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Yellow, red, and brown energy: leveraging water footprinting concepts for decarbonizing energy systems

Emily Grubert[1]

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Abstract

As the energy system changes, metrics used to describe energy use for modelling, socioenvironmental assessment, and other applications should be continually evaluated to ensure ongoing relevance and applicability. Decarbonization highlights the need for fit-for-purpose assessment tools as energy systems undergo an expected transition from mostly fossil to mostly nonfossil resources. Energy use has historically been a high-quality proxy for socioenvironmental impacts of interest, but this characteristic depends on the relatively stable historical relationship between energy use (typically measured as exchanges of marketed energy resources and carriers like natural gas and electricity) and these impacts—a relationship that is increasingly weak. Already, energy use metrics used in tools like energy footprinting and life cycle assessment have developed maladaptations to include nonfossil resources, including many flow resources. For example, nonmarketed energy use is typically ignored; metrics like heat rate are applied to nonthermal resources in ways with limited physical meaning; and definitional exceptions are made without clear justification. Part of the challenge is that energy is a conserved quantity with highly variable quality, but energy footprint metrics have historically implicitly assumed that all energy, and energy use, is the same. The assessment community can improve the clarity and value of energy use quantification under decarbonization by drawing on the experience of footprinting with another highly heterogeneous conserved resource: water. This discussion introduces the concept of a yellow, red, and brown energy footprint framework as an expansion of traditional energy footprinting and analogue of the green, blue, and grey water footprinting framework.

Keywords Energy · Water · Footprint · Environmental assessment · Social assessment · Sustainability

✉ Emily Grubert
egrubert@nd.edu

1 Keough School of Global Affairs, University of Notre Dame, 1010 Jenkins Nanovic Halls, Notre Dame, IN 46556, USA

1 Introduction

The energy system is rapidly changing, with a particular emphasis on reducing the use of fossil fuels because of climate change. Decarbonization is an energy system dynamic that is expected to bring structural changes that are unprecedented during the period since widespread analytical interest in environmental impacts of human systems emerged around the 1960s–1970s (Dunlap, 1991; Guinée et al., 2011). Despite locally relevant differences associated with characteristics like fuel mix, environmental regulations, costs, and access to supply chains, assuming that about 40% of global marketed energy comes from oil, 30% from coal, and 20% from natural gas has been reasonable for decades (BP, 2019, and Fig. 1)—including during the period when tools like energy footprinting and life cycle assessment were developed. Future energy supply systems, however, could heavily rely on renewable resources with qualitatively different characteristics, both physically and environmentally, including nonthermal resources like wind and solar photovoltaic resources (Pehl et al., 2017; Williams et al., 2021).

The industrialized energy system has been relatively consistent for decades, with most energy coming from fossil fuels and a system organized around ensuring that supply can meet demand (Asmus, 2010; BP, 2019). Issues associated with fossil fuels like cost, environmental impacts, health impacts, geopolitical issues, and infrastructural needs are at least categorically similar over space and time. This context of stability has influenced how analytical approaches like energy footprinting have developed. For example, energy use analytical approaches often carry an implicit assumption that energy resources are depletable and create environmental impacts largely during the use phase, both of which encourage an emphasis on energy efficiency and marginal impacts that are less relevant for resources with impacts driven by capital deployment.

An important emerging trend for sustainability assessment focused on energy use is that energy use is becoming a less valuable proxy for relevant socioenvironmental impacts as the energy system decarbonizes. This change is analytically meaningful: fossil fuel energy use has been identified as the primary driver of multicriteria environmental burden for most commodities other than agricultural products (Huijbregts et al., 2010). Efforts to quantify multicriteria sustainability issues using tools like life cycle assessment (LCA) are often challenged by the need for large amounts of data (Reap et al., 2008), so being able

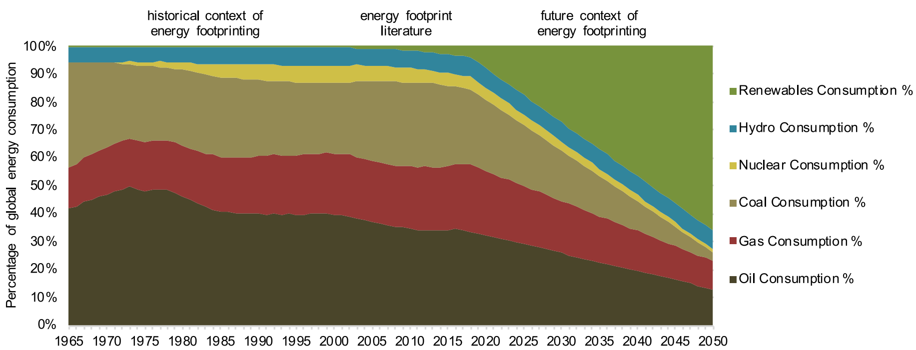

Fig. 1 The energy system is changing from fossil-dominated to renewable-dominated. The transition is likely to disrupt reliable relationships between energy footprints and socioenvironmental proxies. *Sources*: Historical, BP Statistical Review of Energy. Future, IRENA ReMap

