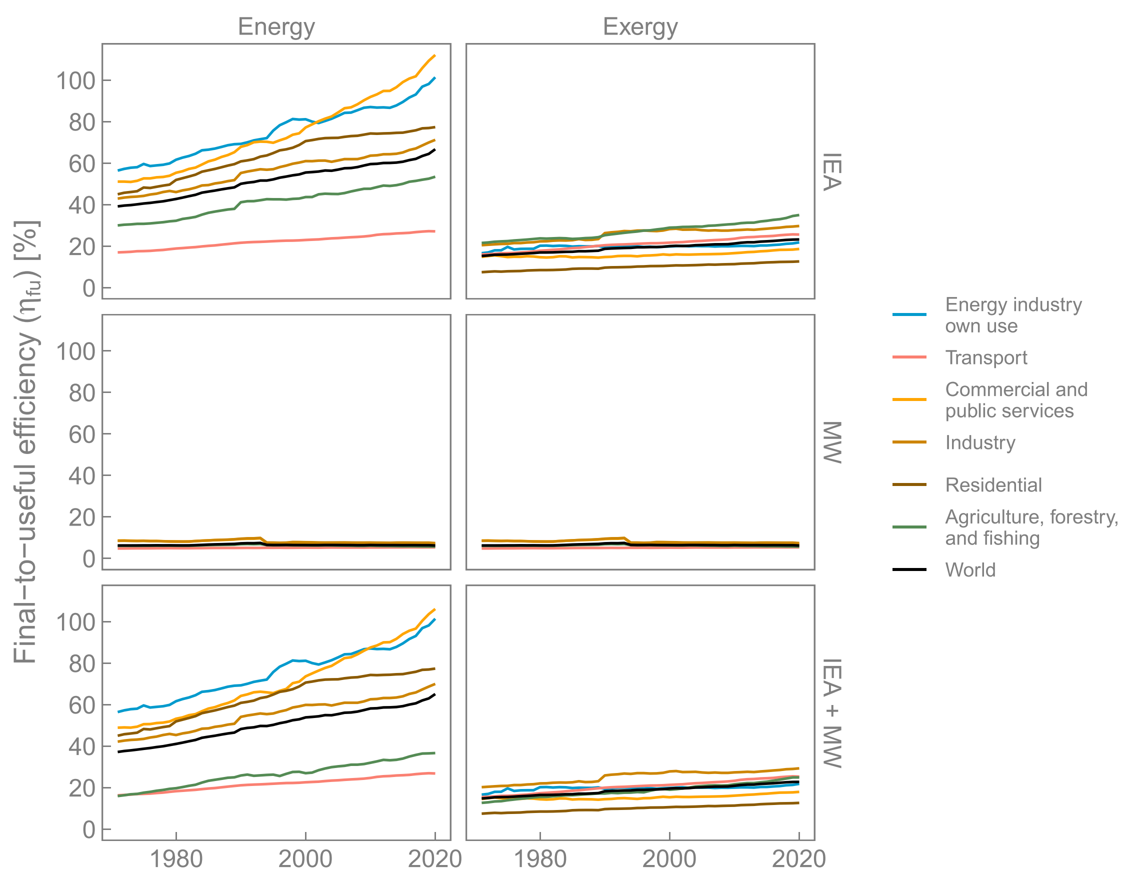

Figure 11. World gross FU efficiency (η_{fu}) by sector. Non-energy uses are excluded.

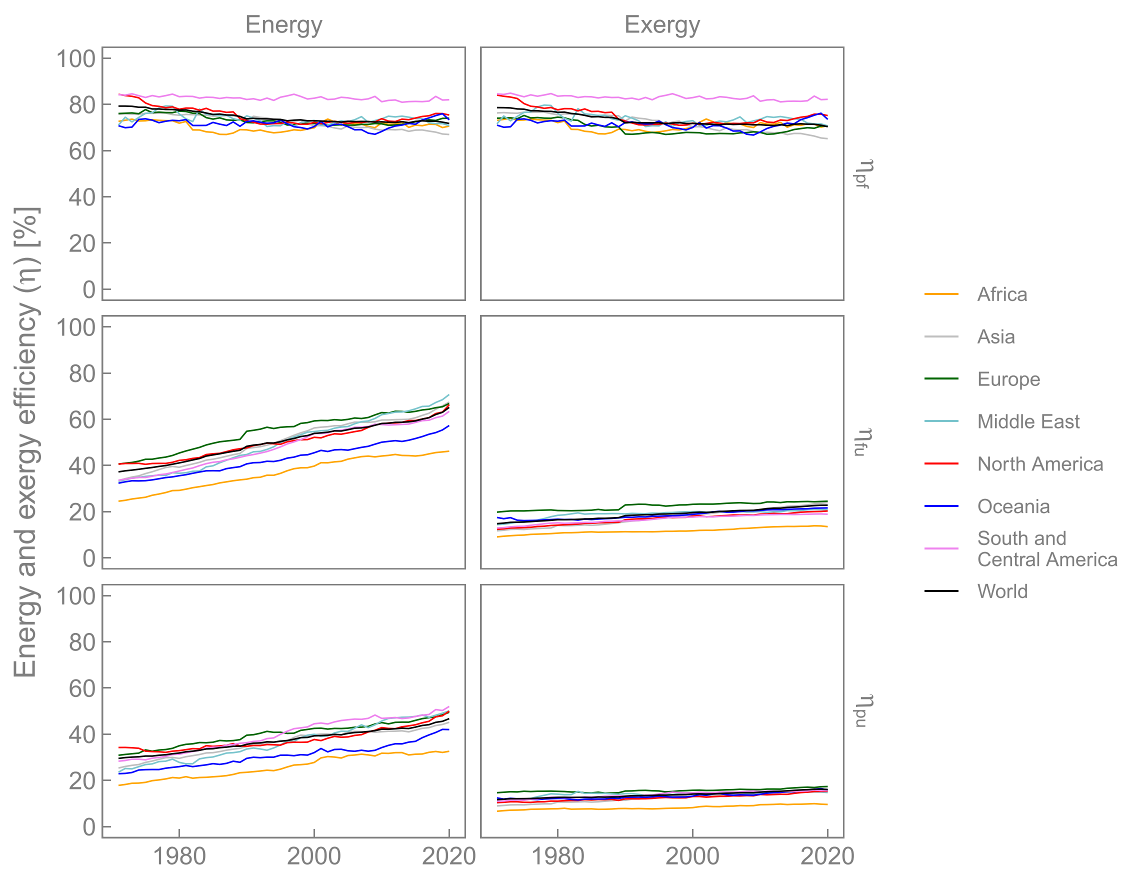

Figure 12. Gross aggregate efficiencies by continent including both IEA and muscle work energy data (IEA + MW). Non-energy uses are excluded.

