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Meeting 2030 primary energy and economic growth goals Mission impossible

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Meeting 2030 primary energy and economic growth goals: Mission impossible?

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HIGHLIGHTS

- A comparative societal exergy analysis of Ghana and the United Kingdom is performed.
- Ghana's projected 5 %/year economic growth requires primary energy growth of 2 %/year.
- Energy efficiency measures are ineffective due to economy-wide feedbacks.
- Energy intensity is not an appropriate metric for primary energy reduction goals.
- Absolute decoupling of energy from gross domestic product appears mission impossible.

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ABSTRACT

To meet climate change mitigation objectives, international institutions have adopted targets aimed at reducing or ending growth of primary energy consumption. Simultaneously, continued economic growth is forecasted to meet human development goals. Together, declining energy consumption and rising gross domestic product (GDP) is called "absolute decoupling." However, absolute decoupling is unprecedented for the world economy as a whole (since at least 1971). Is absolute decoupling "Mission impossible?" Given the high stakes, we need a clearer understanding of the extent of future energy–GDP decoupling. To gain that understanding, we perform societal exergy analyses using a novel Physical Supply Use Table framework to assess historical and future trends of primary energy consumption and economic growth for one medium human development index country and one very high human development index country, Ghana and the United Kingdom (UK), respectively.

Three key results are obtained. First, we find that it will be very difficult to absolutely decouple primary energy consumption from economic activity. This is particularly true for Ghana's rapidly growing economy, where projected economic growth of 5.0 %/year will require growth of primary energy consumption of around 2.0 %/year. It is also true for the UK, where at best primary energy consumption appears constant into the future to provide a projected GDP growth of 2.7 %/year. Second, we find that energy efficiency is not an effective means to reduce primary energy consumption and associated carbon dioxide emissions due to economy-wide feedback effects, placing greater importance on decarbonizing the primary energy supply. Third, we find primary energy intensity is not an appropriate metric to measure energy reduction progress, because meeting primary energy intensity targets does not ensure absolute decoupling will occur. At present, absolute decoupling appears to be mission impossible.

1. Introduction

1.1. Energy and economic targets

To meet climate change mitigation objectives, international institutions such as the United Nations (UN) [1] and the European Commission (EUCO) [2] have adopted energy targets aimed at reducing or ending growth of primary energy consumption. At the same time, global economic growth is forecasted [3]. The combination is assumed to lead to a hospitable planet, enhanced human well-being, and increased economic prosperity. But can we do it? Can we meet primary energy targets while the world economy is growing? Or is that mission impossible?

A related metric is primary energy intensity (I_{E_p}), the ratio of

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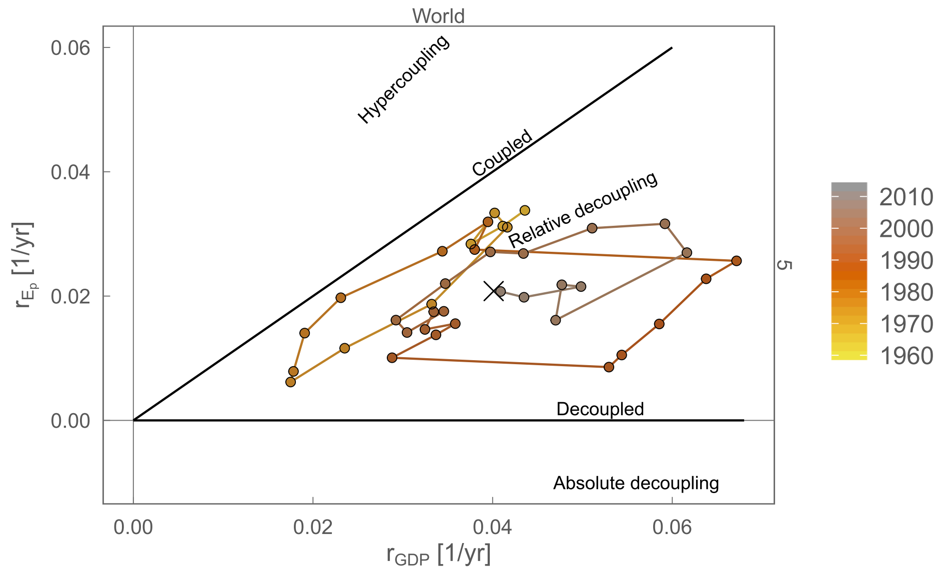

Fig. 1. A state map of the primary energy–GDP decoupling space with world data (1971–2013).

primary energy consumption to Gross Domestic Product (GDP) [4]. (A list of nomenclature is provided in Appendix A.) Primary energy intensity (I_{E_p}) appears in the UN Sustainable Development Goals (SDGs) [1] under Goal 7 ("Ensure access to affordable, reliable, sustainable, and modern energy for all") and Target 7.3 ("By 2030, double the global rate of improvement in energy efficiency [sic]") as Indicator 7.3.1 ("Energy intensity measured in terms of primary energy and GDP").

1.2. The decoupling problem

The simultaneous increase of GDP and decrease of primary energy consumption is called "absolute decoupling" [5]. "Relative decoupling" occurs when total primary energy consumption grows, but less quickly than GDP. A state map of the primary energy–GDP decoupling space is given inFig. 1, where r_{E_p} and r_{GDP} are the compound average annual growth rates (CAAGRs) of primary energy consumption and GDP, respectively, in units of 1/year; GDP is the annual sum of GDP for all countries in 2011USD from the "rgdpo" time series of the Penn World Table (PWT) version 9.0 [6] accessed via an `R` [7] package called `pwt9` [8]; E_p is world total primary energy supply from the IEA's Extended Energy Balances [9]; r values are calculated over a time span of $\Delta t_{diff} = 5$ years; and the historical average for 1971–2013 is indicated by a black ×. On the map of the decoupling space, absolute decoupling occurs when $r_{GDP} > 0$ and $r_{E_p} < 0$. Relative decoupling occurs when $0 < r_{E_p} < r_{GDP}$. Hypercoupling occurs when $r_{E_p} > r_{GDP}$.

The concept of decoupling can be used as a lens to analyze international targets for primary energy consumption and forecasts for economic growth. For example, the International Energy Agency's World Energy Outlook 2017 contains a *Sustainable Development Scenario*, a less-aggressive *New Policies Scenario*, and a business-as-usual *Current Policies Scenario* [3]. The Sustainable Development Scenario "examines what it would take to achieve the main energy-related components of the '2030 Agenda for Sustainable Development' adopted in 2015 by member states of the United Nations" [3, p. 36] and is consistent with the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 2.6 scenario [10], wherein CO_2 emissions are reduced rapidly to meet a 2 °C warming limit. Fig. 2 shows the Sustainable Development Scenario [3] relying heavily on efficiency to achieve a 10% absolute reduction in carbon dioxide (CO_2) emissions relative to the New Policies Scenario (from 32 $GtCO_2$/year in 2017 to 29 $GtCO_2$/year in 2040). This reduction implies a CAAGR of primary energy consumption of $r_{E_p} = -0.004$/year.[1] At the same time, the Organization for Economic Cooperation and Development (OECD) forecasts global CAAGR for GDP for 2017–2040 to be $r_{GDP} = 0.022$/year [11]. Taken together, forecasts of primary energy reduction ($r_{E_p} < 0$) and future economic growth ($r_{GDP} > 0$) implicitly assume that absolute decoupling is possible.

A historical perspective is instructive. Fig. 1 shows that between 1971 and 2010, the world as a whole exhibited only relative decoupling, with historical averages $r_{GDP} = 0.040$/year and $r_{E_p} = 0.021$/year. Relative decoupling is observed despite decades of global energy efficiency investment, reaching \$231 billion/year in 2016 [12, Fig. 4.2], which is equivalent to 14% of \$1.7 trillion total in worldwide energy investment [12, p. 91].

An important potential problem arises: are the energy targets and economic forecasts compatible? In other words, is absolute decoupling possible going forward? Given the stakes (the need to address both climate change and human development concerns), assessing the extent to which absolute decoupling is possible is a global priority, requiring new and innovative analysis methods to understand the relationship between energy and economic growth. This understanding should be obtained for both the world as a whole and for individual countries from low to very high human development, because the dynamics [13] of the interactions among primary energy consumption, energy efficiency, and economic growth may be different along the human development spectrum. It is to one such analysis method that we now turn.

1.3. Societal exergy analysis as an emerging energy analysis tool

Societal exergy analysis is an analysis tool which provides deep understanding of societal Energy Conversion Chains (ECCs, see Fig. 3) and options for access to energy services. When linked to economic performance, societal exergy analysis can provide important insights into the interactions between energy consumption and economic growth. (For a description of societal *energy* analysis, see Roberts [14]. For an example of modern societal *exergy* analysis, see Rocco [15].)

[1] We provide decimal CAAGRs throughout this paper. The annual percentage change can always be obtained by multiplying by 100. For this example, $r_{E_p} = -0.004$/year is the same as 0.4 %/year *reduction* of primary energy consumption.

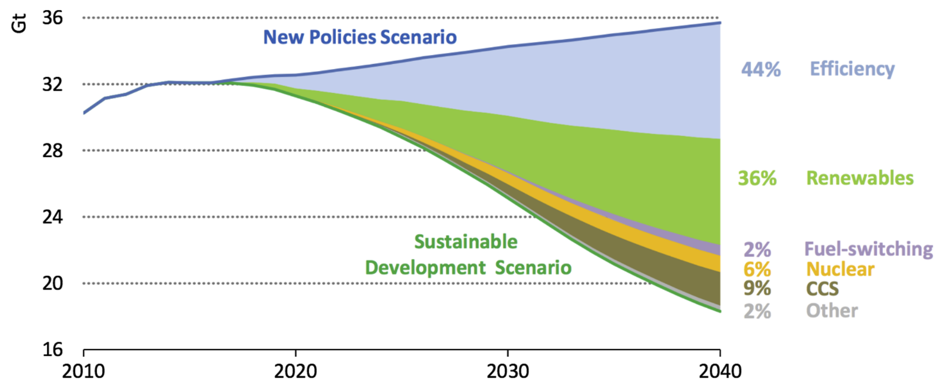

Fig. 2. Global CO_2 emissions reductions in the International Energy Agency's Sustainable Development Scenario relative to the New Policies Scenario [3, Fig. 3.15, p. 139].

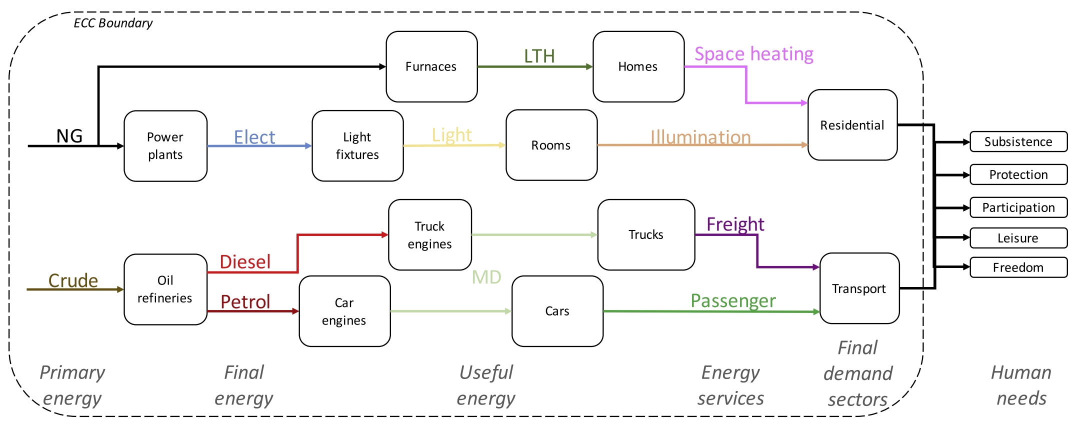

Fig. 3. ECC example [16, Fig. 1]. NG is Natural gas. LTH is Low-temperature heat. MD is Mechanical drive.

"[E]xergy…is formally defined as the maximum amount of work that a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly" [17, p. 192] (e.g., mechanical work extracted from a barrel of oil by a very slow-working, reversible engine). Quantifying energy as exergy provides a robust, thermodynamically-consistent basis for evaluating efficiencies in the ECC and for exploring linkages to the wider economy, because exergy "stems from the requirements of the First and Second Laws" [18, p. 1793].

A key strength of societal energy and exergy analyses is its ability to reach along the entire ECC. We consider all stages of energy conversion and use, from primary energy extraction to final and useful stages of energy consumption (and where relevant to energy services and human needs) as shown in Fig. 3. Our energy carrier boundary contains the main energy flows intended for energy use, similar to Ayres and Warr [19], Serrenho [20], and Brockway et al. [21], but different from a wider biophysical boundary that includes materials as adopted by Scuibba [22] and Krausmann et al. [23].

Numerous societal exergy analyses have been performed since Reistad's study of the U.S. in the 1970s [24]. With reference to the human development index (HDI [25]), societal exergy analyses have been completed for countries with very high HDI (the U.S. [26], Austria, Japan, the UK and the U.S. [27], the EU-15 [28], and the U.S. and the UK [21]) and high HDI (Brazil [29], China [30], and Mexico [31]). However, to our knowledge the only time-series analysis of a medium- or low-HDI country that considered all sectors of useful exergy demand was performed for India [32]. (An analysis of South Africa was limited to industrial sectors [33], and Ghana was analyzed for 1975 only [34, Section 5.2].)

Promising insights from the societal exergy analysis literature relevant to the energy targets and economic forecasts discussed in Section 1.1 include (a) an understanding that exergy (not energy) at the useful stage (not the primary stage) drives economic growth [19]; (b) using the primary stage (instead of the useful stage) to project future energy demand can lead to under-estimation of future primary energy needs [30]; (c) useful exergy intensity (I_{X_u}) is more constant over time than primary exergy intensity (I_{X_p}) [35], therefore useful exergy is more closely related to economic production than primary exergy and "allows us to analyze structural change in energy supply and situates our analysis at the level of satisfied needs" [36, p. 148]; and (d) energy rebound is a potential threat to a low-carbon future [37].

In parallel, a key recent methodological advance in the field has been the development of a matrix-based Physical Supply Use Table (PSUT) exergy accounting method [16]. The PSUT-based technique provides a robust framework for analyzing energy-related questions along part or all of an ECC.

These strands come together to form the analysis approach for this paper: we use a decoupling lens and the new PSUT-based societal exergy analysis technique to address our central question: *To what extent can we meet primary energy reduction and economic growth goals in 2030?* We analyze and compare two countries, Ghana (GH) and the United Kingdom (UK), to assess the dynamics of the interaction between energy and the economy for a medium HDI nation (Ghana) and a very high HDI nation (the UK).

Next, we introduce each country and provide rationale for their selection.

