Method Précis: Energy Flow Analysis

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The analysis of energy flows related to socioeconomic activities is a key method in Social Ecology. Energy flow analysis (EFA) is based on the physical notion of energy as the ability to do work. The abstract notion of energy encompasses mechanical (potential and kinetic) energy, radiant energy, chemical energy, heat, electric energy and nuclear energy. The functioning and sustenance of any biophysical system—including the biophysical structures of society—requires a continuous flow of energy (Smil 1991, 2008).

Energy flows between ecosystems and socioeconomic systems are an important part of socioeconomic metabolism. It is the purpose of this Method Précis to outline methods to account for and analyze such energy flows. Most sustainability problems are directly related to the quantity and quality of energy used by a society. Energy is an indispensable economic resource; almost all technologies used in production, transport, distribution and consumption activities require energy. In the Social Sciences, there is a long-standing, controversial discussion on the extent to which energy can be used to explain social phenomena. Answers range from the outright denial of any explanatory power of an influence of energy on society to the assumption that energy is perhaps the most important driver of socioeconomic change (Cottrell 1955; Martinez-Alier 1987). Although conventional energy statistics and balances are an important data source for socioecological studies of energy, many applications require a broader concept of EFA, explained below after a tour-de-force through important fundamentals of energy analysis.

Different types of energy can be measured with the same units. Unfortunately, different world regions and expert communities traditionally use different units. The energy unit according to the International System of Units (SI) is the joule (J). One joule is a very small amount of energy. In almost all practical contexts, one must deal with multiples constructed using prefixes, such as kilojoule (1 kJ = 10^3 J), megajoule (1 MJ = 10^6 J), gigajoule (1 GJ = 10^9 J), terajoule (1 TJ = 10^{12} J), petajoule (1 PJ = 10^{15} J) and exajoule (1 EJ = 10^{18} J). Table 8.1 provides factors to convert some often-used units into joules.

The laws of thermodynamics are indispensable when trying to understand energy. According to the First Law of Thermodynamics, the amount of energy is constant in a closed system. In other words, energy cannot be destroyed (hence, the term 'energy consumption' is incorrect; energy conversion or energy demand are more accurate formulations). The Second Law, or Entropy Law, states that in a closed system, energy conversions can only take place if entropy increases. Entropy is the foundation of measures of energy quality, such as exergy. For example, mechanical and electrical energy are of high quality (high exergy) because they can, in theory, be converted to other kinds of energy without loss. Other kinds of energy, such as heat, have a lower quality (lower exergy); their conversion to high-quality energy (e.g., mechanical energy) entails substantial losses even under idealized optimal conditions.

Table 8.1 Overview of some common energy units

Abbreviation	Unit	Conversion to Joules
kWh	Kilowatt-hour	1 kWh = 3.6 MJ
Cal	Calorie*	1 cal = 4.1868 J
Btu	British thermal unit	1 Btu = 1.055 kJ
Quad	Quadrillion Btu	1 quad = 10^{15} Btu = 1.055 EJ
Toe	Tons of oil equivalent	1 toe = 41.9 GJ**
Tce	Tons of coal equivalent	1 tce = 29.3 GJ**

* Note that 'food calories' always refer to kilocalories. 1 kcal = 1000 cal (10^3 cal)
** Indicative value: different conventions exist. If possible, always check for the conversion factor assumed

Another important distinction is that between energy and power. Energy refers to a defined amount of work performed regardless of the time required to perform the work. The amount of energy flowing or being converted per unit of time is defined as 'power', measured in the unit watt (W): 1 W = 1 J/s.

Due to the economic importance of energy, national statistical offices as well as international bodies (e.g., the International Energy Agency and the United Nations) regularly collect and publish energy statistics. Energy statistics report energy used in artifacts, such as in technical structures such as motors, power plants, furnaces and boilers, but they exclude biological energy flows such as food, feed and the physical work performed by draft animals and humans (IFIAS 1974). Although any collection of data on technical energy use in different units and related to different economic units, such as economic sectors, is referred to as 'energy statistics', an 'energy balance' provides a consistent view of the energy used in a national economy in one common unit (but, unfortunately, not always in joules). Important notions used in energy balances are the following:

- Primary energy, i.e., energy in the form in which it is extracted from the biosphere. Examples are wood, coal, crude oil, natural gas, water and wind power, solar energy and heat from nuclear fission and geothermal sources. Primary energy use is usually approximated with the indicator 'Total Primary Energy Supply', abbreviated TPES, which is the sum of the domestic extraction of primary energy plus the net import (= import minus export) of energy carriers.
- Conversion processes from primary to final energy, such as electricity and heat generation or the conversion of crude oil to products such as heating oil, gasoline or diesel fuel.
- Final energy is the energy sold to final consumers. This excludes the sale of energy to sectors that convert energy into other forms, e.g., electricity generation. Examples of final energy carriers are wood chips, coke, gasoline, gas, electricity and heat (if it is sold, but not if it is self-generated in a heating system).
- Useful energy is the energy actually flowing when a certain energy service is provided. Examples are the mechanical energy needed to shape, move or lift objects in stationary motors or vehicles; the heat required for heating or

processing purposes; chemical energy needed in the chemical industry; light (radiant) energy; and the data processing services of computers.
- Energy services are those services for which energy is used (Lovins 1979). Examples include transport; the establishment of suitable conditions within a building in terms of temperature, humidity or illumination; the cleaning of clothes; the shaping of objects; and chemical conversions. In contrast to primary, final and useful energy, energy services cannot be measured in energy units (or in any other common unit) and, hence, cannot be aggregated.