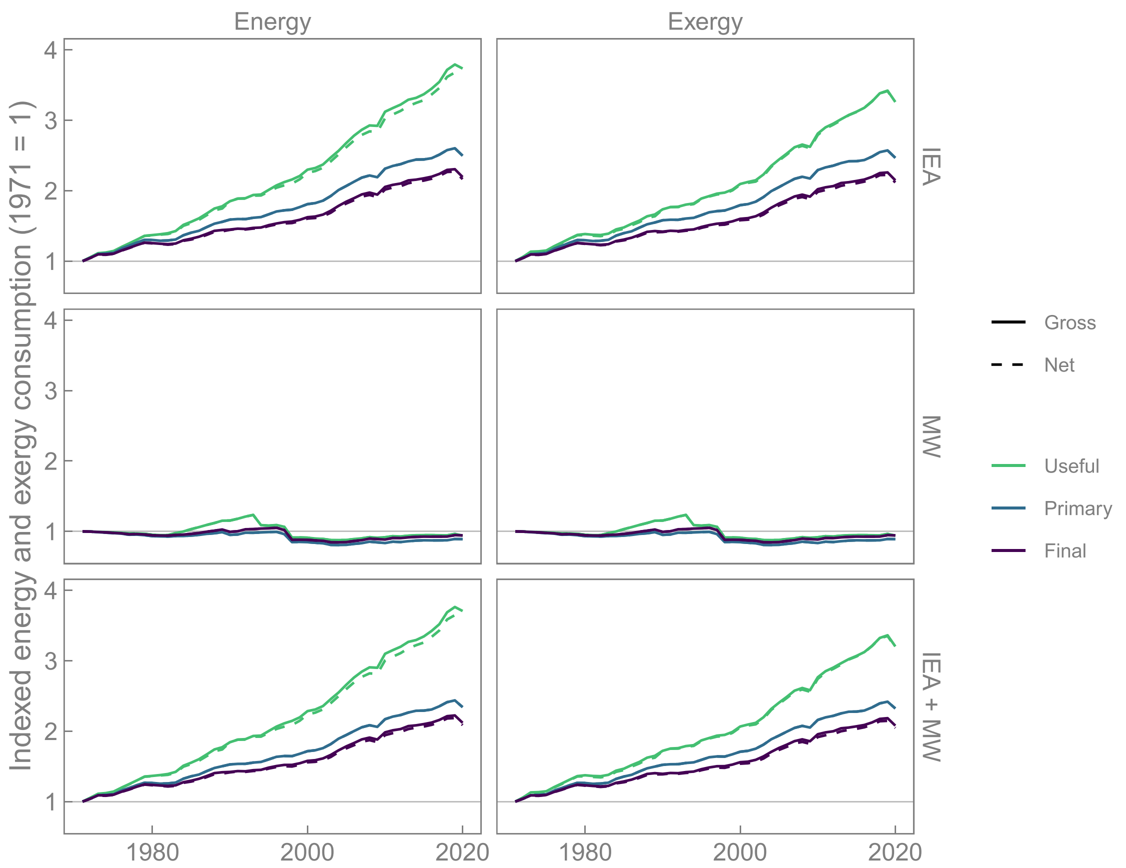

Figure 13. Indexed world primary, final, and useful energy and exergy consumption from figure 8. Non-energy uses are excluded.

Table 5. Gross world primary, final, and useful energy and exergy growth metrics. Both IEA and muscle work data are included. Non-energy uses are excluded.

	Value in 2020 relative to 1971		Annual average growth rate (%/year)	
	Energy	Exergy	Energy	Exergy
Primary	2.34 ×	2.32 ×	1.72	1.70
Final	2.12 ×	2.08 ×	1.51	1.47
Useful	3.71 ×	3.20 ×	2.66	2.36

Second, the average annual percentage growth rates of primary-to-final, FU, and primary-to-useful efficiency ($r_{\eta_{pf}}$, $r_{\eta_{fu}}$, and $r_{\eta_{pu}}$, respectively) are shown in figure 14. We make the following points in observation:

(1) Single year values of annual percentage rate of change of primary-to-final efficiency ($r_{\eta_{pf}}$) are very similar (as expected) in energy and exergy terms, ranging from $-0.95\%\ \text{yr}^{-1}$ to $+0.79\%\ \text{yr}^{-1}$. Across energy and exergy, the average value for $r_{\eta_{pf}}$ is $-0.18\%\ \text{yr}^{-1}$, reflecting the fact that primary-to-final efficiency (η_{pf}) has declined due to the historical expansion of fossil-fuel-based electricity usage, which incurs significant primary-to-final losses.
(2) After tending towards zero, the recent (post-2010) fitted line for η_{pf} has been trending negative. However, the same post-2010 data are noisier (i.e. exhibit larger variations) and include a COVID year, 2020. Therefore it may be unwise to conclude too much from recent trends for η_{pf}.
(3) Single-year annual percentage rates of change of FU efficiency ($r_{\eta_{fu}}$) vary much more, from $-0.11\%\ \text{yr}^{-1}$ to $+3.35\%\ \text{yr}^{-1}$ in energy terms, and $-0.47\%\ \text{yr}^{-1}$ to $+2.24\%\ \text{yr}^{-1}$ in exergy terms. Both have positive average values, of $+1.10\%\ \text{yr}^{-1}$ (energy) and $+0.80\%\ \text{yr}^{-1}$' (exergy), reflecting the fact that FU efficiency (η_{fu}) has increased significantly since 1971.
(4) In energy terms, the fitted line for η_{fu} is trending upward across 2010–2020 for energy but is comparatively flat for exergy. The difference between energy and exergy reflects the growing share of