1.4. Ghana as a case study, with comparison to the UK

There are several reasons why Ghana is a good candidate for societal exergy analysis. First, Ghana is a growing power in West Africa whose HDI (0.579 in 2015) is ranked 139th out of 188 countries in the world [25, Table 1]. However, Ghana is doing well compared to its continental neighbors, and its HDI rank is 14th of 48 African countries. Ghana, a medium HDI country, can reveal dynamics of developing nations with respect to energy, efficiency, and economic growth.

Second, Ghana's economy is growing at a fast pace (r_{GDP} = 0.085/year in 2017 [38]). And from 2000 to 2013, it exhibited a large reduction in primary energy intensity (I_{E_p}), from 7 MJ/2011USD to 4.7 MJ/2011USD yielding $r_{I_{E_p}} = -0.030$/year. These characteristics make Ghana an ideal subject of study relative to energy targets expressed as primary energy intensity reductions.

Third, although nearly 80% of Ghana's population have access to electricity [39], biofuels remain a large portion of total primary energy supply, mostly for domestic cooking and water heating. But the transition away from biofuels is underway, and its dynamics have impacts on the evolving energy picture in the country. Ghana's characteristics can shed light on implications of improving access to electricity and clean cooking, not just for health considerations [40], but also for economic activity, energy consumption, and climate change mitigation targets.

Fourth, with hydroelectric power now fully deployed, Ghana is at an energy crossroads, requiring increased primary energy supply from renewables or fossil fuels to provide future stable electricity supply and avoid *dumsor* (load shedding blackouts) [41]. Ghana can illustrate how developing nations are affected by the economic impacts of energy constraints.

Fifth, the availability of Ghanaian energy data back to 1971 provides possibilities for time series analysis. Data are available from governmental sources including the Ministry of Energy as well as published studies and surveys on cooking stoves and other topics.

Analyzing more than one country enables similarities and differences to be explored, yet comparative, multicountry societal exergy studies are rare. Therefore, we compare Ghana's developing economy with the UK, a large, industrialized nation with very high HDI whose future success or failure at meeting energy and economy targets is relevant at the global level. (See Table 1.) The UK has two additional advantages as a subject of study. First, the UK allows validation of the new PSUT accounting framework, because the UK was previously studied via societal exergy analysis [21]. (See Section 2.3 and the Supplemental Information (SI) for comparison results.) Second, there are historical connections (Ghana being a former British colony) and geographic (land area) similarities between the two countries. And both have a population that is in the tens of millions.

1.5. Questions, novelty, and paper structure

Thus, we focus our central question and identify the knowledge gap addressed by this paper: *To what extent can Ghana and the UK meet both energy targets and economic goals in 2030?* Exploration of the focused central question is facilitated by studying several sub-questions:

(Q1) What is the energy history for each country?
(Q2) What is the relationship between energy consumption and economic output in each country?
(Q3) How much primary energy will each country need in 2030?
(Q4) What is the likely extent of decoupling for each country to the year 2030?

There are several novelties of this work. (1) This paper presents the first application of the PSUT framework for societal exergy analysis, enabling forecasts of primary energy consumption by a disaggregate useful-stage approach. (2) Our decoupling state map is an innovative way of presenting primary energy targets and provides a beneficial lens through which to assess the feasibility of those targets. (3) We provide the first quantitative forecasts of the likely extent of decoupling for two countries at very different stages of development (Ghana and the UK). (4) This paper presents the first forecast of Ghanaian primary energy consumption to 2030.

This paper differs from previous studies in important ways.(1) Previous studies have projected future decoupling via an aggregate primary stage method that we show overestimates the likely extent of future decoupling. (2) No earlier studies performed longitudinal societal exergy analysis of Ghana. (3) Few earlier studies provide comparative societal exergy analysis of two or more countries.

The paper proceeds as follows. In Section 2, we describe analysis methods, sources of data, and assumptions for (Q1)–(Q4). Results for (Q1)–(Q4) are provided in Section 3, followed by discussion of primary energy metrics, decoupling, and CO_2 emissions in Section 4. Conclusions and suggestions for future work appear in Section 5.

2. Methods, data, validation, and assumptions

2.1. Methods

Sub-questions (Q1)–(Q4) are addressed by various analysis methods as shown in Table 2.

2.1.1. (Q1) methods

To address the energy history sub-question (Q1), we construct societal exergy time series for Ghana (1971–2013) and the UK (1960–2013) for primary, final, and useful energy stages. Our method largely follows the work of Ayres and Warr [19], Serrenho [20], Brockway et al. [21], and Brockway et al. [30]. Fig. 4 gives an overview of the societal exergy analysis process, and significant detail can be found in the SI. The societal exergy analyses in this paper are the first application of the new Physical Supply Use Table (PSUT) framework for energy conversion chain (ECC) analysis [16]. The PSUT framework organizes the ECC data in matrix form and efficiently analyzes the ECCs of Ghana and the UK.

The societal exergy analysis time series enable two important analyses. First, the societal exergy time series can be compared against significant historical events in each country. Second, log-mean divisia index (LMDI) decomposition of useful exergy can be performed using the results of the societal exergy analysis. The LMDI approach

Table 1
Comparison between Ghana and the UK for the year 2013. GDP and population data from Penn World Table (PWT) version 9.0 [6]. GDP is "rgdpo." Land area from CIA World Factbook [42]. Primary energy consumption from current study.

	Ghana	UK
GDP [million 2011USD]	96,344	2,437,409
Population [millions]	26	64
GDP/capita [2011USD/person]	3,682	38,111
Area [sq. km]	238,533	243,610
Primary energy consumption [ktoe]	10,880	185,438

Table 2
Sub-questions and analysis methods.

Sub-questions	Analysis methods
(Q1) Energy history?	Societal exergy analysis LMDI decomposition analysis
(Q2) Energy-economy relationship?	Exergy intensity analysis GDP vs. thermodynamic efficiency analysis
(Q3) E_p needs in 2030?	Aggregate primary stage E_p projections Disaggregate useful stage E_p forecasts
(Q4) Extent of Decoupling?	Past and future decoupling analysis Past and future I_{E_p} analysis

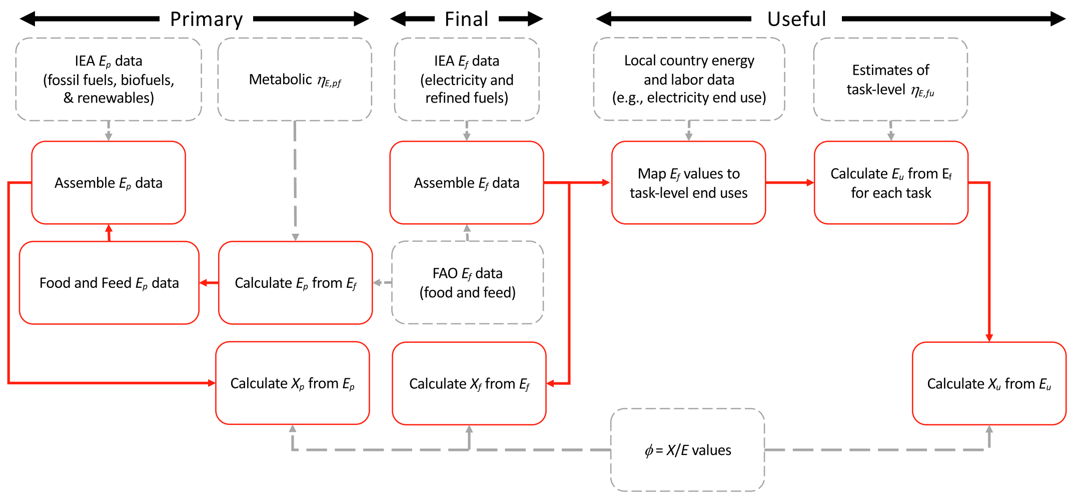

Fig. 4. Societal exergy analysis flow chart. Gray boxes and dashed lines indicate externally-sourced data. Red boxes indicate analysis steps.

pioneered by Ang [43] and described in detail by Liu [44] decomposes an energy aggregate (in our case useful exergy, X_u) by factors. The LMDI analysis reveals the relative importance of primary exergy, structural changes, thermodynamic efficiency, and efficiency dilution to drive changes in useful exergy in each country. (We reserve the term *thermodynamic efficiency* for aggregate primary-to-useful exergetic efficiency, $\eta_{X,pu}$.) Our LMDI approach follows a method developed for China [30] but employs, for the first time, a new matrix-based analysis technique. (Consult the SI for details.)

The societal exergy analysis for (Q1) becomes a building block for both (a) the exergy intensity analysis and the thermodynamic efficiency vs. GDP analysis for (Q2) and (b) the E_p projections and forecasts for (Q3). The LMDI analysis informs the E_p projections and forecasts for (Q3).

2.1.2. (Q2) methods

To address the energy-economy interaction sub-question (Q2), we consider the role that energy plays to enable economic output in each country. In particular, we examine exergy intensity ratios at the primary, final, and useful stages to connect trends through time to the energy history of each country (obtained for Q1). In addition, we investigate the relationship between changes in thermodynamic efficiency ($\eta_{X,pu}$) and changes in GDP through time. We focus on thermodynamic efficiency ($\eta_{X,pu}$), because (a) consumption of primary fuels (X_p) is associated with CO_2 emissions and climate change and (b) useful exergy (X_u) in the form of mechanical work, heat, or light is closer than final exergy (X_f) or primary exergy (X_p) to activities that generate economic value (such as bending steel, moving people and materials, heating buildings, and providing illumination).

We express changes in important aggregate quantities (thermodynamic efficiency ($\eta_{X,pu}$), aggregate primary energy (E_p), primary energy intensity (I_{E_p}), and GDP) as CAAGRs ($r_{\eta_{X,pu}}$, r_{E_p}, $r_{I_{E_p}}$, and r_{GDP}, respectively) in units of year^{-1} as shown in Eq. (1):

$$r_{x(t)} = \left[\frac{x(t+\Delta t_{diff})}{x(t)}\right]^{(1/\Delta t_{diff})} - 1, \quad (1)$$

where x is any variable for which CAAGR is desired ($\eta_{X,pu}$, E_p, I_{E_p}, or GDP), t is the year associated with a particular calculation of r, and Δt_{diff} is the time difference over which $r_{x(t)}$ is desired (5 years in the body of the paper and 1–10 years in Appendix B). Compound average annual percentage growth rates of x at year t are found by multiplying $r_{x(t)}$ by 100, and $r_{x(t)} < 0$ indicates that x is declining at year t over time period Δt_{diff}.

The results of the intensity analyses in (Q2) are a building block for addressing (Q4).

2.1.3. (Q3) methods

To address the energy in 2030 sub-question (Q3), we estimate primary energy consumption to 2030 for each country using an aggregate primary stage projection method and forecast primary energy consumption to 2030 using a disaggregate useful stage forecast method. (We use the term "project" to indicate a high-level extrapolation and the term "forecast" to indicate a detailed, bottom-up prediction.) Additional details of both methods can be found in Appendix C.

The aggregate primary stage projection method is the simpler of the two methods. It extrapolates trends in aggregate primary energy consumption, without regard for task-level efficiencies or structural changes in the economy. The following list summarizes the aggregate primary stage projection method:

1. Plot historical primary energy intensity ($I_{E_p} = E_p/GDP$) for 1971–2013 to find the best-fit decaying exponential equation.
2. Project best-fit I_{E_p} exponential to 2030. Adopt forecasted GDP from growth rates of Section 2.2.2.
3. Multiply 2014–2030 projected I_{E_p} values by forecasted GDP, thereby obtaining estimates of primary energy consumption (E_p) to 2030.

The disaggregate useful stage forecast method was pioneered by Brockway et al. and, to date, has been applied to China only [30]. In contrast to the aggregate primary stage projection method, the disaggregate useful stage forecast method (a) accounts for trends in both task-level efficiencies and economic structural change and (b) utilizes information unavailable to the aggregate primary stage projection method, namely details of the energy pathways from primary through useful stages. Its steps are summarized as follows:

1. Set task-level useful exergy to 2030: First, construct a historical I_{X_u} plot and extrapolate to 2030 using an asymptotic best-fit curve. Multiply extrapolated I_{X_u} values by the forecasted GDP for each country to 2030 to obtain aggregate forecasted useful exergy (X_u) to 2030. Next, construct historical useful exergy shares (in percentage terms) for the four main useful exergy sectors (where subscript j is a

main sector index): heat, mechanical drive, electricity, and muscle work. Third, forecast percentage shares to 2030, based on trends and external information (e.g., saturation of electricity share). Fourth, set task-level useful exergy ($X_{u,ij}$, where subscript i is a task index) to 2030 via extrapolation, also keeping one task-level $X_{u,ij}$ in each main sector floating, to balance against the top-down sector level forecast $X_{u,j}$. Adjust $X_{u,ij}$'s for known external information such as transport demand forecasts.

2. Set task-level exergy efficiency to 2030: First, extrapolate task-level exergetic efficiencies (η_{ij}) to 2030. Adjust as necessary, based on external information, e.g., limitations of mechanical drive or transport efficiency, with Ghana set as 10 years behind UK in some task efficiencies based on engineering judgment and previous societal exergy analysis experience.
3. Estimate primary energy to 2030: First, estimate task-level primary exergy $X_{p,ij}$ by dividing task-level useful exergy by task-level efficiencies ($\eta_{X,pu,ij}$). Sum task-level primary exergy to give main sector primary exergy ($X_{p,j}$). Sum $X_{p,j}$ to give total aggregate primary exergy (X_p) to 2030. Divide X_p by average primary energy to primary exergy ratio (≈ 1.07 from Fig. D.1 in Appendix D) to obtain forecasted aggregate primary energy consumption in each year (E_p).

The E_p projections and forecasts for (Q3) serve as a building block for the past and future decoupling and I_{E_p} analysis for (Q4).

2.1.4. (Q4) methods

Finally, to address the decoupling sub-question (Q4), we perform a decoupling analysis using the state map shown in Fig. 1. We plot historical, projected, and forecasted values of r_{E_p} against r_{GDP}. To facilitate comparison against primary energy targets expressed as energy intensities, we also plot historical, projected, and forecasted values of $r_{I_{E_p}}$ against r_{GDP}.

CAAGRs of primary energy (r_{E_p}) and energy intensity ($r_{I_{E_p}}$) are related mathematically through the GDP growth rate (r_{GDP}). If any two growth rates are known, the third is calculable. Eqs. (2) and (3), respectively, show how to calculate (a) $r_{I_{E_p}}$ when r_{E_p} and r_{GDP} are known and (b) r_{E_p} when $r_{I_{E_p}}$ and r_{GDP} are known. (See Appendix E for derivations.)

$$r_{I_{E_p}} = \frac{1 + r_{E_p}}{1 + r_{GDP}} - 1 \tag{2}$$

$$r_{E_p} = (1 + r_{I_{E_p}})(1 + r_{GDP}) - 1 \tag{3}$$

Results from the study of sub-question (Q4) are used to assess the feasibility of meeting primary energy consumption targets and reducing CO_2 emissions in the Discussion (Section 4).