to reduce parameters by identifying a high-quality proxy for decision-relevant issues, like fossil energy consumption, is helpful. Although some research has focused specifically on energy scarcity (Bardi, 2019; Ritchie & Dowlatabadi, 2017), research has tended to focus on energy use because of its value as a proxy for a variety of financial and socioenvironmental impacts rather than because of an inherent interest in energy use itself. For example, analysts might be interested in energy efficiency (e.g. of a process or economy) because of a desire to compare costs, technological sophistication, reliance on particular fuel supply chains, or negative externalities of energy usage (Brown & Logan, 2008; Elgowainy et al., 2014; Englander et al., 2015; Fisher-Vanden et al., 2006; Heidarinejad et al., 2018; Hong et al., 2007; Wang, 2007). Historically, energy use has been well correlated with negative environmental externalities or pressures like air pollution, climate change, water pollution, water use, solid waste generation, and other issues (Algunaibet & Guillén-Gosálbez, 2019; Andrews, 2004; Dennis Lemly, 2015; EPA, 2018a; Grubert & Sanders, 2018; Höök & Tang, 2013; NREL, 2017; Proops et al., 1996). Social impacts associated with energy provisioning have also received substantial attention (Colvin et al., 2019; Grubert & Skinner, 2017; Haggerty et al., 2018a; Jacquet et al., 2018; Junod et al., 2018; Measham et al., 2015; Olson-Hazboun, 2018; Stedman et al., 2012; Willow & Keefer, 2015).

Research on the relationship between energy and impacts like cost, climate change, air pollution, and others has likely contributed to the motivation and technological advances necessary for energy system transformation—indicative of the power of such analyses, and the value of ensuring similar analyses can describe the transitioning and future energy systems. As Fig. 1 shows, energy system transformation has already begun to shift toward renewable energy, but a much deeper shift is anticipated over the coming decades (Hertwich et al., 2014; Pehl et al., 2017; Pfeiffer et al., 2016; Tong et al., 2019; Williams et al., 2021). Particularly given the world's heavily globalized economy and anticipated unevenness in spatiotemporal shifts associated with the energy sector, the energy-related sustainability assessment community will likely need to carefully consider what questions energy use analyses are designed to answer.

Sustainability quantification methods that use energy consumption as a metric must grapple with the reality that the underlying driver of the reason that energy has been a useful proxy for impacts—a consistent fuel mix—is changing. Furthermore, anticipated fuel mixes are likely to be dynamic for decades and will likely change at different rates in different places, suggesting that metrics will need to account both for stable end points and for dynamic transition periods. Recognizing that the energy footprint—here defined loosely as the total amount of energy used to accomplish a goal—is the basis of energy analysis across multiple methods, this paper thus asks: how can the energy footprint remain a useful and sufficiently disaggregated metric to be valuable for sustainability quantification and socioenvironmental assessment more broadly?

The hypothesis of this work is that energy footprinting as currently practiced is useful for the historical energy system, but is not well suited for analysis during and after structural transition to a primarily nonfossil fuel system. Given the value of being able to evaluate the portion of the energy system that current metrics are well suited for, particularly given that decarbonization is a normative transition for which evaluating counterfactual impact scenarios is relevant for system design, a new approach for energy footprinting should include existing metrics where they work—but expand the analytical scope to cover transition and a future stable system. Recognizing that energy has highly variable quality, both in terms of its physical properties (e.g. exergy) and socioenvironmental properties (e.g. life cycle impacts), is a core element of such an expansion. Being able to describe the difference between one form and/or use of energy and others enables more precise analysis of human use of energy. For example, passive solar, active solar, and coal-fired electricity can all provide heating services, but are clearly different in ways that existing footprinting practice is poorly equipped to reflect. This gap leads to confusing outcomes like classifying passive solar design strategies as methods for reducing energy use, or assuming that total energy demand is less important as a metric for solar versus coal-fired electricity.

This article draws on prior experience with resource footprinting in the form of the water footprint to propose that the energy footprint be expanded to include three major categories with relevantly different sustainability implications: roughly, use of incidentally available energy resources; use of industrially available energy resources (corresponding to existing energy footprinting practice); and energy that would be required to reverse environmental impacts. The remainder of the article describes energy use metrics as they are now and makes the case for expanding the definition of the energy footprint; explains how the water resources community has addressed some of the same problems the energy community increasingly faces; and proposes a yellow, red, and brown energy footprint framework as an analogy to the green, blue, and grey water footprint framework. The article concludes with a call to test the potential value of such an amendment to current energy use quantification practice in life cycle assessment and beyond.