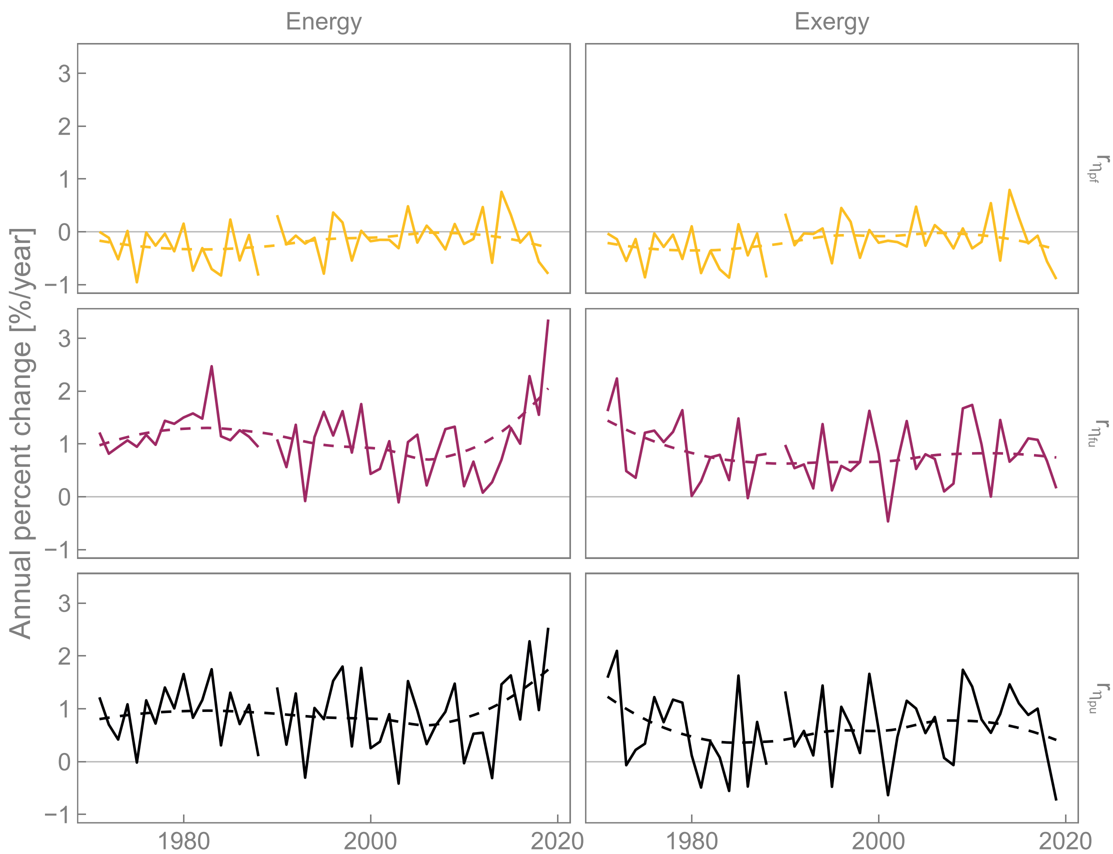

Figure 14. Annual percentage change of gross primary-to-final ($r_{\eta_{pf}}$), gross final-to-useful ($r_{\eta_{fu}}$), and gross primary-to-useful ($r_{\eta_{pu}}$) thermodynamic efficiency shown in the solid lines of the bottom row of figure 10. Both IEA and muscle work are included. Non-energy uses are excluded. The year 1989 (which represents percentage changes from 1989 to 1990) has been removed due to accounting discontinuities caused by the breakup of the Soviet Union. Figure B2 shows the same data with 1989 included.

low-temperature heating and (especially) cooling (e.g. air-conditioning and refrigeration), which have high energy efficiencies ($\eta_{fu,E}$) but low exergy efficiencies ($\eta_{fu,X}$). In addition, the efficiency dilution effect (Williams *et al* 2008), due to the greater use of cooling (with low exergy efficiencies), has a balancing effect on the general increase in FU machine efficiencies ($\eta_{fu,m}$) from technical progress.

(5) Last, the fitted lines for primary-to-useful efficiency growth rate are positive ($r_{\eta_{pu}} > 0$), confirming that overall primary-to-useful efficiency (η_{pu}) has been generally increasing in this period, as the larger, positive growth rates in FU efficiency ($r_{\eta_{fu}}$) have overcome the smaller, negative growth rates in primary-to-final efficiency ($r_{\eta_{pf}}$). Recent trends in the growth rate of primary-to-useful efficiency ($r_{\eta_{pu}}$) in energy and exergy terms essentially follow the trends in FU efficiency growth rate ($r_{\eta_{fu}}$), which exhibit much greater variation than primary-to-final efficiency growth rates ($r_{\eta_{pf}}$).

Looking ahead, as we switch to greater consumption of renewables-based electricity (for which there are no efficiency losses between primary and final energy stages), we expect primary-to-final efficiency (η_{pf}) to increase in both energy and exergy terms, in which case $r_{\eta_{pf}}$ may turn positive. In parallel, increased electrification of major end use technologies such as electric vehicles, which have much higher machine efficiencies (η_m) than their fossil fuel based predecessors, should continue the growth in FU efficiency (η_{fu}), at least in energy terms. In exergy terms, the picture is more nuanced, as future growth rates depend on the relative growth of low (e.g. air conditioning) versus high (e.g. electric vehicles) exergy efficiency electricity-based FU machines.

4.2. Comparison to other world-level PFU studies

We know of three other world-level PFU studies (Nakićenović *et al* 1996, Cullen and Allwood 2010, De Stercke 2014). Before comparing results quantitatively below, we first compare features of the CL-PFU database and previous global studies. (See table 6.) The comparison indicates that the CL-PFU database provides the most comprehensive energy and exergy dataset yet assembled.

Next, we compare the CL-PFU database against other PFU world-level studies in terms of FU energy and exergy efficiencies ($\eta_{fu,E}$ and $\eta_{fu,X}$). Figure 15 compares our FU energy and exergy efficiencies ($\eta_{fu,E}$ and $\eta_{fu,X}$)

Table 6. Comparison of existing world-level PFU datasets.

	Nakićenović *et al* (1996)	Cullen and Allwood (2010)	De Stercke (2014)	CL-PFU database (2023)
PFU energy coverage	◕	●	●	●
PFU exergy coverage	●	●	●	●
World aggregation	●	●	●	●
Region aggregation	◑	○	◕	●
Country coverage	○	○	◑	●
Sector coverage	◑	◑	◕	●
End-use coverage	◔	◔	◑	●
Non-energy inclusion in PFU stages	◕	○	●	●
Non-energy exclusion in PFU stages	◕	◔	○	●
EIOU inclusion in FU stages	○	○	○	●
EIOU exclusion in FU stages	●	●	●	●
Time-series coverage (1960–2020)	○	○	●	●
Muscle work inclusion	○	○	○	●

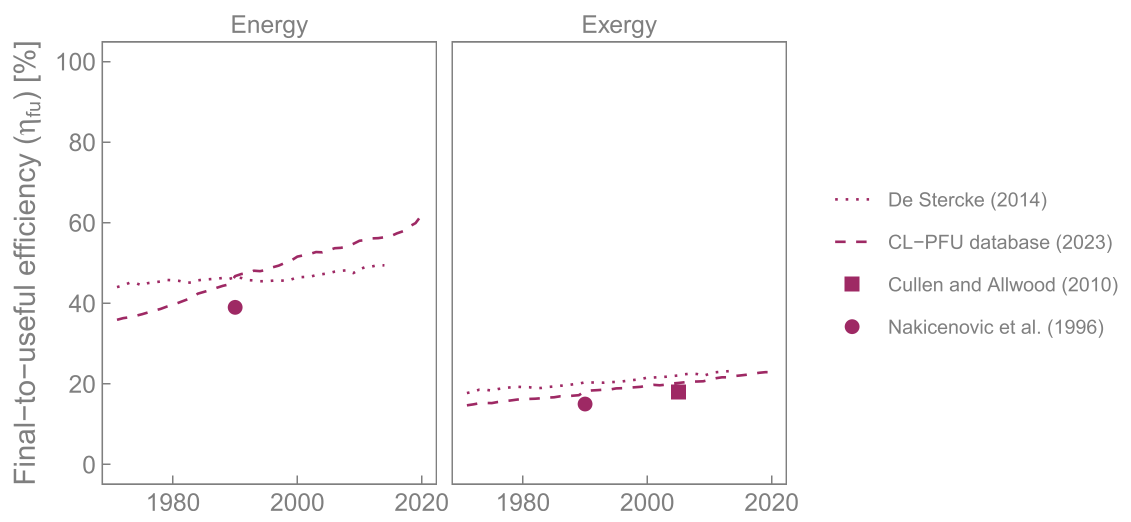

Figure 15. Comparison of world net FU energy and exergy efficiency (η_{fu}) among Nakićenović *et al* (1996), Cullen and Allwood (2010), De Stercke (2014), and the CL-PFU database (2023). Non-energy uses are excluded.

with comparable estimates found in the three other global PFU studies (Nakićenović *et al* 1996, Cullen and Allwood 2010, De Stercke 2014). We see that the CL-PFU database FU efficiencies ($\eta_{fu,E}$ and $\eta_{fu,X}$) are in a similar range of values to other published estimates.