2.2. Data

2.2.1. Primary and final energy data and mapping to useful energy categories

The key data source for primary and final energy is the IEA's Extended Energy Balances [9]. These time series are used for (Q1)–(Q4). In addition to primary and final energy datasets and targets, other energy datasets and time series are required for the 1971–2013 historical societal exergy analyses for Ghana and the UK (especially for (Q1) in Section 3.1). See Brockway et al. [21] for details of the UK data.

A few notes about the Ghanaian energy data are germane here, and extensive details can be found in the SI. We gathered or estimated a significant amount of country-specific data for Ghana, including time series for muscle work energy starting from UN Food and Agriculture Organization (FAO) data [45]; allocation of final energy to useful energy categories [20]; final-to-useful device conversion efficiencies from Ayres and Warr [19], Brockway et al. [21], and Brockway et al. [30]; manual laborer counts by employment type from a 1976 report [46] and from the 1960 [47], 1970 [48], and 2012 [49] censuses; and draught animal counts from the FAO [45] and Ramaswamy [50]. We obtained substantial local energy datasets, including the Strategic National Energy Plan [51]; National Energy Statistics reports [52]; the first [53], third [54], fourth [55], fifth [56], and sixth [57] rounds of the Ghana Living Standard Survey published in 1989, 1995, 2000, 2008, and 2014, respectively; Demographic and Health surveys [58]; the National Household Transport survey [59]; Volta Aluminum Company electricity consumption from country reports [60] and their corporate profile [61]; GridCo electricity sales data from 2010 [62], 2011 [63], 2012 [64], and 2013 [65]; and Textile and leather sector production history [66].

Where possible, we use country-specific information for allocation of final energy to end uses at the useful energy stage. For example, the Energy Commission of Ghana (ECG) [67] provides statistics for 2010 for end-use household electricity consumption in the following categories: refrigeration, lighting, televisions, irons, and other appliances. The purpose of some fuels is intuitively clear (e.g., wood for cookstoves). Some allocations of final energy to end uses at the useful energy stage are less clear and a source of uncertainty (e.g., electricity in the Non-specified industry category). To our knowledge, there are no comprehensive, time series studies of fleet average final-to-useful energy efficiencies in Ghana for the following machines: Electric motors, Diesel cars, Diesel trains, Boat engines, Tractors, Industry static diesel engines, Petrol cars, Industrial electric heaters, and Industrial heat/furnace. Our estimates of energy efficiencies for these machines is taken from the work of Brockway et al. [21], lagged by 10 years. For example, Brockway et al.'s UK industrial electric motor efficiency in 1961 is 0.7033, so we assume Ghanaian industrial electric motor efficiency in 1971 to be 0.7033. (Ten years is an estimate informed by lived experience of author MKH in Ghana.) We smoothed irregularities in the IEA's primary solid biofuel data for Ghana after confirming that discontinuities were caused by changes in survey methodology. (See the SI.)

2.2.2. GDP data and growth rate forecasts

For the analysis of (Q2) (relationship between energy and economy) and (Q3) (energy needs in 2030), GDP datasets are needed. For (Q2), we use the Penn World Table (PWT) version 9.0 for GDP time series [6]. Specifically, we select the purchasing power parity (PPP) *rdgpo* time series (in 2011 USD) for Ghana (1971–2013) and the UK (1960–2013) which provides "real GDP using prices that are constant across countries and are also constant over time. … [*rgdpo* is] well-suited for comparisons across countries and over time" [6, p. 3153]. (An analysis of the effect of choosing different GDP measures in the PWT can be found in Appendix F. The effect of GDP measure is minor.)

For (Q3), GDP growth rate forecasts to 2030 are needed. For Ghana, we assume real GDP growth is constant at $r_{GDP} = 0.05$/year for 2013–2030, which is slightly below its recent average (0.054/year [6] for 2000–2014), but slightly above both (a) the 2000–2016 average for Africa (0.041/year) and (b) the 2016–2030 forecast for Africa (0.041/year–0.044/year) [3, Table 1.2].

For the UK, we adopt the OECD's year-by-year, long-term forecast for CAAGR of GDP which averages about $r_{GDP} = 0.027$/year for 2013–2030 [11].

2.2.3. Primary energy and primary energy intensity targets for 2030

For (Q3) and (Q4), we utilize the best available primary energy or primary energy intensity targets for each country. For Ghana, we apply

Table 3
Summary of targets for primary energy, primary energy intensity, and GDP expressed as CAAGRs.

		Ghana	UK
r_{GDP} [1/yr]		0.050	0.027
r_{E_p} [1/yr]	EUCO + 33	n/a	−0.0161
$r_{I_{E_p}}$ [1/yr]	SDG-7.3	−0.0528	−0.0478

Table 4
Primary energy targets (r_{E_p}) expressed in terms of primary energy intensity ($r_{I_{E_p}}$) as calculated by Eq. (2).

		Ghana	UK
r_{GDP} [1/yr]		0.050	0.027
r_{E_p} [1/yr]	EUCO + 33	n/a	−0.0161
$r_{I_{E_p}}$ from Eq. (2) [1/yr]	EUCO + 33	n/a	−0.0420

target 7.3 for the UN's SDG-7, which specifies that the CAAGR of primary energy intensity shall be doubled in 2010–2030 compared to the baseline period of 1990–2010 [1]. Using historical energy [9] and GDP[6] datasets, we calculate Ghana's CAAGR of primary energy intensity to be − 0.0264/year in the period 1990–2010, thereby setting the primary energy intensity target for 2010–2030 at $r_{I_{E_p}} = -0.0528$/year.

For the UK, we apply two primary energy targets. The first is derived from the overall EU-28 energy targets [68], namely the EUCO + 33 scenario which models a 33% reduction in primary energy consumption relative to a baseline forecast made in 2007 by the PRIce-driven and agent-based simulation of Markets Energy System (PRIMES) model [69]. The EUCO + 33 scenario is closest to the recently-agreed 32.5% EUCO energy target for 2030. Given that the UK's total primary energy supply was 222,779 ktoe in 2005 and the UK's contribution to the EUCO + 33 target for primary energy consumption is a reduction to 148,507 ktoe in 2030, the implied CAAGR of r_{E_p} (see Eq. (1)) is

$$r_{E_p} = \left(\frac{148{,}507\,\text{ktoe}}{222{,}779\,\text{ktoe}}\right)^{\left(\frac{1}{2030-2005}\right)} - 1 = -0.0161/\text{year}. \quad (4)$$

The second primary energy target for the UK is obtained by applying the SDG 7.3 target to the UK in a manner similar to Ghana. We calculate the UK's average annual rate of change of primary energy intensity to be − 0.0239/year in the period 1990–2010, thereby setting the primary energy intensity target for 2010–2030 to be $r_{I_{E_p}} = -0.0478$/year. A summary of primary energy and energy intensity targets is shown in Table 3.

We note that the EUCO + 33 primary energy target for the UK (expressed as r_{E_p}) can also be expressed in terms of primary energy intensity given forecasted CAAGRs of GDP, as shown in Eq. (2). Table 4 shows the EUCO + 33 target expressed as CAAGR of primary energy intensity.

Furthermore, the SDG-7.3 primary energy intensity targets (expressed as $r_{I_{E_p}}$) can be expressed in terms of primary energy given forecasted CAAGRs of GDP, as shown in Eq. (3). Table 5 shows the SDG-7.3 targets expressed in terms of CAAGR of primary energy.

Table 5
Primary energy intensity targets ($r_{I_{E_p}}$) expressed in terms of primary energy (r_{E_p}) as calculated by Eq. (3).

		Ghana	UK
r_{GDP} [1/yr]		0.050	0.027
$r_{I_{E_p}}$ [1/yr]	SDG-7.3	−0.0528	−0.0478
r_{E_p} from Eq. (3) [1/yr]	SDG-7.3	−0.0054	−0.0221

2.3. Validation

This paper represents the first empirical application of the PSUT framework [16]. We therefore undertook numerous checks and verifications to validate our analyses.

First, we performed energy and exergy balances on all ECCs for both countries for every year included in this study. All products were found to be in balance for both countries and all years. All energy conversion industries conserve energy for both countries and all years. Furthermore, we verified that the aggregate embodied energy (exergy) of products consumed by final demand is equal to aggregate primary energy (exergy) supply as required.

Second, we compared the UK results from the PSUT framework to previous UK results obtained with an earlier analysis toolchain developed by Brockway et al. [21]. Figs. S9 and S10 in the SI show that the results from the PSUT framework are in close alignment with previous results. We investigated differences and concluded that the analyses for the present paper are improvements over previous work.

Third, log-mean divisia index analysis was conducted in two separate numerical toolchains: one in Excel and one in `R` using the PSUT framework. (See the SI.) Results were found to be identical, thereby validating the new PSUT toolchain for LMDI analyses.

Fourth, we scrutinized per-industry efficiencies for unusual features. Any unusual features were investigated and either corrected or explained. For example, step-changes in Ghana's aggregate efficiency and electricity consumption were observed. Further investigation of the historical record revealed that documented production stoppages at the VALCO aluminum smelter in Tema, Accra were the cause. See the SI for details.

Finally, all PSUT framework analysis code is freely available online as `R` packages. Four packages are involved: `matsbyname` [70], `matsindf` [71], `Recca` [72], and `LMDIR` [73].

2.4. Assumptions

Several assumptions and limitations are common across the analyses for multiple sub-questions. Unless stated otherwise, for the remainder of this paper all analyses are conducted and results presented assuming the IEA's Physical Content Method (PCM) [74] when accounting for the primary energy of renewable electricity. We neglect non-energy uses for energy carriers, going so far as to perform an "upstream swim" through the ECC [16, p. 1139] to exclude the primary energy associated with non-energy uses of energy carriers in final demand. All aggregations are presented on a gross (not net) basis, as we include self-consumption of energy in output.

As stated in Section 2.2.2, we use "rgdpo" from the PWT for historical GDP time series. (To see the effects of different GDP measures, see Appendix F.) Where a time difference is required, we present results for $\Delta t_{diff} = 5$ years in the body of the paper. (The effects of different values for Δt_{diff} can be seen in Appendix B.)

When making task-level, final-to-useful efficiency projections to 2030 for (Q3), we do not include exogenous, macro-level linkages between thermodynamic efficiency and economic growth, as doing so is beyond the scope of this paper. (An integrated energy-economy system dynamics model would be required.) However, in the Discussion (Section 4), we include economy-wide feedback between thermodynamic efficiency and GDP using results from our study of the energy-economy relationship (Q2).

Several assumptions are made when building projections and forecasts of primary energy (E_p) consumption to 2030 for (Q3). First, we assume a macro-level link between primary energy (E_p) and GDP via primary energy intensity (I_{E_p}) for the aggregate primary stage projection method. Second, we assume a micro-level link between useful exergy (X_u) and GDP via useful exergy intensity (I_{X_u}) for the disaggregate useful stage forecast method. Third, there is no "efficiency headroom" restriction placed on aggregate thermodynamic efficiency

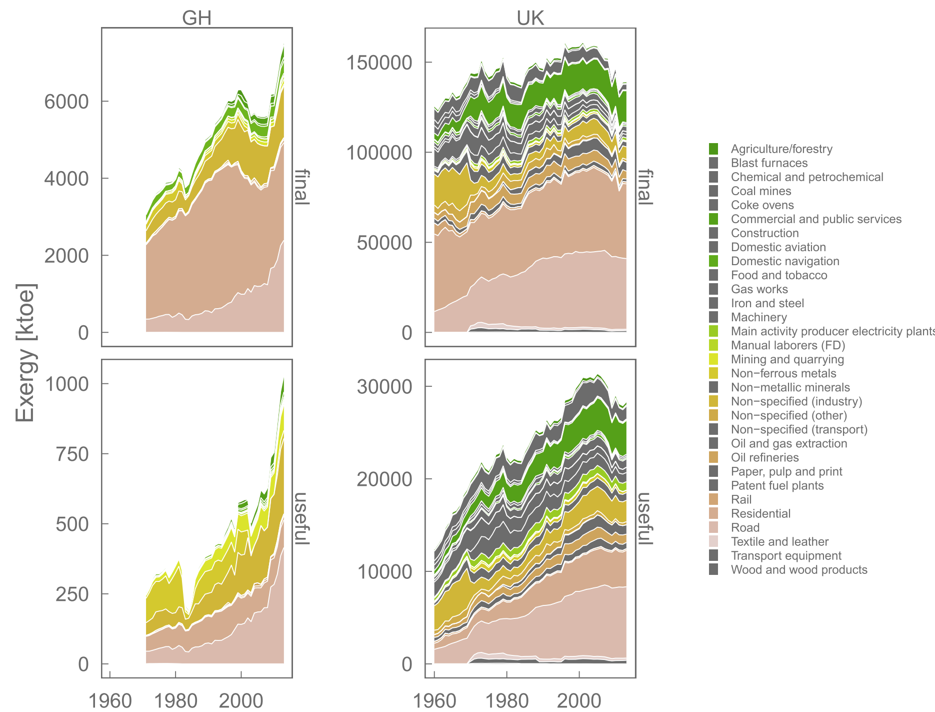

Fig. 5. Final exergy consumed and useful exergy produced within final demand sectors. Ghanaian final demand sectors are shown in colors, while final demand sectors that appear in the UK only are gray.

($\eta_{X,pu}$), though some task-level efficiencies are restricted to thermodynamic limits (e.g., boiler efficiencies). Fourth, regarding the mix of energy carriers, no assumptions are made for the aggregate primary stage projection method, because no disaggregation is required. For the disaggregate useful stage forecast method, we make some selected assumptions, based on future estimates of task-level useful exergy requirements, e.g. exogenous projections of road transport fuel consumption for petrol, diesel, and electric vehicles. We also assume that primary-to-useful Ghanaian electricity efficiency is constant from 2013 to 2030, balancing a decline in primary-to-final efficiency (due to increasing proportion of imported fuels vs. domestic hydroelectricity) against improvements in final-to-useful electrical task-level device efficiencies. In addition, we project historical primary exergy-to-energy ratios ($\phi \equiv X_p/E_p$) to 2030 for the disaggregate useful stage forecast method when forecasting primary energy (E_p) consumption to 2030. (See Appendix D.)

3. Results

We now apply the methods, data, and assumptions from Section 2 to study sub-questions (Q1)–(Q4) of Section 1.5. For each sub-question, we provide several observations and conclude with implications.

3.1. (Q1)—What is the energy history for each country?