Two concepts are important when interpreting data in energy statistics and balances:

- There are two conventions for the energy equivalent of combustible materials (coal, oil, gas and biomass). The gross calorific value (higher heating value) measures the total amount of energy released in combustion measured in a bomb calorimeter. It includes the energy released in the condensation of water vapor in the flue gas. Because the energy released by condensation is often unusable, it is excluded in the second convention, the net calorific value (or lower heating value). The difference between the net and gross calorific value is generally 5–15 %.
- Different conventions exist to account for the primary energy equivalent of non-combustible energy technologies, such as hydropower, wind power, geothermal and nuclear energy. These conventions may differ by factors of up to three to four. Thus, understanding the conventions followed in a particular data source is mandatory to avoid misinterpretation or flawed comparisons.

Because the food, feed and muscle power of humans and draft animals are of fundamental importance in a socioecological context, even if food or work flows are relatively small compared to fossil fuel flows in industrial society, EFA methods have been developed to establish energy balances that include biomass and work flows. In principle, EFA follows the above-outlined logic of energy balances, that is, it traces the flow of energy through the socioeconomic system from primary energy supply to useful energy (Fig. 8.5), but it adds biomass and work to the technical energy flows considered in the conventional energy balance (Haberl 2001). Whereas conventional energy balances account for biomass only if it is used in artifacts (e.g., power plants, heating systems, as engine fuel), EFA also includes the biomass converted by endosomatic processes.

EFA considers all energy crossing the nature-society boundary based on its physical energy content, or the gross calorific value. The nutrition of humans and livestock is considered an energy conversion process within society. The processing of primary biomass to food and feed is regarded as a conversion from primary to final energy. Food and feed are defined as final energy and human as well as animal labor as useful energy (Haberl 2001). EFA can generate indicators such as the following:

- Direct energy input (DEI): all energy entering a society (the same concept as ‘direct material input’ used in material flow analysis, MFA).
- Domestic energy consumption (DEC): direct energy input minus export (the same concept as ‘domestic material consumption’ used in MFA).

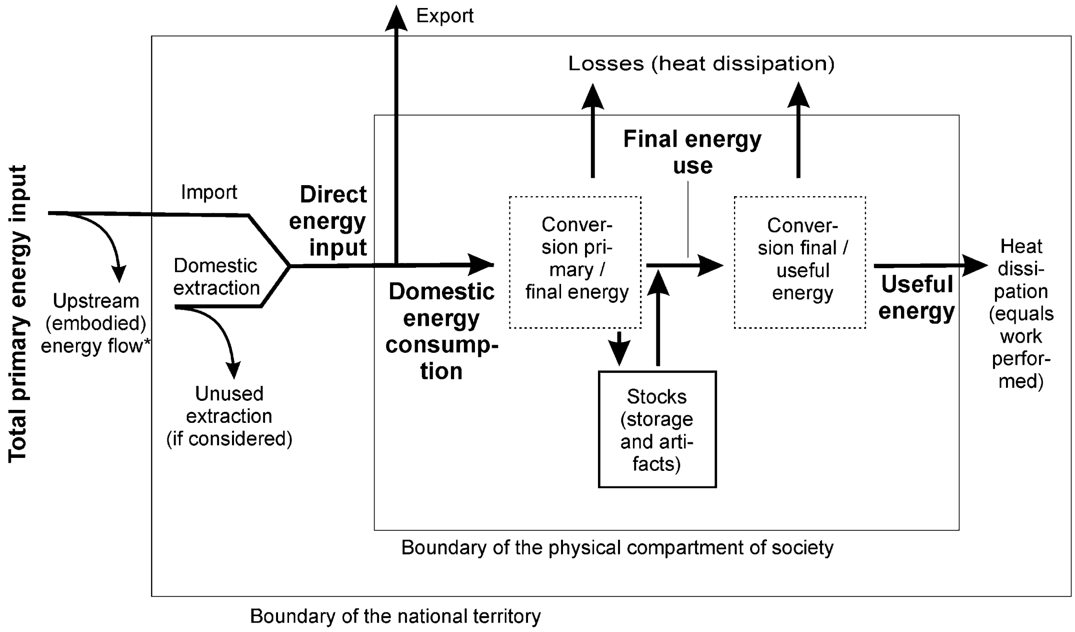

Fig. 8.5 Flow chart of an energy flow analysis (EFA) consistent with the material flow analysis (MFA) approach as used in socioeconomic metabolism studies. (Redrawn after Krausmann and Haberl 2002, Fig. 1). * Upstream flows related to import may (or may not) include foreign unused extraction—needs to be made explicit in each case

- Indicators of final and useful energy as they are used in conventional energy balances.
- 'Upstream flows': includes energy expended in providing imported energy carriers ('embodied' energy). Energy mobilized during energy extraction but not actually entering socioeconomic metabolism (e.g., crop residues) is termed 'unused extraction' and may (or may not) be considered appropriate for the respective research question.

EFA complements MFA methods to form the combined 'material and energy flow analysis' (MEFA) framework, which has been shown to be useful for studying sustainability and socioecological transitions (see also Chaps. 3, 6, 20, 21 and 22).

References

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