Considering energy efficiency ($\eta_{fu,E}$), our comparable value in 1990 to Nakićenović *et al* (1996) is higher (48% versus 39%). A contributing factor is our higher transport efficiencies for diesel/gasoline road vehicles (15%–20% versus 10%–12%). Considering exergy efficiency ($\eta_{fu,X}$), our comparable efficiency values are larger in 1990 compared to Nakićenović *et al* (1996) (19% versus 15%) and in 2005 compared to Cullen and Allwood (2010) (20% versus 18%). Our higher transport efficiencies are again one cause.

Comparing with De Stercke (2014), the only other multi-year study, we find that our aggregate primary and final energy values are quite similar, as expected, given that both rely largely on IEA primary and final energy data. There are a few differences, such as we include food and feed (for muscle work), but our primary and final energy (and exergy) results compared to De Stercke (2014) are very similar.

Moving to the useful stage, we have notable differences in FU energy efficiency ($\eta_{fu,E}$), but not in FU exergy efficiency ($\eta_{fu,X}$), as shown in figure 15. Considering FU exergy efficiency ($\eta_{fu,X}$), we find the CL-PFU database efficiencies are very similar to De Stercke (2014), with our values lower in 1971 (15% versus 17%) and even closer in 2010 (21% versus 22%). We have similar shares of major energy conversion machines, i.e. heating, cooling, and internal combustion engines, and broadly similar FU exergy efficiencies compared to De Stercke. Thus, overall FU exergy efficiency values and trends are similar between the two databases.

However, for FU energy efficiency ($\eta_{fu,E}$), the trends are very different: our values start lower in 1971 (37% versus 44%), but finish higher in 2010 (58% versus 48%). We should expect some differences, given that we have many more FU machines (85 versus 7 for De Stercke). However, the main reason seems to be that the CL-PFU database includes low-temperature cooling, which has very high associated energy

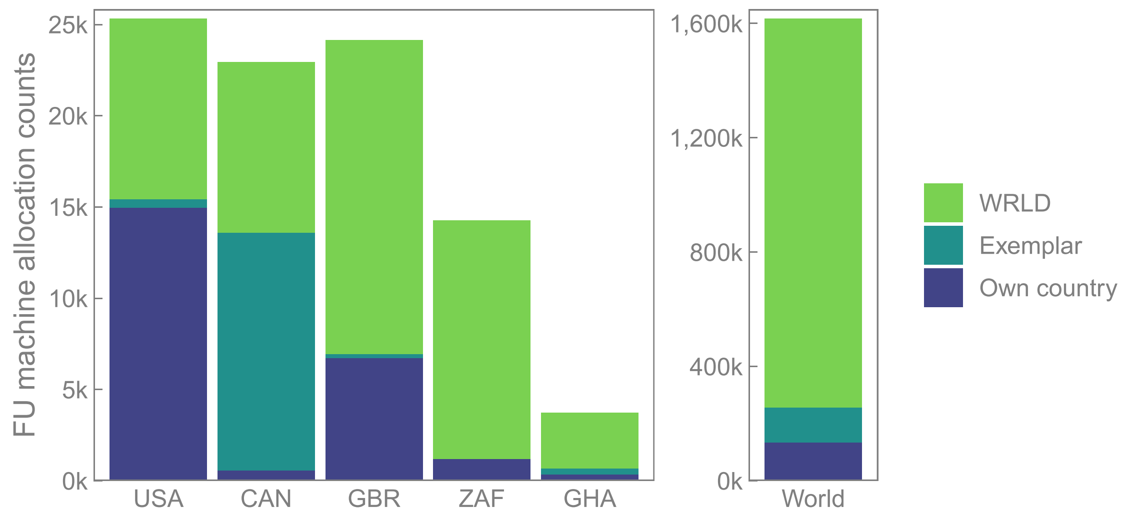

Figure 16. Final-to-useful (FU) machine allocation counts for selected countries (USA, Canada, Great Britain, South Africa, and Ghana) and the World. 'World' is the sum of all countries in the CL-PFU database. 'WRLD' is a 'country' with all possible FU machine allocations, which provides fallback allocations when own-country and exemplar country allocations are unavailable. Note different vertical scales for countries and the World.

efficiencies (with coefficient of performance now typically over 300% (International Energy Agency 2020a)), while De Stercke does not. Although we have similar sums for low-temperature end uses compared to De Stercke, low-temperature end uses in the CL-PFU database are split between heating and cooling (see figure 7), whereas all of De Stercke's low-temperature end uses are assigned to heating, being one of the 7 end uses shown in De Stercke (2014), figure 14. Thus, as the share of energy consumption for low-temperature cooling grows over the period covered by the database, our FU energy efficiencies ($\eta_{\text{fu,E}}$) rise comparatively faster than De Stercke's. (Also note that the exergy efficiencies of low-temperature heating and cooling are both similarly low, leading to smaller differences in the exergy comparison with De Stercke relative to the energy comparison with De Stercke in figure 15.)

4.3. Data limitations

There are four main data limitations to the CL-PFU database. The first is the IEA energy data itself, which is a core input data resource. The IEA data availability can be patchy, especially in the early years of countries or new energy fuels or uses. We use the IEA data as downloaded, only making rare adjustments, where clear and obvious errors are observed. (See appendix A for details.) Note, though, that we do not inter/extrapolate IEA data for countries and years for which the IEA does not report data. The IEA data also undergo rare but abrupt shifts, for example when energy previously unassigned (called 'not elsewhere specified') becomes assigned to a known sector or when countries split (such as the Soviet Union and Yugoslavia), where we find differences in total and sectoral energy use. Limitations notwithstanding, the IEA's EWEB data are the most comprehensive primary and final energy datasets available in terms of country coverage, sectoral granularity, and timescale.

The second limitation is the FU machine allocations, which can be based on few studies for a given sector and country. We have data for own-country allocations from 24 countries, which we believe to be the most ever assembled for a single dataset. For countries without own-country allocations, we apply the exemplar system (section 2.1.5) in which FU machine allocations from an exemplar country, region, or the world are applied.