The useful exergy time series for Ghana and the UK is the starting point for addressing (Q1). Fig. 5 shows the evolution of final and useful exergy for each country. Useful exergy values are much smaller than final exergy values for both countries because of the low final-to-useful exergetic efficiency for each sector.

The societal exergy time series shown in Fig. 5 enable calculation of the thermodynamic efficiency ($\eta_{X,pu}$) of each economy as shown in Fig. 6. Dashed lines indicate (a) Ghana's thermodynamic efficiency recovery after the economic collapse following the political coup of 31 December 1981 and (b) slow-down in UK thermodynamic efficiency gains since 2000.

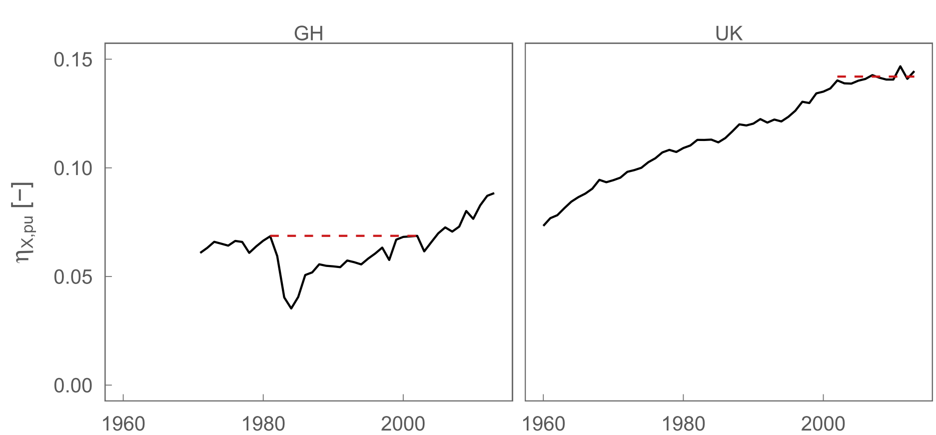

Fig. 6. Thermodynamic efficiency ($\eta_{X,pu}$) time series.

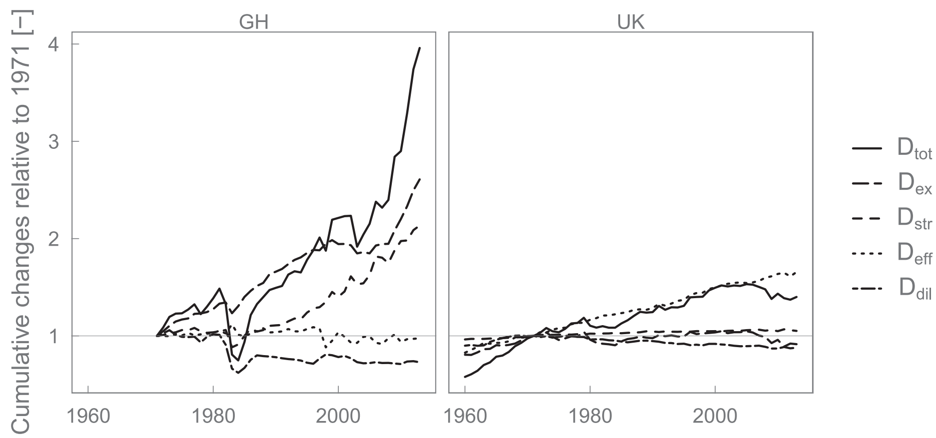

Fig. 7. LMDI decomposition analysis of useful exergy supplied to the economies of Ghana and the UK.

To explore the causes of the long-run trends in useful exergy for both countries, we employ a matrix-based LMDI decomposition analysis as shown in the SI. Fig. 7 and Table 6 show the results of the LMDI analysis.

With Table 6 and Figs. 5–7 in hand, we make the following observations about each country's energy history.

The UK far exceeds Ghana in exergy consumption. Fig. 5 shows that the UK's final and useful exergy consumption is more than an order of magnitude larger than Ghana's (for both final and useful exergy), due to its larger industrial base, northern climate, and larger economy.

Opposing economic growth and exergy trends. Fig. 5 shows that in recent years, Ghana is dramatically increasing both final and useful exergy consumption, while the UK is trending in the opposite direction. These trends reflect Ghana's recent strong economic growth and the UK's low-growth regime with possible secular stagnation. (See Summers [75] and Rawdanowicz et al. [76] for discussions of secular stagnation.)

Developing vs. developed economy. The differences between developing and developed economies are shown in Fig. 5 by the low exergy consumption of Ghana's Commercial and public services sector relative to the UK, the dominance of residential final exergy consumption in Ghana compared to the UK, and the relatively large size of industrial exergy consumption in the UK compared to Ghana.

Ghana's exergy valleys. Fig. 5 shows that Ghana experienced a dramatic collapse and recovery of useful exergy consumption in the early 1980s following a series of political coups (1978, 1979, and 1981). A smaller drop and recovery occurred in the early 2000s. Although all sectors experienced the exergy consumption valley in the early 1980s, the largest useful exergy drop occurred in the Non-ferrous metals sector when the Volta Aluminum Company (VALCO) ceased its aluminum smelting operations. The valley in the early 2000s was caused almost exclusively by another cessation of VALCO operations. (See the SI for details.) Because smelting operations supply a large amount of high-temperature heat to the economy (and therefore raise thermodynamic efficiency), the valley in useful exergy is more pronounced relative to overall exergy consumption than the valley in final exergy.

Ghana's slow thermodynamic efficiency recovery. Political coups devastated the Ghanaian economy in the early 1980s. Fig. 6 shows that the energy effects of the coups were similarly damaging: 20 years passed before Ghana's thermodynamic efficiency ($\eta_{X,pu}$) regained its pre-coups level. And since the early 2000s, Ghana's thermodynamic efficiency has been growing at a faster rate.

The UK's thermodynamic efficiency slowdown. Fig. 6 shows that although the UK has seen rising thermodynamic efficiency ($\eta_{X,pu}$) for much of the past 50 years (1960–2000), $\eta_{X,pu}$ gains appear to be slowing down at $\eta_{X,pu} \approx 0.14$ since 2000, a development first noticed by Brockway et al. [21] for 2000–2010 and extended to 2013 here.

Ghana's thermodynamic efficiency headroom. If the UK is experiencing slowdown in thermodynamic efficiency gains toward possible stagnation, Fig. 6 shows that Ghana's thermodynamic efficiency has ample headroom for future improvement, assuming that Ghana's thermodynamic efficiency would saturate at the same level as the UK ($\eta_{X,pu} \approx 0.14$).

Effect of offshoring in the UK. In the European Union, "the share of embodied energy in imports has reached 81% of final energy consumption in economic activities" [77, p. 54], meaning that offshoring of energy consumption is artificially reducing energy intensity. The trend in UK final and useful exergy from 2000–2013 (Fig. 5) has been affected by offshoring, too. Hardt et al. [78, p. 124] say

Table 6
Decadal LMDI results.

Country	Decomposition factor		1971–1980	1980–1990	1990–2000	2000–2013	1971–2013
Ghana	Useful exergy (X_u) change	D_{tot}	1.39	1.08	1.48	1.79	3.96
	Primary exergy (X_p) change	D_{ex}	1.28	1.30	1.17	1.34	2.61
	Main class structural change	D_{str}	1.04	1.07	1.26	1.52	2.13
	Task-level efficiency change	D_{eff}	1.03	1.01	1.00	0.94	0.98
	Sub-class structural change	D_{dil}	1.02	0.77	1.00	0.93	0.73
UK	Useful exergy (X_u) change	D_{tot}	1.10	1.13	1.20	0.94	1.40
	Primary exergy (X_p) change	D_{ex}	0.96	1.02	1.06	0.88	0.92
	Main class structural change	D_{str}	1.02	1.02	1.00	1.00	1.05
	Task-level efficiency change	D_{eff}	1.17	1.10	1.16	1.11	1.66
	Sub-class structural change	D_{dil}	0.96	0.98	0.97	0.96	0.88

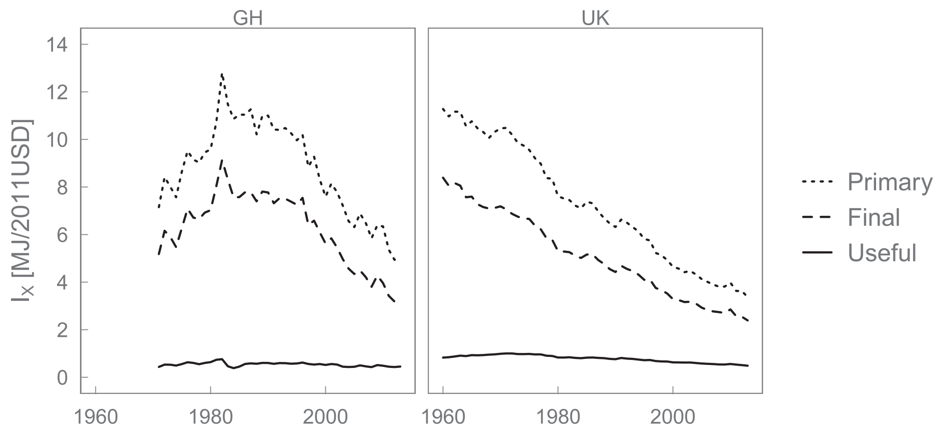

Fig. 8. Exergetic intensity of economic activity.

the majority of [final] energy savings from structural change [in the industrial sector] are a result of offshoring, which constitutes the second biggest factor reducing energy consumption. In recent years the contributions of all decomposition factors have been declining with very little change in [industrial sector] energy consumption after 2009. This suggests that a return to the strong reductions in [final] energy consumption observed between 2001 and 2009 in the UK productive sectors should not be taken for granted.

Improvements in exergy intensity and final-to-useful exergy efficiency also made contributions to reducing exergy consumption (or at least cancelling growth). Trends in primary energy (shown below in Figs. 10 and 11) are similar to the trends for final exergy.

We also note that from an environmental point of view and to the extent that offshoring is responsible, the recent reductions of UK primary energy consumption are largely illusory. The atmosphere still absorbs CO_2 emissions driven by UK consumption, whether the point source of those emissions is in the UK or elsewhere.

Primary exergy and structural change drive Ghanaian useful exergy. In Fig. 7, we observe that Ghana's primary exergy driver (D_{ex}) tracks total change (D_{tot}) closely from 1971 to 2000, meaning that increases in useful exergy were supplied mainly by increases in primary exergy during that period.

Fig. 6 shows increasing overall thermodynamic efficiency ($\eta_{X,pu}$) from 1990 onward, and Table 6 unpacks those gains. In the 1990–2000 and 2000–2013 columns for Ghana, we note that task-level efficiency (D_{eff}) and sub-class structural change (D_{dil}) are nearly 1. In contrast, main class structural change (D_{str}) is 1.26 and 1.52 for 1990–2000 and 2000–2013, respectively, meaning that structural changes (D_{str}) between the main classes of useful exergy (heat, mechanical drive, muscle work, and electricity) caused by modernization of Ghana's energy carriers are the important drivers of useful exergy increases in recent decades. Task-level technical efficiency changes (D_{eff}) are close to 1 over both recent years (D_{eff} is 1.00 and 0.94 for 1990–2000 and 2000–2013, respectively) and over the entire time period of this study (0.98 for 1971–2013).

Rising technical efficiency drives UK useful exergy. In contrast, Fig. 7 shows that the UK's task-level exergetic efficiency driver (D_{eff}) runs parallel to total useful exergy change (D_{tot}), meaning that increases in thermodynamic efficiency ($\eta_{X,pu}$) shown in Fig. 6 have driven the UK's changes in useful exergy.

Again, Table 6 helps to unpack the changes. In the 1971–2013 column, we see primary exergy supply decreasing by 8% ($D_{ex} = 0.92$), a result that is partially attributable to offshoring [78]. There has been minor main-class structural change ($D_{str} = 1.05$), while sub-class structural change ($D_{dil} = 0.88$) indicates increasing use of less-efficient processes within each main class. However, task-level efficiencies have increased much more ($D_{eff} = 1.66$), confirming that the rise of useful exergy delivered to the UK economy has been driven by task-level technical efficiency changes since the early 1970s.

Although Fig. 6 shows that both countries have seen nearly 50% gain in thermodynamic efficiency from 1971–2013 (Ghana: 6.1% to 8.8%, or 44%; UK: 9.5% to 14.1%, or 48%), the drivers of those gains have been very different.

Implications. **Primary energy supply is likely to be a key future challenge for both Ghana and the UK.** Ghana has future thermodynamic efficiency ($\eta_{X_{p,u}}$) headroom, but further rapid increases in useful exergy supply will require additional primary energy sources to overcome already maximized domestic hydroelectricity and primary solid biofuel supplies. For the UK, if the recent slowdown of $\eta_{X,pu}$ gains continues, future useful exergy gains to support economic growth will need to be driven by growth of primary energy consumption instead of

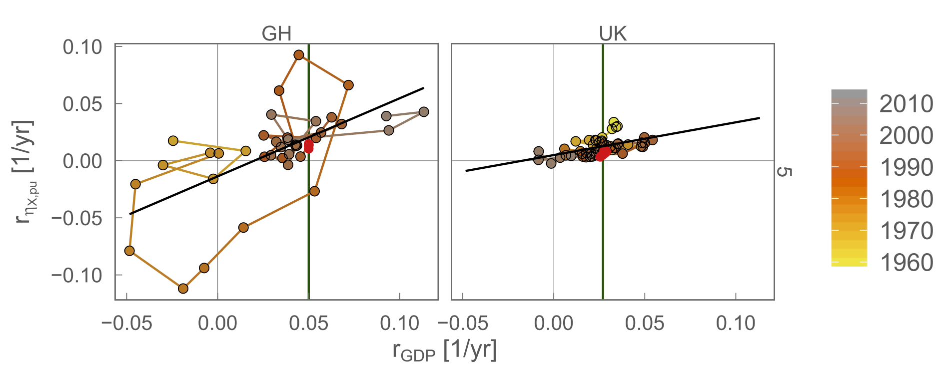

Fig. 9. CAAGR of thermodynamic efficiency ($r_{\eta_{X,pu}}$) vs. CAAGR of GDP (r_{GDP}).

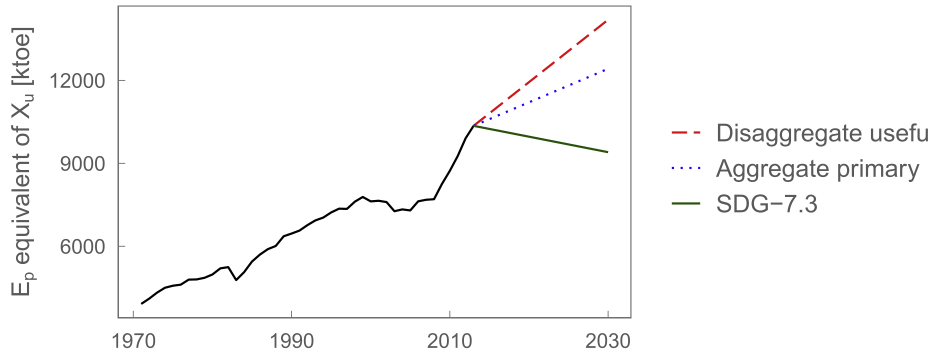

Fig. 10. Primary energy equivalent of useful exergy consumption for Ghana. Black line shows historical primary energy consumption.

thermodynamic efficiency.