2 Why energy use metrics need to be reconsidered

There are a variety of metrics aimed at assessing sustainability through the lens of energy use, often designed to achieve different goals. One of the most common classes of energy-related sustainability analysis, and the one generally used for footprinting and sustainability assessment, focuses on the total amount of energy deployed to produce a product or service. For example, the concepts of cumulative energy demand (Huijbregts et al., 2010), embodied energy (Chen et al., 2018), and most applications of the energy footprint essentially aim to quantify the amount of energy that is deployed toward a given end, restricted by some boundary conditions. In practice, these tools usually define energy as commercial energy (e.g. coal rather than informal biomass) and use as transformation via some conversion process (e.g. in a power plant or appliance). Although energy use metrics are often converted to socioenvironmental or financial metrics via intensity factors, a practice that includes the implicit assumption that impacts are driven by marginal use of energy, the primary goal of these methods is to quantify energy flows participating in formal market systems. That is, informal or nonmarket energy resources like dung or solar heat are generally excluded, as are energy quality issues (both exergetically and from a pollution perspective).

Other energy-related sustainability metrics do account for nonmarket energy and energy quality issues, reflecting the point that energy is not a single, completely standardized resource. For example, emergy analysis seeks to account for all prior energy inputs required to make a product or service, including, e.g. the solar energy embodied in more recently available fuels (Brown & Ulgiati, 1999; Kharrazi et al., 2014; Law et al., 2017; Odum, 1998). The concept of energy return on energy invested (EROI) addresses the energy footprint of energy, providing an indicator of the energy's quality (particularly with respect to cost) (Arvesen & Hertwich, 2015; Beal et al., 2012; Brandt et al., 2018; Hall et al., 2014; Henshaw et al., 2011; Masnadi et al., 2018), though it usually truncates the boundary of energy invested to focus on commercial energy rather than all the way back to solar or other original inputs. Exergy analysis considers the thermodynamic quality of energy and the degree to which a substance is out of equilibrium with the environment

(Rosen & Dincer, 1999). Exergy both measures value destruction and enables the consideration of nonenergy resource inputs in the same units as energy, which has informed its use as an environmental impact-oriented way of measuring energy use (Finnveden et al., 2016; Rosen & Ao, 2008; Rosen & Dincer, 1999). The breadth of quality categories considered—energy intensity, thermodynamic, financial, and socioenvironmental—is testament to the broad range of analyses that energy use quantification informs.

Extending the energy footprint concept to capture more of the types of observed energy-related analyses within a consistent framework is likely to usefully advance the practice of energy footprinting in a changing global energy system. Current practice for quantifying energy footprints is somewhat ambiguous, but more clearly distinguishing among different goals for assessing energy use can improve both precision and compatibility across analyses. The remainder of this section describes the relationship between energy use and socioenvironmental impacts, with the intent of contextualizing the case to extend the energy footprint to more completely reflect the reality of diverse energy resources and use cases.

2.1 The environmental footprint of the energy system

Environmental impacts of interest are highly correlated with fuel type. Other drivers include technology and regulatory structure, largely related to the presence and effectiveness of pollution control systems. As Fig. 1 shows, approximating the global energy system as a relatively static mix of oil, coal, and natural gas has been reasonable for several decades, which has contributed to relatively stable environmental implications of energy use. Although regional and local differences in efficiency, policy, and other issues have certainly driven variability in environmental impacts of interest (Akber et al., 2017; Peer et al., 2019; Rosenfeld, 1999; Stamford & Azapagic, 2012; Sudarshan, 2013), in general, the energy system has been associated with climate change pollution, conventional air pollution, water resource use and pollution, solid waste issues, scarcity concerns, and other issues primary related to the use of fossil fuels. Particularly as the issue of climate change has become more salient for sustainability quantification (Grubert, 2017), energy use has been an important proxy for environmental impacts due to the major contributions of fossil fuel-based energy systems to greenhouse gas emissions (EPA, 2018b).

As the energy system changes, both structurally and in relation to fuel mix, environmental footprints are expected to change meaningfully as well. Figure 2 illustrates the way that fuel mix alone can influence environmental footprints: depending on what fuels are used, environmental outcomes diverge substantially.

With an expected shift to mostly renewable resources, environmental concerns might shift from air pollution (including climate change) to questions of land occupation, embodied impacts associated with infrastructure—like mining for particular resources used for variable renewable energy systems (Berrill et al., 2016)—and other fuel-specific concerns.