To illustrate, figure 16 shows coverage of FU machine allocations for five sample countries and the world. Coverage is quantified by counts of FU machine allocations in which a single allocation is a fraction of a final energy flow assigned to a single FU machine in either a sector (in the **Y** matrix) or an energy producing industry (in the $\mathbf{U}_{\text{EIOU}}$ matrix). There are over 1.6 million allocations across all countries and years in the CL-PFU database. Figure 16 shows that the USA and Great Britain (GBR) have good own-country coverage, while Canada (CAN) draws heavily from its exemplar (USA). South Africa (ZAF) has some own-country allocations but relies mainly on WRLD. Similarly, Ghana (GHA) relies mainly on WRLD but picks up some allocations from its exemplar, South Africa. FU machine allocations for the sum of all countries (World) are supplied mainly by the WRLD 'country,' due to more countries being similar to Ghana and South Africa than to the USA and Canada. (Note: this simple data coverage metric could be enhanced in future work by weighting according to the magnitude of each energy flow. All counts in figure 16 are equal across all countries such that, e.g. annual electricity consumption has the same weight for the USA and Ghana.)

The third limitation relates to the 83 FU (non-muscle work) machine efficiencies, which are based on an extensive set of scientific papers and reports. We believe we have collected one of the most (if not *the* most) comprehensive dataset of FU machine efficiencies, as seen in the SI. However, limitations exist. For example, industrial sub-sector efficiencies (such as the chemical sector) are based on the assessed efficiency of one typical energy conversion machine. In another limitation, to avoid numerical instabilities of matrix inversion during upstream swims, we set minimum values of FU efficiency (η_{fu}) for certain FU machines. An example is computer efficiency which is set to 0.1%.

Fourth are the limitations surrounding muscle work calculations. Available data on draft animals and manual human labour is not complete. Estimations were required, e.g. in the split of human labour working on manual tasks in each sector (e.g. industry, agriculture, services, mining). We also assumed that manual workers were working at an average activity and power level, for all working hours in the day, which may be an overestimate of work, given the need for rest breaks and other non-work activities.

Whilst a sensitivity analysis is beyond the scope of this current paper and database version, it is helpful to consider the relative scale of potential effects of the limitations discussed above, as this helps prioritise future improvements. From the list above, the largest expected impact relates to missing FU machine allocations (second limitation) and associated FU machine efficiencies (third limitation). Also, allocations and efficiencies are least well known in industry sectors, so improvements to such data will have the largest effects. Next, though muscle work is small at the world level, for some lower-income countries it is more likely to provide a large percentage of aggregate primary, final, and useful energy and exergy. Therefore, improvements to muscle work, including filling any missing data (fourth limitation), could affect results for some countries, even if not at a global level. Last, changes to IEA input data (first limitation) would be expected to make the least impact on overall results, as the data are quite robust, except for a few known cases of accounting discontinuities around the dissolution of countries, such as the Soviet Union and Yugoslavia.

Overall, even if we were to obtain all missing data, such as to fix all data limitations, it seems unlikely there would be substantial impacts on the CL-PFU results, at least at the aggregate global level. The reasons for this are three-fold. First, the primary and final energy IEA EWEB data, which forms the bulk of the primary and final energy data, is well-established, so not much would change for overall primary and final energy and exergy data. Second, despite our CL-PFU database having the most comprehensive set yet assembled of FU allocation and efficiency data, our overall FU efficiency values are in similar ranges to previous global estimates from Nakićenović *et al* (1996), Cullen and Allwood (2010), and De Stercke (2014). The relative closeness of aggregate global FU efficiencies and growth trends suggests we have similar allocations and efficiencies for key sectors and end uses, which is supported by the close comparison in section 4.2. Third, following on, the granularity of the CL-PFU database means we have 83 non-muscle work machines covering end uses of energy. Thus if any of those FU machine efficiencies were in serious error, it would not affect the overall global FU efficiencies greatly. There is robustness in granularity.

These are reasonable statements of uncertainty and impact at a global level and for large energy consuming countries and regions (e.g. USA, China, EU-28) where comprehensive data on allocations and efficiencies are available. It is therefore at a country level, when countries are lacking (especially) own FU machine allocations and efficiencies where the issues described above could lead to substantial impacts on country-level results.

4.4. CL-PFU database improvements

The CL-PFU database can, of course, be improved in future versions. We list suggestions on four topics, based on the discussion of limitations in the previous section.

First, for IEA-based energy input data (see section 2.1) additional FU machine allocations and efficiencies for more end uses, machines, sectors, and countries will be beneficial. The goal is to reduce the number of countries that require exemplars. It will also be beneficial to have additional temperatures for specific uses of heat to improve ϕ coefficients, particularly in industry.

Second, for muscle work data, we can implement an exemplar system for muscle work allocations, to better fill gaps in muscle work sectors. For example, we could fill missing human manual workers via known fractions of working age population from exemplar countries. Furthermore, we could more closely link muscle work to the agriculture, forestry, and fishing sectors in the IEA data, to provide a better estimate of muscle work contributions in those sectors.

Third, to guide future improvements, the data coverage analysis (section 4.3) can be further developed to assist prioritisation among sector allocations, countries, and machine efficiencies to deliver the greatest gains in energy coverage.

Finally, the development of a formal uncertainty assessment would be beneficial, for example a semi-quantitative evaluation via a pedigree-matrix approach, such as proposed by Laner *et al* (2015).

4.5. Future applications

We have demonstrated that the CL-PFU database can be used to estimate world-level PFU energy and exergy use and efficiencies. However, the CL-PFU database is suitable for a wide range of additional applications and research areas.

First, it was necessary for this current paper, due to space constraints, to provide mainly global results. But the opportunity is present for future research to study energy use and efficiency at sector, country (e.g. see the country-level plots of figures 12 and C1), or end-use levels, expanding on the SEA studies completed to date.

Second, the CL-PFU database provides the opportunity for energy and exergy-based decomposition studies (e.g. Serrenho *et al* (2014)) which will benefit from the granular energy and exergy data now available.

Third, research communities beyond SEA could see benefits from using the primary, final, useful, and efficiency data of the CL-PFU database in energy-economy studies and models. Two examples are (a) Integrated Assessment Models (e.g. Messner and Schrattenholzer (2000)) that use FU data for future projections of energy service demands and (b) MRIO models (such as EORA and EXIOBASE) which could use their trade matrices to produce consumption-based PFU energy and exergy accounts for all countries. In economics, the CL-PFU database could be used to study energy intensity and energy productivity at primary, final, and useful stages with comparison to UN Sustainable Development Goals targets. (See Heun and Brockway (2019).)

Finally, future studies could use CL-PFU database information to examine issues about the coming energy transition such as the shift to a largely electrified world, which will feature abrupt increases in FU energy efficiency (Eyre 2021) and possibly associated large rebound effects.

5. Conclusion

This paper (a) describes the process we used to create the CL-PFU database, (b) describes the database itself, and (c) presents, for the first time, world-level results for 1971–2020 derived from the CL-PFU database. Only one such multi-country database has been attempted before (De Stercke 2014). Our database provides much improved granularity in terms of coverage of countries (152 and 3 rest-of-world regions), sectors (7 aggregate and 46 detailed), 68 final energy products, and 85 FU energy conversion machines. The computational environment and PSUT analysis framework (outlined in section 2.5) both enables the creation of the global CL-PFU database and facilitates future improvements.