3.2. (Q2)—What is the relationship between energy consumption and economic output in each country?

To address this sub-question, we perform exergy intensity analysis and evaluate the relationship between thermodynamic efficiency ($\eta_{X,pu}$) and GDP. Fig. 8 shows exergetic intensity for the primary, final, and useful stages for GDP expressed as "rgdpo," while Appendix F shows exergetic intensity of economic activity for all GDP types in the PWT. Fig. 9 shows the evolution of r_{GDP} and $r_{\eta_{X,pu}}$ for $\Delta t_{diff} = 5$ years, while Appendix B expands Fig. 9 to cover $1 \text{ year} \leqslant \Delta t_{diff} \leqslant 10$ years. Solid dark green vertical lines show forecasted CAAGR of GDP (Section 2.2.2). Red dots give results of disaggregate useful stage forecasts from Section 3.3 below. Black lines show linear best fits.

Using Figs. 8 and 9, we make the following observations about the relationship between energy consumption and economic output in each country.

Similar exergetic intensity levels and trends. Fig. 8 shows striking exergy intensity similarities between Ghana and the UK, despite fundamentally different economies and societies. In 2013, useful exergy intensity (I_{Xu}) was 0.45 MJ/2011USD in Ghana and 0.49 MJ/2011USD in the UK.

Fig. 8 also shows that both countries are experiencing declines in exergetic intensity from 1980 to 2013 at the primary and final ECC stages.

Thermodynamic efficiency and GDP appear to be related. Most points in Fig. 9 are in quadrants I and III (upper right and lower left, respectively), meaning that changes in $\eta_{X,pu}$ are associated with like changes in GDP. When $\eta_{X,pu}$ is increasing, GDP is usually increasing; when $\eta_{X,pu}$ is decreasing, GDP is usually decreasing. In fact, surprisingly few points (only 7 of 85, less than 10%) are in quadrant II or IV (upper left and lower right, respectively), wherein changes in $\eta_{X,pu}$ and GDP are in opposite directions.

This result indicates that the two CAAGRs ($r_{\eta_{X,pu}}$ and r_{GDP}) are intertwined. Possible mechanisms for the relationship between $r_{\eta_{X,pu}}$ and r_{GDP} include (a) rising GDP means more money available to invest in new final-to-useful machines and equipment with higher energy efficiency, thereby increasing $\eta_{X,pu}$ over time and (b) rising thermodynamic efficiency means that less money is spent on purchasing primary and final energy, more money is available for other economic activity, and GDP increases as a result.

There are other economic "factors of production" besides $r_{\eta_{X,pu}}$ that can affect r_{GDP} (e.g., capital and labor). And there are other factors besides r_{GDP} that can affect $r_{\eta_{X,pu}}$ (technological advances, structural change, etc.). As a result, it is unreasonable to expect perfect correlation between $r_{\eta_{X,pu}}$ and r_{GDP}. But the trends observed in Fig. 9 are novel, insightful, and striking.

We note that others have asserted that gains in thermodynamic efficiency are a means to drive economic growth [79,80]. The evidence in Fig. 9 shows a linkage between $r_{\eta_{X,pu}}$ and r_{GDP} but provides no evidence of causality in one direction or another. Analyzing causality is beyond the scope of this paper.

Implications. **The linkage between thermodynamic efficiency gains and economic growth create opposing economic pressures for the two countries.** For Ghana, rapid economic growth (>5 %/year) can continue in an era of sufficient thermodynamic efficiency headroom, provided that primary energy supply constraints can be overcome. In contrast, difficulties arising from the slowdown in thermodynamic efficiency gains mean that the UK may continue to experience low economic growth (<2 %/year) into the future.

3.3. (Q3)—How much primary energy does each country need in 2030?

To address (Q3), we implement the two methods for predicting future primary energy consumption: a top-down "aggregate primary stage" projection method and a bottom-up "disaggregate useful stage" forecast method. The two methods are summarized in Section 2.1.3.

Fig. 10 shows projections and forecasts of the aggregate primary energy equivalent of useful exergy supplied to the Ghanaian economy using both the aggregate primary stage projection method (dotted blue line) and the disaggregate useful stage forecast method (dashed red line). The SDG-7.3 target (solid dark green line) from Section 2.2.3 is also shown. The primary energy equivalent of useful exergy is different from total primary energy supply (TPES) in the IEA's extended energy balances [9], because it excludes from final demand both non-energy uses of energy carriers and transfers to bunkers and storage. The difference between TPES and "primary energy equivalent of useful exergy" is relatively small, e.g. 9.8% for the UK in 2013. Our approach is appropriate for the analysis at hand, because our focus is on the useful exergy supplied to the economy, i.e. the energy that enables economic activity and contributes to economic growth. Henceforth, we will simplify by saying "primary energy" when we mean "primary energy equivalent of useful exergy."

Fig. 11 shows projected (using the aggregate primary stage method, dotted blue line) and forecasted (using the disaggregate useful stage method, dashed red line) UK primary energy consumption to 2030. The EUCO + 33 (dashed dark green line) and SDG-7.3 targets (solid dark green line) from Section 2.2.3 are also shown.

Figs. 10 and 11 lead to the following observations.

Ghana future trends. Fig. 10 shows that the aggregate primary stage projection method suggests a 20% increase in Ghana's primary energy

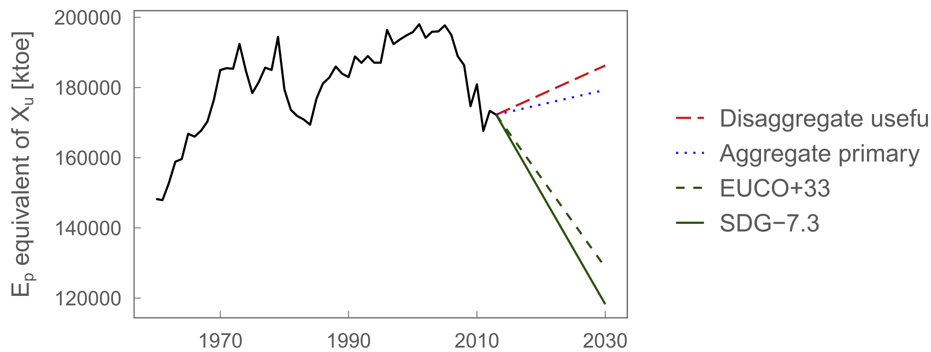

Fig. 11. Primary energy equivalent of useful exergy consumption for the UK. Black line shows historical primary energy consumption.

(E_p) consumption from 2013 to 2030. On the other hand, the disaggregate useful stage forecast method suggests a 37% increase in primary energy (E_p) consumption over the same time period, the difference being the relative slowdown in task-level technical efficiency gains that are picked up by the disaggregate useful stage forecast method but invisible to the aggregate primary stage projection method. The SDG-7.3 target expressed as primary energy consumption requires a 9.2% reduction over the same period.

UK future trends. Fig. 11 shows that the aggregate primary stage projection method indicates a 4% increase in the UK's primary energy (E_p) consumption from 2013 to 2030, as it follows the overall trend from 1971 to 2013. On the other hand, the disaggregate useful stage forecast method suggests an 8% increase over the same time period, the difference being the relative slowdown in task-level technical efficiency gains. The EUCO + 33 primary energy consumption target requires a 25% decrease in primary energy consumption between 2013 and 2030, while the SDG-7.3 primary energy intensity target (combined with forecasted r_{GDP} = 0.027/year) requires a 31% decrease in primary energy consumption from 2013 to 2030.

We constructed the aggregate primary stage projection and disaggregate useful stage forecast based on overall trends (1971–2013) in UK historical data. In doing so, we implicitly assume a reversion to the long-term mean, cognizant of the time-limited effects of offshoring and slowdowns in thermodynamic efficiency gain discussed above.

It is noteworthy that the EUCO + 33 and SDG-7.3 targets in Fig. 11 closely follow the 2005–2013 trend, implicitly assuming that the beneficial effects of offshoring will continue into the future, in contrast to the warning of Hardt et al. [78] that the beneficial effects might not continue.

Disaggregate useful method forecasts higher E_p consumption than aggregate primary method. For both countries, the disaggregate useful stage forecast method gives higher levels of primary energy consumption in 2030 than the aggregate primary stage projection method. The difference is due to the fact that the disaggregate useful stage forecast method accounts for expected slowdowns in task-level efficiency gains. The aggregate primary stage projection method cannot account for such trends, because it focuses exclusively on the primary stage of the ECC.

Implications. **Achieving primary energy targets in 2030 may be much more difficult than expected for both developing and developed economies.** Fig. 10 shows that Ghana is highly unlikely to meet the SDG-7.3 target without unprecedented changes to its economy. Fig. 11 shows that the UK is also unlikely to meet its targets unless it can both (a) continue the offshoring-driven trend of 2000–2013 and (b) overcome the slowdown in aggregate efficiency gains.

Ghana shows that developing economies may struggle to slow the economic-growth-driven demand for primary energy through thermodynamic efficiency gains, even when thermodynamic efficiency headroom is present. In fact, to the extent that thermodynamic efficiency gains act as a driver of economic growth, the problem is exacerbated. For developed nations, the UK example shows that decreases in primary energy consumption helped by offshoring may be difficult to sustain. Even so, such gains are illusory from a global environmental point of view.

3.4. (Q4)—What is the likely extent of decoupling?

Using results from (Q1)–(Q3), we can now assess (Q4). Fig. 12 is based on the decoupling state map of Fig. 1, adding country-specific historical and future data for Ghana and the UK. The solid dark green vertical lines show forecasted CAAGR of GDP (Section 2.2.2). The dashed and solid dark green horizontal lines show the UK contribution to EUCO + 33 primary energy target and the SDG-7.3 primary energy intensity target, respectively, expressed in terms of primary energy where needed. Blue dots give results of aggregate primary stage projections. Red dots give results of disaggregate useful stage forecasts. The gray diagonal line gives the boundary between relative decoupling and hypercoupling, as shown in Fig. 1.

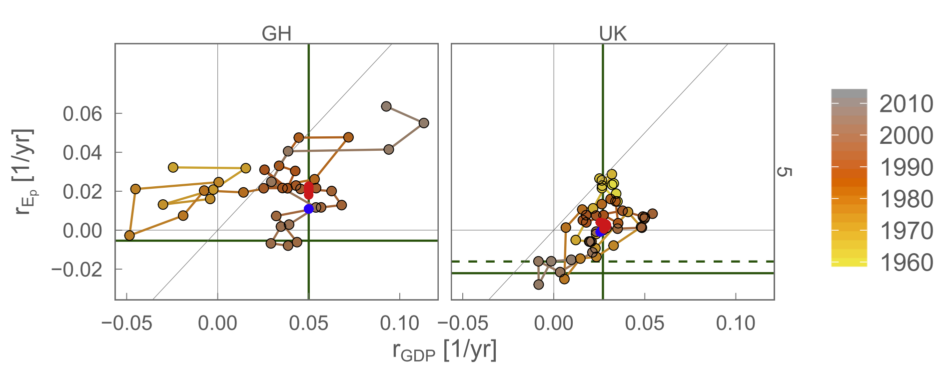

Fig. 12. CAAGR of primary energy (r_{E_p}) vs. CAAGR of GDP (r_{GDP}).

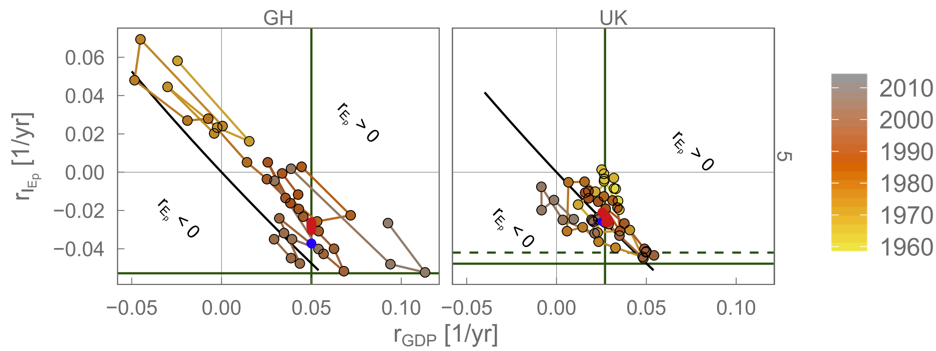

Fig. 13. CAAGR of primary energy intensity ($r_{I_{E_p}}$) vs. CAAGR of GDP (r_{GDP}).

Fig. 13 shows the CAAGR of primary energy intensity ($r_{I_{E_p}}$) vs. the CAAGR of GDP (r_{GDP}). Green lines, blue dots, and red dots have the same meaning as in Fig. 12, expressed in terms of primary energy intensity where needed. The black line provides the locus of points where $r_{E_p} = 0$ and separates zones where $r_{E_p} > 0$ (above and to its right) and $r_{E_p} < 0$ (below and to its left). The equation for the $r_{E_p} = 0$ line is found by setting r_{E_p} to zero in Eq. (3).

Figs. 12 and 13 allow several observations about historical and future trends in the level of decoupling of primary energy consumption from GDP.

Targets assume absolute decoupling will occur. In Fig. 12, all horizontal dark green lines fall below the *x*-axis and all vertical dark green lines are placed to the right of the *y*-axis, indicating that, in combination, the targets presume decreasing primary energy consumption and increasing GDP for both countries. Thus, the combination of energy and economy targets implicitly assumes absolute decoupling can and will occur.

The SDG-7.3 target is unprecedented. Not only do the primary energy consumption targets implicitly assume absolute decoupling, Fig. 13 shows that the SDG-7.3 target (solid horizontal dark green line) is unprecedented and extremely ambitious: the CAAGR of primary energy intensity ($r_{I_{E_p}}$) has never surpassed the SDG-7.3 target.

The results in Fig. 13, which pertain to our specific countries (Ghana and the UK), largely agree with Loftus et al. [80, Fig. 3] who indicate that 17 decarbonization scenarios for the *world* economy assume unprecedented rates of primary energy intensity reduction. “[The scenarios' primary energy intensity reduction] rates fall far outside the range of historical experience and also significantly exceed the fastest sustained rates of [primary] energy intensity decline observed in any individual OECD nation from 1971 to 2006” [80, p. 100]. We extend that observation to a developing nation (Ghana) here.

