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A physical supply-use table framework for energy analysis on the energy conversion chain

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HIGHLIGHTS

- Today, energy analysis addresses topics all along the energy conversion chain.
- The field of energy analysis would benefit from a common analysis framework.
- In response, a physical supply-use table framework is presented.
- Real-world examples demonstrate the range of applicability of the framework.
- Benefits include data structure uniformity and methodological consistency.

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ABSTRACT

In response to the oil crises of the 1970s, energy accounting experienced a revolution and became the much broader field of energy analysis, in part by expanding along the energy conversion chain from primary and final energy to useful energy and energy services, which satisfy human needs. After evolution and specialization, the field of energy analysis today addresses topics along the entire energy conversion chain, including energy conversion systems, energy resources, carbon emissions, and the role of energy services in promoting human well-being and development. And the expanded field would benefit from a common analysis framework that provides data structure uniformity and methodological consistency.

Building upon recent advances in related fields, we propose a physical supply-use table energy analysis framework consisting of four matrices from which the input-output structure of an energy conversion chain can be determined and the effects of changes in final demand can be estimated. Real-world examples demonstrate the physical supply-use table framework via investigation of energy analysis questions for a United Kingdom energy conversion chain.

The physical supply use table framework has two key methodological advances over the building blocks that precede it, namely extending a common energy analysis framework through to energy services and application of physical supply-use tables to both energy and exergy analysis. The methodological advances enable the following first-time contributions to the literature: (1) performing energy and exergy analyses on an energy conversion chain using physical supply-use table matrices comprised of disaggregated products in physical units when the last stage is any of final energy, useful energy, or energy services; (2) performing structural path analysis on an energy conversion chain; and (3) developing and utilizing a matrix approach to inhomogeneous units. The framework spans the entire energy conversion chain and is suitable for many sub-fields of energy analysis, including net energy analysis, societal energy analysis, human needs and well-being, and structural path analysis, all of which are explored in this paper.

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1. Introduction

1.1. A recent history of energy analysis: expansion through revolution and evolution

The modern field of energy analysis is rooted in energy accounting, which emerged in the 1950s from Leontief's input-output (IO) methods [1] and Barnett's energy balance tables [2]. With studies of the U.S. economy by Schurr and Netschert [3] and Morrison and Readling [4], the field remained closely aligned to energy accounting methods through the 1960s (see Berndt [5] for an overview of the early history of energy analysis).

The 1970s oil crises caused a revolution in the field: its focus expanded from merely accounting for production and sale of primary and final energy carriers to many other aspects of energy in society and the economy. Reistad [6, p. 429] said, "In this period of concern for our energy resources and the environment, it is imperative to consider the manner in which our energy resources are consumed." The study of technical energy efficiency became prominent, illustrated by a 1973 conference presentation by Hatsopoulos [7] and the 1975 American Institute of Physics reports on second-law efficiency [8], automobiles [9], and industrial processes [10]. At an economy-wide level, studies of net energy [11], useful energy [6], and energy services [12] were conducted. Furthermore, new studies of interactions between energy and the economy appeared, covering topics such as the energy impact of consumption decisions [13], the entropic nature of economic processes [14], energy and "potential" GDP [15], and questioning the value of the concept of energy intensity [16]. In 1978, Roberts [17, p. 200] noted that the term "energy *analysis*" was now preferred to "energy *accounting*," the name change signifying that the revolution was underway.