The world-level results provide new insights to global PFU energy conversion over the period 1971–2020.

(1) PFU energy results: Overall, we find a much larger gains in useful energy to 2020 (3.71×1971 value) and useful exergy (3.20×1971 value) than at primary energy (2.33×1971 value) or final energy (2.10×1971 value) stages. Muscle work contributions are small ($< 10\%$) and decline from primary to useful stages. Industry is a high consumer of both useful energy and exergy, whilst the residential and commercial and public services sectors move from a high share of useful energy to a low share of useful exergy, due to large usage of low temperature heating and cooling, which has high energy but low exergy efficiency.

(2) Global PFU energy conversion efficiency trends: Gross primary-to-final efficiency ($\eta_{\mathrm{pf,E}}$ and $\eta_{\mathrm{pf,X}}$) for total energy consumed (IEA plus muscle work) exhibit a long-term steady decline from 1971 to 2020 from 79% to 72% for energy and from 79% to 70% for exergy, largely due to the growing share of fossil-fuel-based electricity use within IEA final energy use, which has significant primary-to-final energy losses. In contrast, FU efficiency (η_{fu}) grows significantly in the period covered by the CL-PFU database in both energy (from 37% to 65%) and exergy (from 15% to 23%) terms. Increases to FU machine efficiencies and a growing share of low temperature cooling (with high energy efficiencies) are key reasons.

Looking ahead, we close with two final points. Firstly, researchers are encouraged to contact the authors to suggest or provide open access datasets to improve country-specific coverage of (a) sectoral end use FU machine allocations and (b) FU machine efficiencies. Incorporating additional data will improve future versions of the database for all researchers. Secondly, the development of the open access CL-PFU database provides a basis for many new avenues of research by acting as a focal data source for energy-economy researchers worldwide. It overcomes the previous lack of data, which has for decades served as a barrier to entering the field of SEA. Analyses are now possible for all sectors, energy products, and end uses as well as at country, region, and world levels.

Data availability statement

The IEA EWEB data are not publicly available; the user needs to access IEA data through a valid license. The packages given in table 3 to create the CL-PFU database are available under the MIT open source license on CRAN or GitHub.

The Supplementary Information (SI) is available online and contains:

(a) a summary of the FU machine allocations to end use categories (at the useful energy stage) for the 24 countries with own-country allocations.
(b) a summary of the calculation basis and assumptions used for estimating the final-to-useful efficiencies for the 83 individual FU machines which convert IEA final energy to useful energy products.
(c) the list of over 250 references used to produce the FU machine allocations and associated efficiencies.

There are two associated University of Leeds Data Repositories:

(a) a CL-PFU database v1.2 input data repository, available at https://doi.org/10.5518/1536, with excel files containing concordance mapping (e.g. sectors, energy products and countries), phi constants, and muscle work calculations.
(b) a CL-PFU database v1.2 output data repository, available at https://doi.org/10.5518/1199, with csv files containing primary, final and useful exergy data, at world, country, and sector levels.

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CRediT authorship contribution statement

Author contributions for this paper are shown in table 7.

Table 7. Author contributions following CRediT (contributor roles taxonomy) (NISO 2023).

	P.E.B.	M.K.H.	Z.M.	E.A.	P.S.	T.R.	M.W.	J.K.	A.S.	J.I.
Conceptualization	●	●								
Data curation	●	●	●	●	●	●	●	●	●	●
Formal analysis	●	●	●	●	●					
Funding acquisition	●	●								
Investigation	●	●	●	●	●	●	●	●	●	●
Methodology	●	●	●		●					
Project administration	●	●								
Resources	●	●								
Software		●	●	●						
Supervision	●	●	●							
Validation	●	●	●	●						
Visualization	●	●								
Writing–original draft	●	●	●							
Writing–review & editing	●	●	●	●						

Nomenclature

Nomenclature for this paper is described in tables 8–10.

Table 8. Symbols.

Symbol	Meaning [example units]
η	efficiency [–]
ϕ	exergy-to-energy ratio [–]
r	annual percentage growth rate [%/year]

Table 9. Subscripts.

Subscript	Meaning
E	energy
EIOU	energy industry own use
FF	fossil fuels
f	final stage
feed	pertains to feedstock
fu	between final and useful stages
m	pertains to final-to-useful machines
MW	muscle work
p	primary stage
pf	between primary and final stages
pu	between primary and useful stages
u	useful stage
X	exergy

Table 10. Abbreviations.

Abbreviation	Meaning
CL-PFU	country-level primary, final, and useful
CRAN	comprehensive R archive network
ECC	energy conversion chain
EIOU	energy industry own use
EU	European Union
EWEB	extended world energy balance
FAO	Food and Agriculture Organization
GDP	gross domestic product
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis (Vienna)
ILO	International Labour Organization
MW	muscle work
OECD	Organization for Economic Cooperation and Development
PCM	physical content method
PSM	partial subsitution method
RCM	resource content method
RoW	rest of world
RUVY	resource, use, make, and final demand matrices
SEA	societal exergy analysis
SDG	sustainable development goal
TFP	total factor productivity
UK	United Kingdom
UN	United Nations
USA	United States of America

Appendix A. Adjustments to IEA EWEB data

As discussed in section 4.3, we use the IEA EWEB data without modification, except where obvious errors are observed. We make 6 adjustments to IEA data listed below:

(1) For Columbia's electricity production for the years 1971–1977, we use the 2021 release of the IEA's EWEB data. The 2022 release inadvertantly introduced energy imbalances.

(2) Other Americas charcoal production plants for 1971–2010 produce charcoal without consuming energy, therefore exhibiting infinite efficiency. To rectify, we include upstream primary solid biofuels production and consumption for charcoal production for Other Americas in those years.
(3) We include upstream natural gas production for Other Americas gas works gas production by gas works for 1971–1976 to address the case where its gas works produce gas works gas without consuming any feedstock, therefore exhibiting infinite efficiency.
(4) For 1990–1999, growth in Ghana's primary solid biofuel consumption is smoothed to match survey data for 2000 (Heun and Brockway 2019).
(5) For 1990–1992, Russian and Estonian not elsewhere specified heat is reassigned to industry, residential, commercial and public sector, and agriculture, forestry and fishing sectors. This fix restores the heat that is present in these former Soviet Union Countries after 1993.
(6) From 2013 onward, Australia's blast furnaces are the only consumers of blast furnace gas. Furthermore, starting in 2010, the iron and steel industry consumes no blast furnace gas, in apparent contradiction to the IEA's policies for reporting blast furnace gas consumption. We ensure that Australia's iron and steel industry always consumes blast furnace gas, according to the IEA's assumed efficiency of 40%.

Appendix B. Alternative figures

Figure 12 in section 3.2 shows efficiencies (η_{pf}, η_{fu}, and η_{pu}) for each continent. The continental efficiencies are calculated from aggregated country-level primary, final, and useful energies and exergies. Figure B1 shows individual country efficiencies, coloured by the continents of figure 12.