Absolute decoupling is rare; relative decoupling is common. Fig. 12 shows that absolute decoupling between primary energy and GDP is rare for Ghana: only three points are present in quadrant IV. For the UK, points in quadrant IV are from recent years (>1990) indicating that offshoring is likely responsible for the presence of absolute decoupling. (See Section 3.1.) The years of absolute decoupling are also correlated with years of low GDP growth, because the predominant pattern of historical dots in Fig. 12 has a positive slope.

In Section 2.4, we noted that the dynamics of feedback loops between thermodynamic efficiency gains and economic growth are not included in the forward projections and forecasts of primary energy consumption (Figs. 10 and 11). If these dynamics were to be included, the direction would be toward even higher GDP, even higher primary energy consumption, and even less likelihood of absolute decoupling.

We note that if this analysis were conducted on a footprinting basis to include the embodied energy of international trade, the results for the UK might look rather different, with points in recent years shifting upward in the UK graph of Fig. 12. Both Ward et al. [5, Fig. 1] and Fig. 1 show that the aggregate world economy (which cannot offshore production because it is a closed system) exhibits relative decoupling and has never been absolutely decoupled.

Implications. **The likely extent of decoupling is insufficient to achieve the SDG-7.3 target (Ghana and the UK) and the EUCO + 33 target (UK).** Absolute decoupling of primary energy consumption from economic growth appears to be a very difficult task: economies simply need energy to function, and they need more energy to grow. Although relative decoupling is common for both Ghana and the UK, absolute decoupling is rare.

4. Discussion

In combination, two of the previous observations ((a) energy and economic targets presume absolute decoupling and (b) the historical global reality of relative decoupling as shown in Fig. 1) indicate that primary energy consumption targets that assume absolute decoupling are unlikely to be met, regardless of the development stage of the country. Indeed, our projections and forecasts for primary energy consumption (Section 3.3) fall far short of the international targets for primary energy (Fig. 12) and primary energy intensity (Fig. 13). The shortfall is true for *both* the aggregate primary stage projection method (blue dots) and the disaggregate useful stage forecast method (red dots).

Fig. 13 shows that increased GDP provides energy intensity benefits while Fig. 12 shows that increased GDP is consistent with increased primary energy consumption. Thus, a perverse dynamic exists: countries can perform better on the SDG 7.3.1 metric by increasing GDP, but evidence from Ghana and the UK suggests they are likely to consume more primary energy (and therefore emit more CO_2) in the process.

We can use today's Ghana as an example. If Ghana is to meet the SDG 7.3.1 metric from Table 3, it needs

$$r_{I_{E_p}} \leqslant -0.0528/\text{year}. \tag{5}$$

Substituting Eq. (2) for $r_{I_{E_p}}$ gives

$$\frac{1 + r_{E_p}}{1 + r_{GDP}} - 1 \leqslant -0.0528/\text{year}. \tag{6}$$

Solving for r_{E_p} and substituting Ghana's blistering 2017 GDP growth rate ($r_{GDP} = 0.085$/year) gives

$$r_{E_p} \leqslant 0.028/\text{year}. \tag{7}$$

That is to say, with the CAAGR of GDP at $r_{GDP} = 0.085$/year, Ghana can *grow* primary energy consumption by $r_{E_p} = 0.028$/year and still meet the SDG 7.3.1 metric ($r_{I_{E_p}} = -0.0528$/year). This example shows that a primary energy target assessed as primary energy intensity (such as the SDG-7.3 target and its SDG-7.3.1 primary energy intensity metric) does not ensure that primary energy consumption will decline, as would be

Table 7
Coefficients for linear fits to data in Fig. 9. Linear model is of the form $r_{GDP} = a\, r_{\eta_{X,pu}} + b$.

	a	b
Ghana	0.567	0.031
UK	0.838	0.017

required to meet climate change mitigation objectives.

Many suggest that technical efficiency is a reasonable prescription to meet primary energy targets and sustain GDP growth: increased thermodynamic efficiency could reduce primary energy consumption while maintaining constant levels of useful exergy supplied to the economy. Warr and Ayres [79, p. 1692] say "increased energy efficiency as a driver of growth provides hope for sustained future wealth creation." Grubler et al. [82] develop an efficiency-based future scenario that limits global temperature rise to 1.5 °C. And the IEA's Sustainable Development Scenario (Fig. 2) assumes that efficiency gains are one of the key responses to climate change considerations.

However, Fig. 9 shows that increasing thermodynamic efficiency is associated with increasing GDP. And Fig. 12 shows that increasing GDP is associated with increasing primary energy consumption. Thus, based on evidence from these two economies, thermodynamic efficiency gains do not seem to be an effective means of reducing primary energy consumption, due to economy-wide feedback loops discussed by, among others, Herring [83], Sorrell [84], and Arrobbio and Padovan[85]. We believe that our results provide a partial explanation why Fig. 1 shows there is no historical precedent for absolute decoupling on the worldwide scale [5, Fig. 1]. Our results are consistent with recent work by Saunders [86] (who says that energy rebound effects [87] may be larger than we think) and Brockway et al. [37] (who identify energy rebound as a potential threat to a low-carbon future).

To understand these relationships more deeply and to bring focus to the CO_2 emissions problem that is the driving force behind primary energy targets in the first place, we begin with the following equation (derived in Appendix G) which describes the conditions under which CO_2 emissions decline ($r_{CO_2} < 0$):

$$\frac{(1 + r_{GDP})(1 + r_{I_{X_u}})(1 + r_{c_{X_p}})}{(1 + r_{\eta_{X,pu}})} < 1, \tag{8}$$

where $r_{c_{X_p}}$ is the CAAGR of primary-exergy-specific CO_2 emissions (the ratio of CO_2 emissions to primary exergy consumption, X_p). As the left side of Eq. (8) becomes smaller and further from 1, the CAAGR of CO_2 emissions (r_{CO_2}) becomes more negative, as required to meet climate change objectives.

We can use the results of this paper to simplify Eq. (8) to gain policy insights. First, Fig. 8 shows that I_{X_u} is very constant, so we can approximate $r_{I_{X_u}} \approx 0$. Second, we can include thermodynamic efficiency–GDP feedback through the economy by substituting linear fits in Fig. 9 into Eq. (8). The best-fit linear relationship between GDP and $\eta_{X,pu}$ in Fig. 9 can be expressed as $r_{GDP} = a\, r_{\eta_{X,pu}} + b$. Substituting both simplifications into Eq. (8) yields

$$\frac{1 + a\, r_{\eta_{X,pu}} + b}{1 + r_{\eta_{X,pu}}}(1 + r_{c_{X_p}}) < 1. \tag{9}$$

The ineffectiveness of thermodynamic efficiency as a means to reduce CO_2 emissions is clear from Eq. (9): to the extent that $a \approx 1$ and $b \approx 0$, the value of the fraction in Eq. (9) will be 1. If the value of the fraction in Eq. (9) is 1, changing $r_{\eta_{X,pu}}$ will have no effect on the value of the left side of Eq. (9) and, therefore, no effect on CO_2 emissions.

The values of a and b coefficients for Ghana and the UK are shown in Table 7. Substituting the coefficients from Table 7 into Eq. (9), we obtain for Ghana

$$\frac{1.031 + 0.567\, r_{\eta_{X,pu}}}{1 + r_{\eta_{X,pu}}}(1 + r_{c_{X_p}}) < 1 \tag{10}$$

and for the UK

$$\frac{1.017 + 0.838\, r_{\eta_{X,pu}}}{1 + r_{\eta_{X,pu}}}(1 + r_{c_{X_p}}) < 1. \tag{11}$$

For both Ghana and the UK, $b \approx 0$ is a good approximation. For the UK, a is nearly 1 (0.838). For Ghana, a is not as close to 1 (0.567). But for any reasonable value of $r_{\eta_{X,pu}}$, say $0.0/\text{year} < r_{\eta_{X,pu}} < 0.1/\text{year}$, the value of the fractional term in Eq. (9) is within 0.03 of 1, confirming that thermodynamic efficiency has little effect on reducing CO_2 emissions. For both countries, thermodynamic efficiency–GDP feedback through the wider economy "takes back" efficiency-driven CO_2 emissions reductions.

In contrast, Eq. (9) shows that any improvement in decarbonizing primary exergy (i.e., a negative value of $r_{c_{X_p}}$) directly reduces CO_2 emissions on a 1:1 basis. Thus, the most promising approach to reducing CO_2 emissions appears to be rapid reduction of the carbon content of primary exergy. **Investment in and delivery of low- or zero-carbon primary energy sources is, therefore, an even more urgent priority.**

5. Conclusions and future work

5.1. Conclusions

From our study of (Q1)–(Q4) in Section 3 and the discussion in Section 4, we can draw several important conclusions. First, we see the benefit of the physical supply use table framework for societal exergy analysis [16], because its analysis of historical energy conversion chain data enables insights into future thermodynamic efficiency, economic growth, and primary energy requirements.

Second, taken together, Figs. 12 and 13 show that increasing GDP both (a) decreases the growth rate for energy intensity ($r_{I_{E_p}}$) and (b) increases the growth rate for primary energy consumption (r_{E_p}). For example, if Ghana achieves its economic growth projection ($r_{GDP} = 0.05/\text{year}$), we expect both increasing primary energy consumption at a rate of $r_{E_p} = 0.02/\text{year}$ (Fig. 12) and decreasing primary energy intensity at a rate of $r_{I_{E_p}} = -0.025/\text{year}$ (Fig. 13). Thus, for the countries in this study (Ghana and the UK), meeting the Sustainable Development Goal 7.3.1 metric via economic growth will lead to more primary energy consumption ($r_{E_p} > 0$), not less! If primary energy supply is not decarbonized faster than primary energy consumption grows, our findings suggest a perverse outcome is likely: success on the Sustainable Development Goal-7.3.1 metric will mean *increased* carbon dioxide emissions.

Third, we find that thermodynamic efficiency gains have minimal effect on primary energy consumption due to economy-wide feedback effects. Specifically, we see that for any reasonable rate of increase of thermodynamic efficiency, say $0.0/\text{year} < r_{\eta_{X,pu}} < 0.1/\text{year}$, the value of the fractional term in Eq. (9) is within 0.03 of 1. Thus, our results show that thermodynamic efficiency gains will not be an effective means to reduce carbon dioxide emissions.

Fourth, in a world in which most countries (and the planet as a whole) show only relative decoupling of primary energy consumption from GDP growth, energy intensity is *not* an appropriate metric for measuring progress toward primary energy reduction goals. Depending on the gross domestic product growth rate (r_{GDP}), a country could end up on either side of the $r_{E_p} = 0$ line in Fig. 13, even if primary energy intensity is declining ($r_{I_{E_p}} < 0$). For example, we found that Ghana can increase primary energy consumption by $r_{E_p} = 0.028/\text{year}$ and still meet its Sustainable Development Goal 7.3.1 metric ($r_{I_{Ep}} = -0.0528$/year) if it continues its very high economic growth rate ($r_{GDP} = 0.085$/year).

Finally, it appears that it will be very difficult to decouple primary energy consumption from GDP for Ghana and the UK, with the caveat that offshoring may continue to give the appearance of decoupling for the UK. If we (a) generalize from the two countries of this paper, (b) assume that GDP growth is desirable for human well-being considerations, and (c) assume that GDP growth will continue, primary energy consumption will rise into the future. Under those assumptions, meeting primary energy and energy intensity targets simultaneously appears to be mission impossible for both developing and developed economies alike.

We conclude, based on the analyses of this paper, that unless interventions are focused on decarbonizing primary energy supply, Paris' 2 °C ambitions are unlikely to be met. Additional strategies (beyond thermodynamic efficiency improvements) for rapid carbon dioxide emissions reductions will likely be required. Investment in and delivery of low- or zero-carbon primary energy sources is, therefore, an even more urgent priority.

5.2. Future work

As discussed in Section 3.1, future studies could better account for the effects of offshoring and the effects of international trade on both net importing and net exporting countries. Embodied energy associated with net imports of goods to the UK should be included, while for Ghana the primary-to-final transformation losses associated with the rising net importation of finished fuels (e.g. diesel) should be included.

Additional low, medium, high, and very high human development index countries should be analyzed, thereby generating a larger set of data from which patterns could be assessed. Questions to be addressed include: do all low and medium human development index countries have the same exergy/economy characteristics as Ghana? And do all high and very high human development index countries have the same exergy/economy characteristics as the UK?

More broadly, we found evidence in Fig. 9 that rising thermodynamic efficiency ($\eta_{X,pu}$) is positively correlated with economic growth. We also saw that thermodynamic efficiency has plateaued in the UK, possibly indicating that its energy-economy system is thermodynamically constrained and that future thermodynamic-efficiency-driven economic growth may be difficult to achieve. Ghana, on the other hand, appears to have thermodynamic efficiency "headroom" to continue efficiency-driven economic growth. Further exploration of an "efficiency headroom" hypothesis is merited, because it has key implications for energy resources, energy conversion, and energy conservation.

Finally, this paper raises the question of whether GDP is a helpful indicator of human well-being in the first place [88]. Many of the analyses herein could be repeated using human development index, the genuine progress indicator, life expectancy, or other indicators on the x-axis of Figs. 9, 12, and 13.

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Appendix A. Nomenclature

Table A.1 lists the nomenclature for this paper.

Table A.1
Nomenclature.