Following the 1970s, evolution and specialization led to the creation of several energy analysis sub-fields. Net energy analysis evolved from the study of single fossil fuel sources (e.g., oil, coal, gas) [18] to renewables [19,20] and to the consideration of economy-wide issues such as the minimum energy return on (energy) invested (EROI) required for a functioning society [21], the implications of declining EROI [22], energy expenditure and economic growth [23], and input-output methods to determine national-level EROI [24]. World-wide issues also received attention, including detailed studies of oil and gas production [25], correlations between EROI and oil prices [26], and social implications [27]. The empirical study of energy efficiency and rebound [28] specialized into evaluation of direct [29], indirect [30], and sectoral and economy-wide rebound for energy in the UK [31] and for energy intensity as opposed to energy efficiency [32]. A new sub-field, societal exergy analysis, emerged. Building on the earlier work of Reistad [6], Wall [33], and Kümmel et al. [34], Ayres and co-authors made significant advances on the role of physical resources flows in endogenous growth models [35], the role of physical work in economic growth [36], efficiencies of specific energy and economic sectors [37], and the impact of natural resource consumption and technological change on economic growth [38]. Recent work has standardized allocation of final energy to useful exergy categories [39], improved estimates of exergetic efficiencies [40], and explored theoretical efficiency limits of end-use devices [41]. Another new sub-field (energy decomposition analysis) expanded greatly largely due to the efforts of Ang who developed log-mean divisia index (LMDI) methods [42], compared them against other decomposition approaches [43], applied them to monitoring energy intensity [44], and provided a practical guide for implementation [45]. Further specialization of energy analysis occurred as researchers considered the role of energy in economic growth in terms of energy constraints [46], primary energy sources [47], empirical evidence from many countries [48], and causality directions and substitution possibilities via time-series analysis [49]. The benefits [50] and limitations [51] of the metaphor "the economy is society's metabolism" were explored by several authors, and the magnitude of the industrial energetic and material metabolism has been estimated for the EU [52] and the world [53]. Others have explored the role that energy plays in satisfying human needs [54] across various nations [55], have studied how energy enables well-being [56], and have developed a sufficiency framework for decoupling human well-being from energy consumption [57]. Lastly, analysis of long-run energy transitions has received much recent attention, with researchers studying countries (the UK [58], the U.S. [59], and Sweden [60]), causes (energy cost share [61] and policy [62]), and policy needs for a transition away from oil [26] and toward a sustainable future [63].

1.2. The energy conversion chain (ECC)

A notable feature of this history is an expanding analysis boundary. In the 1960s, energy accountants were focused on primary energy sources and final energy carriers. Today, energy analysts also consider the consumption of useful energy produced by consumer-owned devices [39] to generate energy services [64,65] that satisfy human needs and enable human well-being and development [57]. The expanded boundary covers the entire *energy conversion chain* (ECC), a term (to our knowledge) introduced by Crowe [66, p. 3] to describe energy conversion processes in diesel generators and fuel cells. We find the phrase to be apt for all types of energy analysis, so we define it more broadly to be a set of energy carriers, energy transformation devices, and energy services within spatial and temporal boundaries of interest. In this paper, we focus on economy-spanning ECCs comprised of primary, final, and useful energy carriers as well as the energy services they enable.

Fig. 1 shows an example ECC with two pathways: Natural gas (NG) to Residential end use and Crude to Transport end use. Activities in the

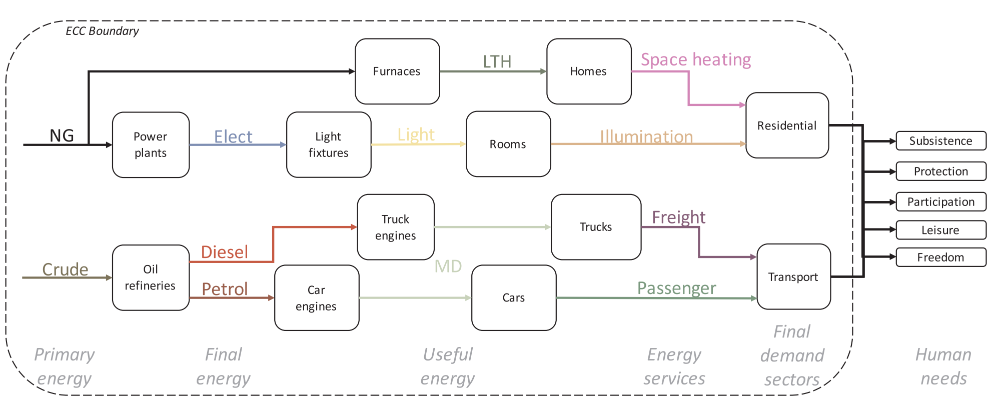

Fig. 1. Energy conversion chain (ECC) example. NG is Natural gas. LTH is Low-temperature heat. MD is Mechanical drive. Line colors indicate products and match Figs. 3, 7, 11 and B.1.