In section 4.1, figure 14 omits the year 1989. Figure B2 includes the year 1989, showing the size of the discontinuity of the annual percentage rate of change in efficiency (r_η).

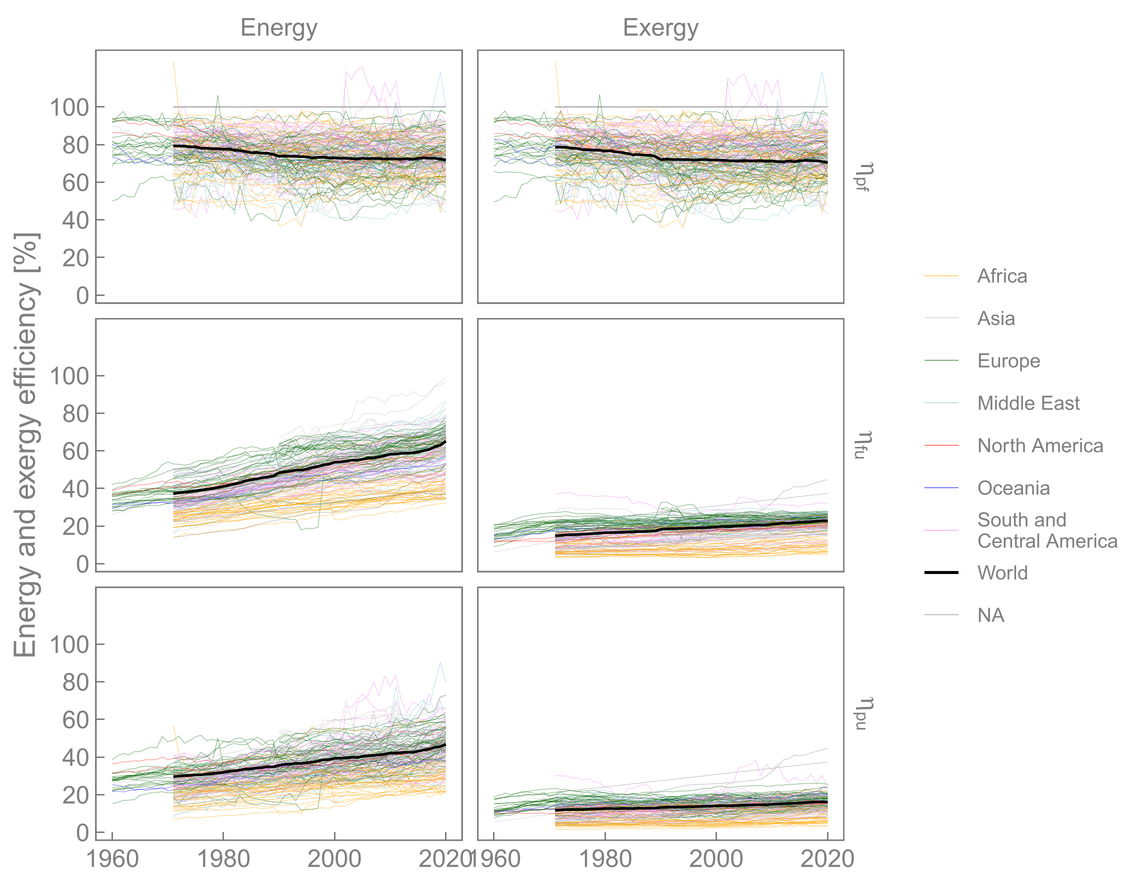

Figure B1. Gross aggregate energy and exergy efficiencies for all countries (colored by continent) and World (black) including both IEA and muscle work information. Non-energy uses are excluded.

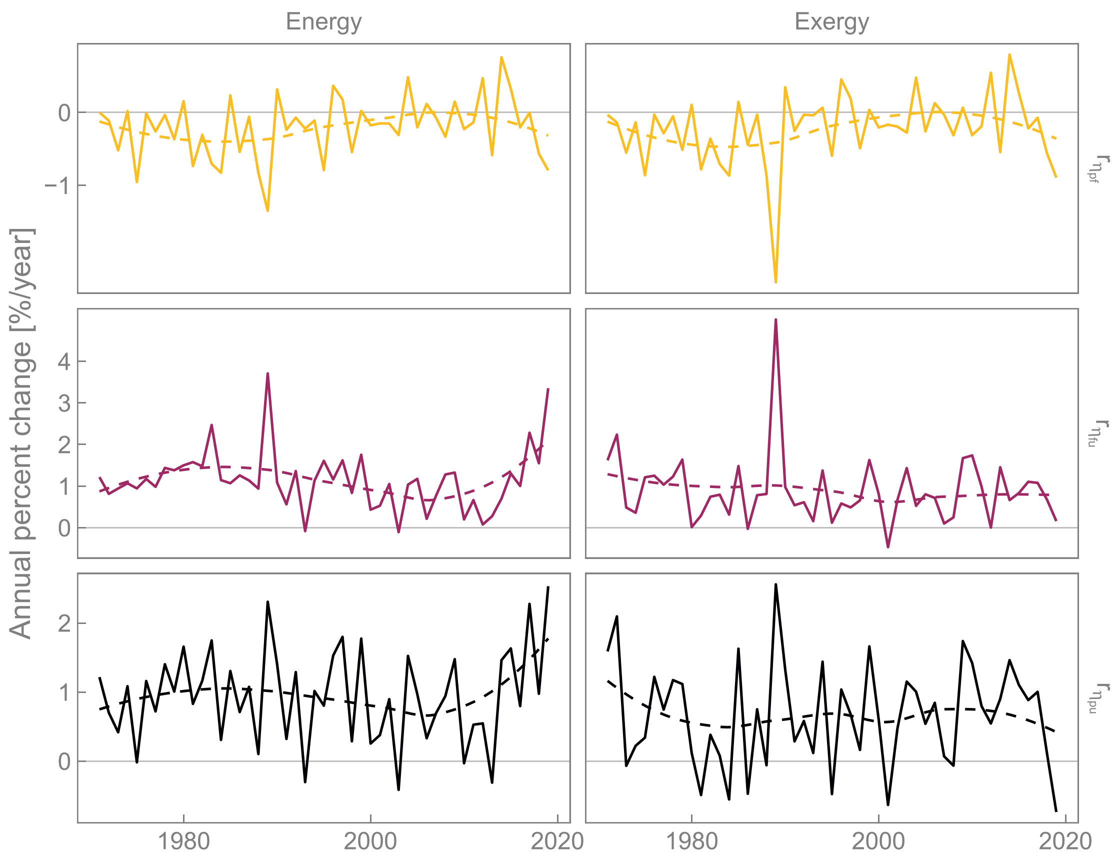

Figure B2. Annual percentage change of gross primary-to-final ($r_{\eta_{pf}}$), gross final-to-useful ($r_{\eta_{fu}}$), and gross primary-to-useful ($r_{\eta_{pu}}$) thermodynamic efficiency shown. Both IEA and muscle work are included. Non-energy uses are excluded. Figure 14 shows the same data with the year 1989 removed.