Symbol	Description
a	Slope of a best-fit line
b	Intercept of a best-fit line
c	Primary-exergy-specific CO_2 emissions
D	Multiplicative changes in useful exergy
E	Energy quantities
I	Energy or exergy intensity of economic activity
r	Compound average annual growth rate
t	Time
X	Exergy quantities
x	Any variable for which r is desired or an LMDI factor
Acronyms/abbreviations	
CAAGR	Compound average annual growth rate
CO_2	Carbon dioxide
ECC	Energy conversion chain
ECG	Electricity company of Ghana
EUCO	European commission
FAO	UN food and agriculture organization
GDP	Gross domestic product
GH	Ghana
HDI	Human development index
HTH	High-temperature heat
IEA	International energy agency
IPCC	Intergovernmental panel on climate change
LMDI	Log-mean divisia index

(continued on next page)

Table A.1 (*continued*)

Symbol	Description
LTH	Low-temperature heat
MD	Mechanical drive
NG	Natural gas (primarily methane, CH_4)
OECD	Organization for economic co-operation and development
PCM	Physical content method
PPP	Purchasing power parity
PRIMES	PRIce-driven and agent-based simulation of Markets Energy System
PSUT	Physical supply-use table
PWT	Penn world table
RCP	Representative concentration pathway
SDG	Sustainable development goal
SI	Supplemental information
sq.	Square
TPES	Total primary energy supply
UK	United Kingdom
UN	United Nations
U.S.	United States
USD	United States dollar
VALCO	Volta aluminum company
Units	
°C	Celsius
km	kilometer
ktoe	kilotons of oil equivalent
MJ	megajoules
yr	year
Greek	
Δ	Indicates a difference
ϕ	Exergy-to-energy ratio at a point in the ECC
η	Efficiency (energy or exergy)
Subscripts	
1	Pertains to an initial condition or time
2	Pertains to a final condition or time
c	Pertains to primary-exergy-specific CO_2 emissions
CO_2	Pertains to carbon dioxide
$diff$	Pertains to a difference
dil	Pertains to dilution (task-level structural change)
E	Pertains to energy
eff	Pertains to efficiency
ex	In LMDI analysis, pertains to primary exergy supply
f	Pertains to final energy or exergy
p	Pertains to primary stage of the ECC
pu	Pertains to primary-to-useful stages of the ECC
str	Pertains to structural changes
t	Pertains to time
tot	Pertains to a total
u	Pertains to useful stage of the ECC
X	Pertains to exergy
x	Pertains to a generic quantity

Appendix B. Graphs of $\eta_{X,pu}$, r_{E_p}, and r_{IE_p} vs. r_{GDP} for 1 year $\leqslant \Delta t_{diff} \leqslant$ 10 years

This appendix provides graphs akin to Figs. 9, 12, and 13. However, the figures in this appendix show results for 1 year $\leqslant \Delta t_{diff} \leqslant$ 10 years (see Figs. B.1, B.2, B.3).

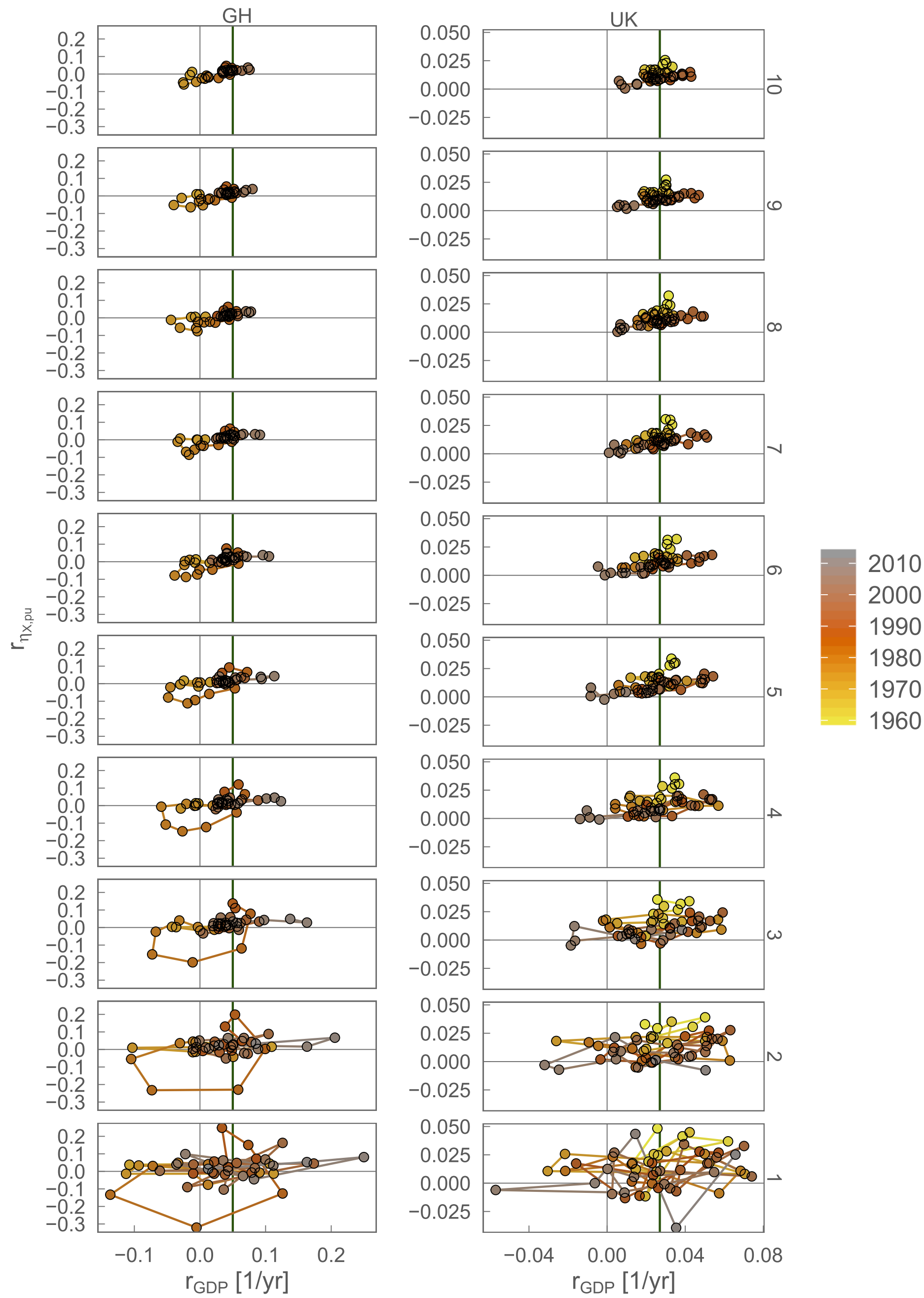

Fig. B.1. CAAGR of thermodynamic efficiency ($r_{X,pu}$) vs. CAAGR of GDP (r_{GDP}). Δt_{diff} (in years) is given by row label. See Fig. 9 for description.

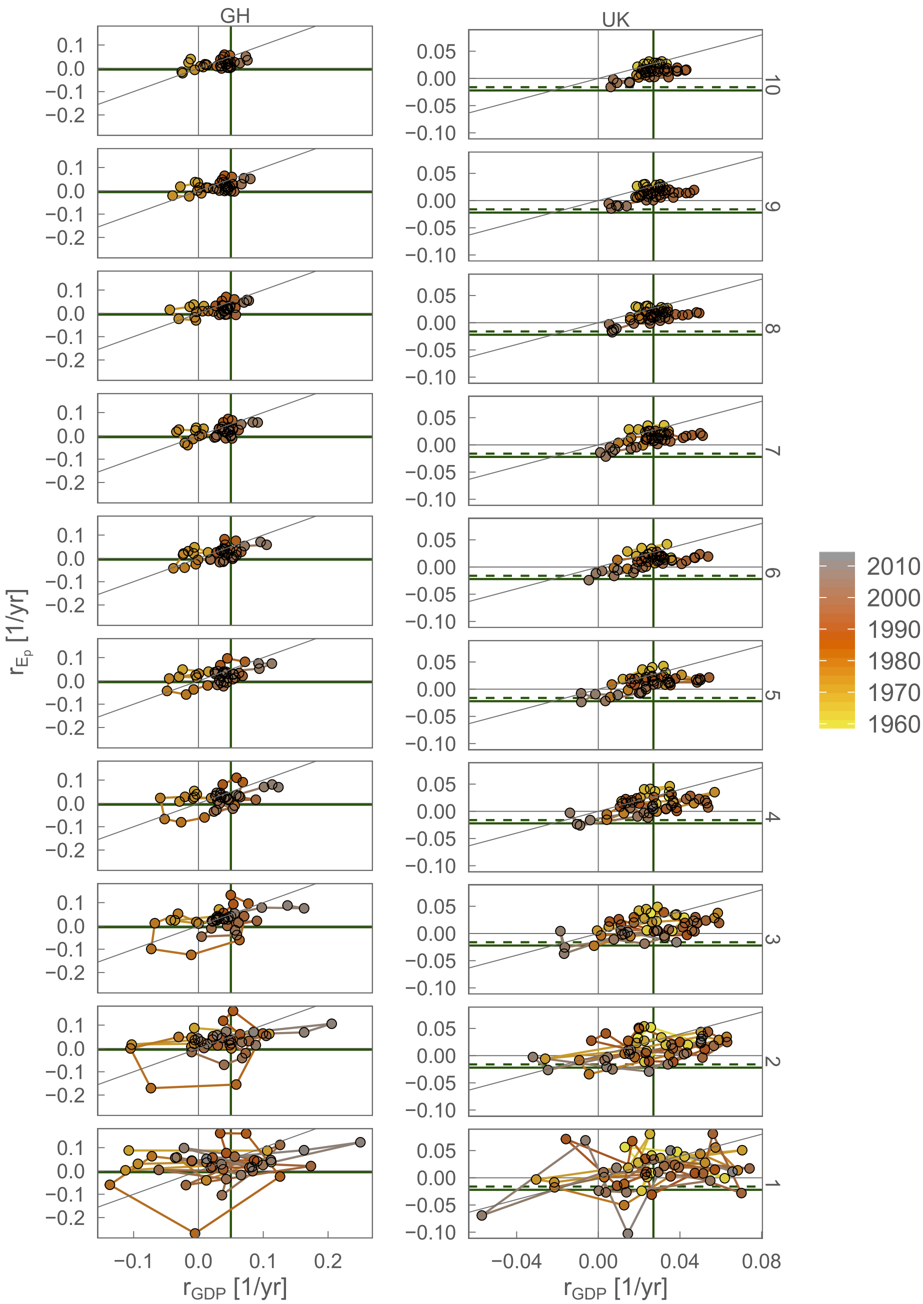

Fig. B.2. CAAGR of primary energy vs. CAAGR of GDP Δt_{diff} (in years) is given by row label. See Fig. 12 for description.

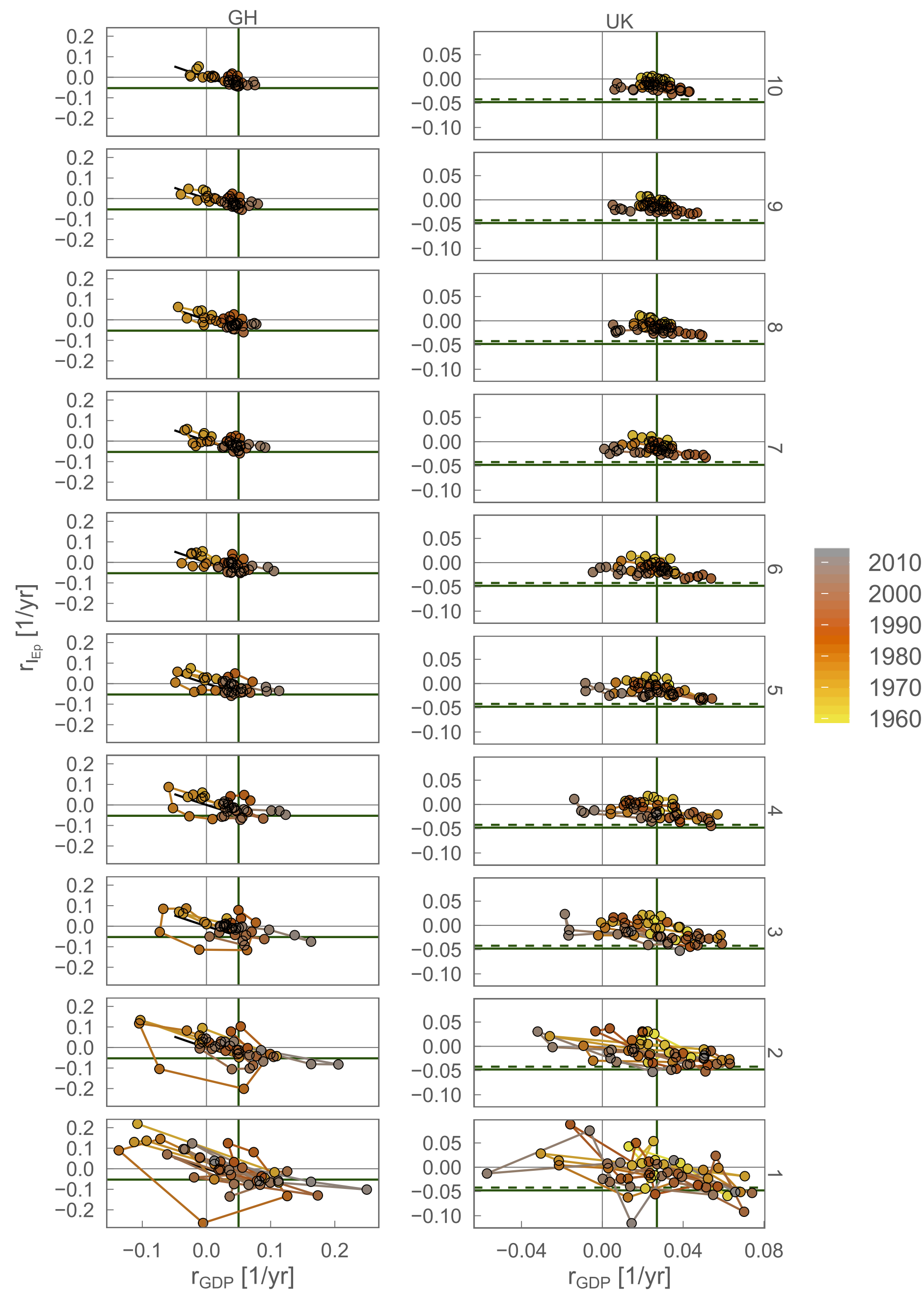

Fig. B.3. CAAGR of primary energy intensity ($r_{I_{Ep}}$) vs. CAAGR of GDP (r_{GDP}). Δt_{diff} (in years) is given by row label. See Fig. 13 for description.

Appendix C. Primary energy projection and forecast methods

This appendix describes the calculation process to estimating energy consumption to 2030. See [30] for details.

C.1. Disaggregated useful stage energy forecast method

Step 1: Set task-level useful exergy demand to 2030

(a) Forecast aggregate useful exergy (X_u) to 2030.
- Construct historical X_u/GDP plot.
- Extrapolate X_u/GDP time series to 2030 using asymptotic best fit to historical X_u/GDP as a guide.
- Obtain time series *GDP* forecast to 2030.
- Multiply forecasted U/GDP time series by forecast *GDP* time series to obtain forecast X_u demand to 2030.

(b) Forecast main sector (*j*, heat, mechanical drive, electricity, and muscle work) useful exergy ($X_{u,j}$) to 2030.
- Calculate time series of historical shares of main sectors.
- Forecast main sector share time series to 2030, based on extrapolation, external data, and engineering judgment, especially for share

saturation.

(c) Calculate task-level (i) useful exergy ($X_{u,ij}$) time series to 2030.
- Construct task-level useful exergy ($X_{u,ij}$) time series to 2030, via extrapolation.
- Keep one task-level ($X_{u,ij}$) in each main sector floating, to balance against the top-down sector level forecast ($X_{u,j}$).
- Adjust $X_{u,ij}$ time series for known external issues and/or points to be matched, e.g., transport demand forecast from external sources.