Appendix C. FSU and Former Yugoslavia efficiencies

As discussed in section 3.2, there are energy accounting discontinuities between 1989 and 1990 caused by the dissolutions of the Soviet Union and Yugoslavia. These discontinuities result in a small jump in Europe's FU energy and exergy efficiencies, seen in figure 12. Figure C1 shows primary-to-final (η_{pf}), FU (η_{fu}), and primary-to-useful (η_{pu}) gross energy and exergy efficiencies including both IEA and muscle work data for the Soviet Union and former Soviet states. Figure C2 shows the same data for Yugoslavia and former Yugoslav states. Together, figures C1 and C2 illustrate the challenges inherent in estimating Europe's efficiencies in the 1989–1990 timeframe.

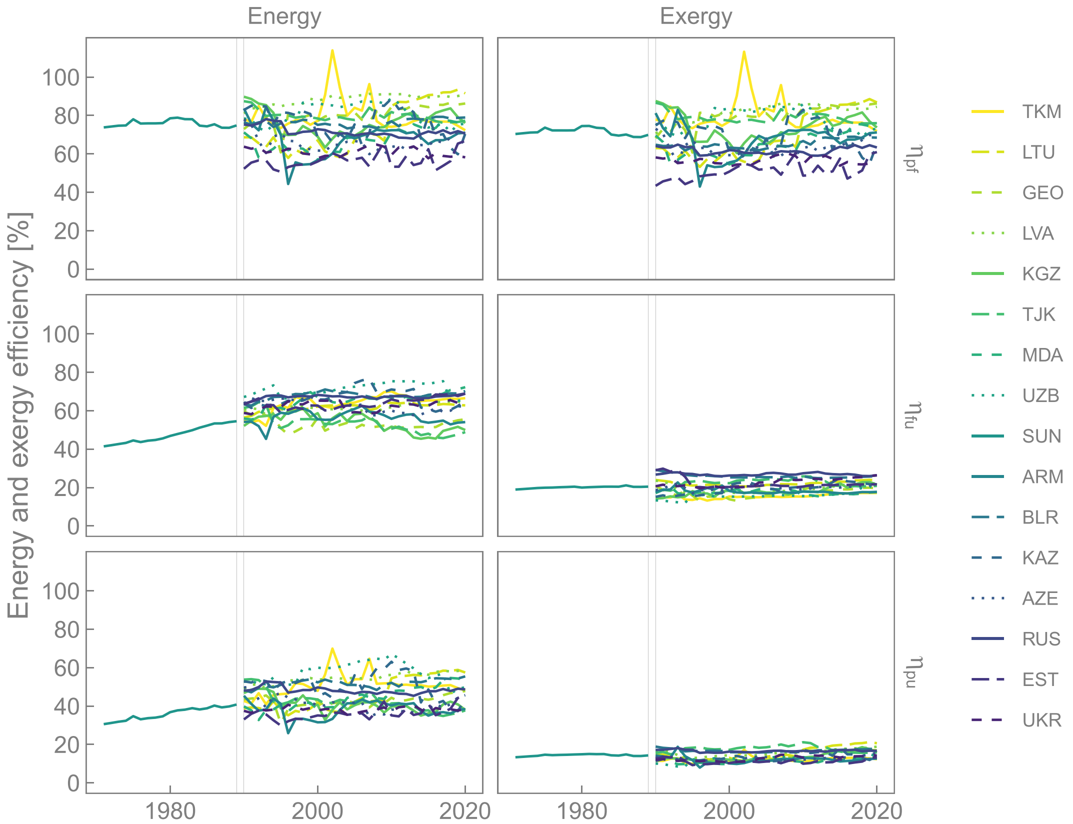

Figure C1. Gross aggregate energy and exergy efficiencies for countries in the Former Soviet Union including both IEA and muscle work data. Non-energy uses are excluded.

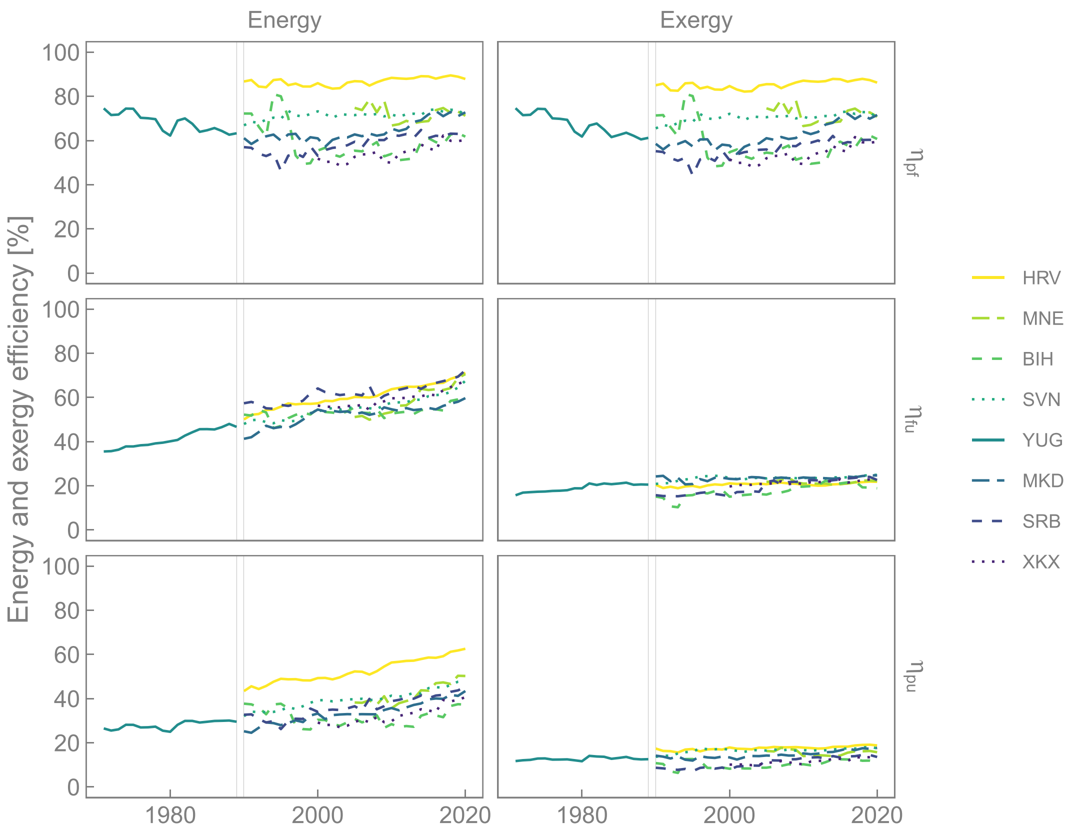

Figure C2. Gross aggregate energy and exergy efficiencies for countries in the Former Yugoslavia including both IEA and muscle work data. Non-energy uses are excluded.

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