Step 2: Set task-level exergetic efficiency to 2030

(a) Extrapolate primary-to-useful task-level efficiency $\eta_{pu,ij}$ time series to 2030.
(b) Adjust $\eta_{pu,ij}$ time series based on external information. For example, the UK is approaching a maximum first law efficiency limit for domestic gas boilers. For Ghana, examples include assuming that VALCO smelters resumed operations in 2014 (raises HTH efficiency above long term trend); raising of LPG cook stove efficiencies to account for the effect of improved cook stove policies (affects MTH efficiencies); and the assumption that primary-to-useful electricity efficiency is constant 2013–2030 (balancing the effects of a decline in primary-to-final efficiency from increasing consumption of imported fuels, against improvements to final-to-useful task-level electrical efficiencies).

Step 3: Estimate primary energy to 2030

(a) Estimate task-level primary exergy ($X_{p,ij}$) time series by dividing task-level useful exergy ($X_{u,ij}$) time series by task-level efficiency ($\eta_{pu,ij}$) time series.
(b) Sum task-level primary exergy ($X_{p,ij}$) time series over tasks (i) to obtain main sector primary exergy ($X_{p,j}$) time series.
(c) Sum $X_{p,j}$ over main sectors to obtain aggregate primary exergy (X_p) time series to 2030.
(d) Divide X_p time series by average primary exergy to primary energy ratio ($\phi \approx 1.07$) to obtain estimated primary energy (E_p) time series.

C.2. Aggregated primary stage energy projection methods

The estimated primary energy (E_p) time series developed via Steps 1–3 in Section C.1 above can be compared to estimates of primary energy from the aggregate *primary* stage projection method discussed below.

C.2.1. Primary energy intensity (E_p/GDP) projections

- Curve fit historical E_p/GDP time series.
- Project curve fit to obtain projected E_p/GDP time series to 2030.
- Multiply by *GDP* forecast time series to give aggregate E_p to 2030.

Appendix D. Exergy-to-energy ratio (ϕ)

Fig. D.1 shows the aggregate exergy-to-energy ratio (ϕ) for all energy stages, with and without non-energy uses of energy carriers. Note that forecasts for ϕ_p are shown for years 2014–2030.

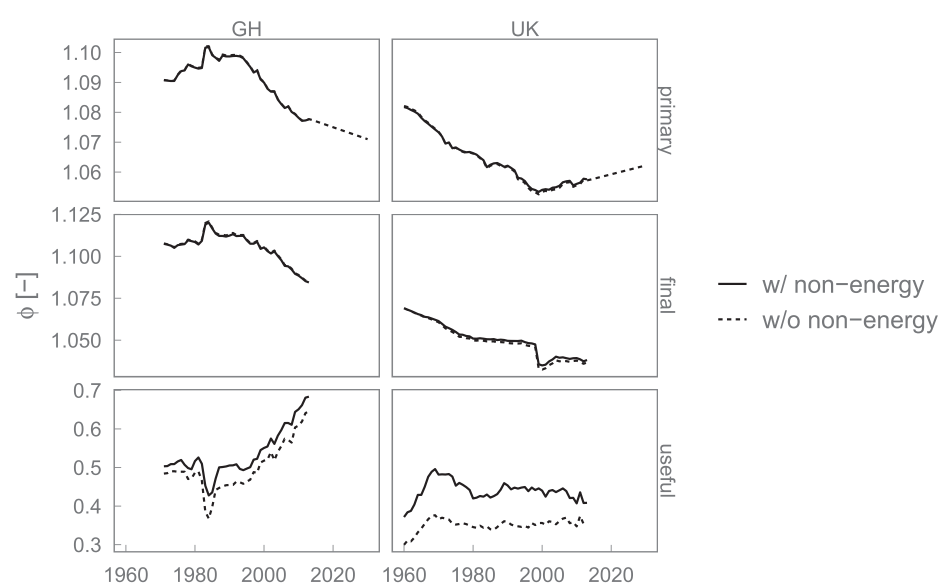

Fig. D.1. Exergy-to-energy ratio (ϕ).

Appendix E. Primary energy and primary energy intensity targets

Policy targets for Ghana and the UK are expressed either in terms of primary energy (by the European Commission (EUCO) [89]) or in terms of energy intensity (by the United Nations [1]). But we desire to present projections, forecasts, results, and analyses in terms of annual compounding growth rates (*r*, see Eq. (1)) of *both* primary energy and primary energy intensity. (See Figs. 12 and 13.) This appendix shows the derivation of Eqs. (2) and (3) which translate in both directions between goals expressed in terms of CAAGRs of primary energy (r_{E_p}) and goals expressed in terms of CAAGRs of primary energy intensity ($r_{I_{Ep}}$).X If one knows r_{E_p} and r_{GDP}, a value of $r_{I_{Ep}}$ is implied. Similarly, if one knows $r_{I_{Ep}}$ and r_{GDP}, a value of $r_{I_{Ep}}$ is implied.

E.1. Implied r_{E_p} (Eq. (3))

We begin by stating the CAAGR equations for GDP and energy intensity (I_{E_p}) between the years 2013 (the last year of historical data in this paper) and 2030 (the last year of projections and forecasts in this paper), a period of 17 years:

$$\text{GDP}_{2030} = \text{GDP}_{2013}(1 + r_{GDP})^{17}, \tag{E.1}$$

and

$$I_{E_p,2030} = I_{E_p,2013}\left(1 + r_{I_{Ep}}\right)^{17}. \tag{E.2}$$

Primary energy consumption in 2030 is

$$E_{p,2030} = I_{E_p,2030}\,\text{GDP}_{2030}. \tag{E.3}$$

Substituting Eqs. (E.1) and (E.2) into Eq. (E.3) gives

$$E_{p,2030} = I_{E_p,2013}\left(1 + r_{I_{Ep}}\right)^{17}\text{GDP}_{2013}(1 + r_{GDP})^{17}. \tag{E.4}$$

Primary energy consumption in 2030 ($E_{p,2030}$) can be expressed as an annual growth rate ($E_{p,2030} = E_{p,2013}\left(1 + r_{E_p}\right)^{17}$), and substituting into Eq. (E.4) gives

$$E_{p,2013}\left(1 + r_{E_p}\right)^{17} = I_{E_p,2013}\left(1 + r_{I_{Ep}}\right)^{17}\text{GDP}_{2013}(1 + r_{GDP})^{17}. \tag{E.5}$$

Solving Eq. (E.5) for r_{Ep} gives

$$r_{E_p} = (1 + r_{I_{Ep}})(1 + r_{GDP}) - 1. \tag{3}$$

Eq. (3) gives the implied CAAGR for primary energy consumption (r_{E_p}) when the CAAGRs for primary energy intensity ($r_{I_{Ep}}$) and GDP (r_{GDP}) are known.

E.2. Implied $r_{I_{Ep}}$ (Eq. (2))

To derive the implied value of CAAGR of energy intensity ($r_{I_{Ep}}$) when the CAAGRs for primary energy (r_{E_p}) and GDP (r_{GDP}) are known, we begin with the definition of primary energy intensity applied to 2030:

$$I_{E_p,2030} = \frac{E_{p,2030}}{\text{GDP}_{2030}}. \tag{E.6}$$

Substituting Eqs. (E.1) and (E.3) into Eq. (E.6) yields

$$I_{E_p,2030} = \frac{E_{p,2013}\left(1 + r_{E_p}\right)^{17}}{\text{GDP}_{2013}(1 + r_{GDP})^{17}}. \tag{E.7}$$

$I_{E_p,2030}$ can be expressed as a CAAGR ($I_{E_p,2030} = I_{E_p,2013}\left(1 + r_{I_{Ep}}\right)^{17}$), substituted into Eq. (E.7), and solved for $r_{I_{Ep}}$ to obtain

$$r_{I_{Ep}} = \frac{1 + r_{E_p}}{1 + r_{GDP}} - 1. \tag{2}$$

Eq. (2) gives the implied CAAGR for primary energy intensity ($r_{I_{Ep}}$) when the CAAGRs for primary energy consumption (r_{E_p}) and GDP (r_{GDP}) are known.

Appendix F. Exergetic intensity of economic activity: all GDP measures

Fig. F.1 shows energy intensity of economic activity for all GDP types available in the PWT. Fig. F.1 is a counterpart to Fig. 8. The "rgdpo" row Fig. F.1 is identical to Fig. 8.

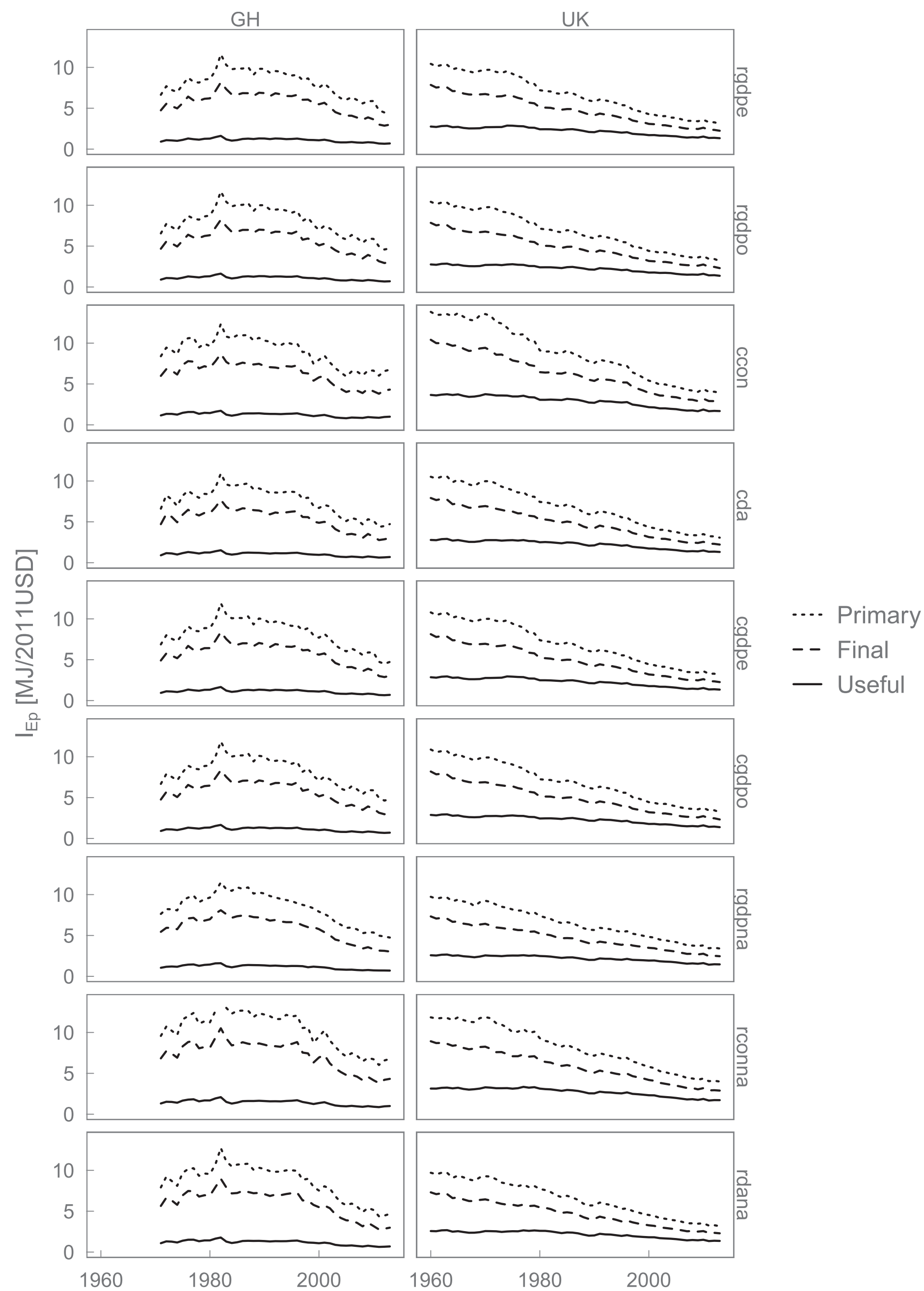

Fig. F.1. Energy intensity of economic activity with all measures of GDP from PWT.

Appendix G. Derivation of CO_2 identity

The derivation of Eq. (8) begins with an equation similar to the IPAT equation and the Kaya identity:

$$CO_2 = \text{GDP}\frac{X_u}{\text{GDP}}\frac{X_p}{X_u}\frac{CO_2}{X_p}. \tag{G.1}$$

We note that $\frac{X_u}{\text{GDP}}$ is the useful exergy intensity of economic production (I_{X_u}), $\frac{X_p}{X_u}$ is the inverse of the thermodynamic efficiency of the economy ($\eta_{X,pu}$), and $\frac{CO_2}{X_p}$ is primary-exergy-specific CO_2 emissions (c_{X_p}). Substituting into Eq. (G.1) gives

$$CO_2 = GDPI_{X_u} \frac{1}{\eta_{X,pu}} c_{X_p}. \quad (G.2)$$

If Eq. (G.2) is taken at time t_2, each term (x) can be expressed by its CAAGR (r_x) relative to a prior time (t_1):

$$x_{t_2} = x_{t_1}(1 + r_x)^{(t_2 - t_1)}. \quad (G.3)$$

Substituting Eq. (G.3) for each term into Eq. (G.2) gives

$$(1 + r_{CO_2}) = \frac{(1 + r_{GDP})(1 + r_{I_{Xu}})(1 + r_{c_{Xp}})}{(1 + r_{\eta_{X,pu}})}. \quad (G.4)$$

Eq. (G.4) can be solved for r_{CO_2} to obtain

$$r_{CO_2} = \frac{(1 + r_{GDP})(1 + r_{I_{Xu}})(1 + r_{c_{Xp}})}{(1 + r_{\eta_{X,pu}})} - 1. \quad (G.5)$$

For a declining CO_2 emissions rate, $r_{CO_2} < 0$, and

$$\frac{(1 + r_{GDP})(1 + r_{I_{Xu}})(1 + r_{c_{Xp}})}{(1 + r_{\eta_{X,pu}})} < 1, \quad (8)$$

which is the same as Eq. (8).

Supplementary material

1. Supplemental Information (SI) associated with this article can be found in the online version, at https://doi.org/10.1016/j.apenergy.2019.01.255.
2. Data associated with this work including longitudinal trends of final-to-useful efficiencies are available from the Research Data Leeds repository under a CC-BY license at https://doi.org/10.5518/559. Further info: https://library.leeds.ac.uk/research-data-epsrc, http://bit.ly/2uIzCPS and/or http://bit.ly/2u01mlj.
3. All PSUT framework analysis code is freely available online as `R` packages. Four packages are involved: `matsbyname` [70], `matsindf` [71], `Recca` [72], and `LMDIR` [73].

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