As the energy system changes, metrics for understanding what a particular energy use means for the environment must also adapt. For example, fuel conversion efficiency to electricity is a highly environmentally meaningful metric for fossil fuels because of the implications of fuel combustion. Reporting the same figure for wind and solar power plants seems inappropriate because the environmental impacts of interest are not related directly to fuel use: metrics like required land area or total mining burden per unit of output are more environmentally relevant efficiency metrics than the traditional "fuel in / electricity out." Recording and reporting information about fuel, technology, and conversion

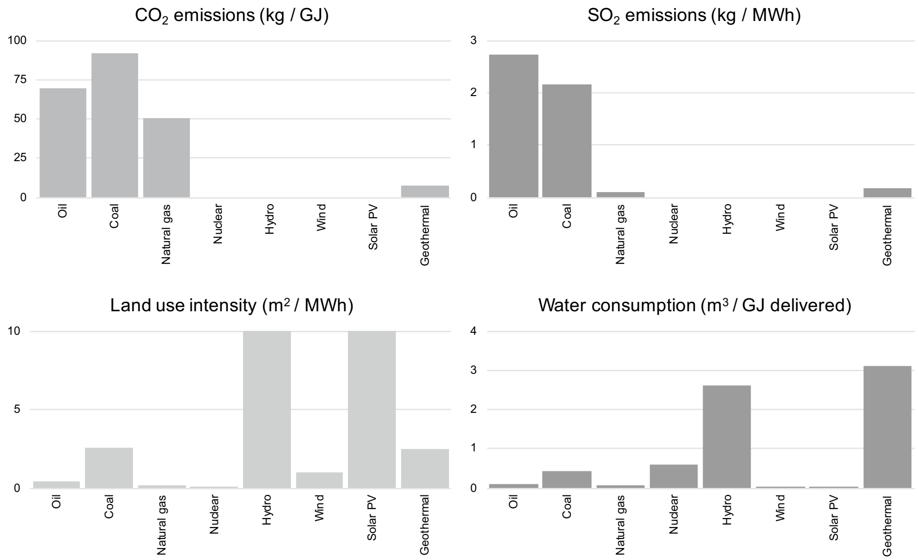

Fig. 2 Different fuels have different environmental impacts. Examples shown, clockwise from top left: CO_2 emissions per GJ, SO_2 emissions per MWh, land use intensity per MWh, and water consumption per GJ delivered. *Sources*: EIA, eGRID, Fritsche et al. 2017, Grubert & Sanders, 2018

processes and associated losses can substantially improve the ability to link energy use data to environmental footprint data.

2.2 The social footprint of the energy system

Quantifying social impacts associated with energy use is challenging and subject to widespread disagreement about whether social impacts should be quantified, and if so, how (Grubert, 2020). Despite challenges with quantification, however, it is clear that energy systems do cause social impact. Some of these impacts are fuel specific, including many real and perceived health issues, while others are more related to distributional equity issues, different value systems, and community context. Underlying many of the challenges with describing social impact is the fact that many of the most salient social impacts are nonproduction-specific (Weidema, 2018), not easily associated to marginal (or any) use of a production pathway (Colvin et al., 2019), or nonmonotonic—that is, an impact might be good for some people and bad for others (Di Cesare et al., 2016).

As with drivers of environmental impact, the relationship between social impact drivers and the energy system is changing as the system itself changes. For example, individual power plants are getting smaller and more distributed (EIA, 2019a), even as a shift from primarily underground, concentrated energy resources to primarily above-ground, unconcentrated energy resources contributes to high land use (Miller & Keith, 2018; Mulvaney, 2017). Industrialization (e.g. in the form of building unconventional fossil and renewable infrastructure in new locations) and deindustrialization (e.g. in the form of closing fossil-fired infrastructure) are both major drivers of social impact (Bazilian et al., 2014; Boudet, 2019; Haggerty et al., 2018b; Mills et al., 2019) that have yet to be fully explored.

Most sustainability quantification methods and standards do not rigorously address social impacts [see, e.g. (Pelletier et al., 2019; Toniolo et al., 2019)]. In general, assessing true social impacts requires substantial amounts of data that are specific to time, place, and sociocultural context, which hampers generalized quantification associated with a single metric like energy use. The type of information needed for linking energy use metrics with social impact assessment is different for that needed for environmental impact assessment. For example, fuel type is highly relevant for predicting air emissions, but specific community (Boudet, 2019; Kroepsch et al., 2019) and even country (Ekener-Petersen et al., 2014) are likely far more relevant for understanding social context. Expanding the energy footprint to cover a wider range of resources could also enable clearer articulation of when, and how, social impacts of energy use matter.

3 Learning from water footprinting

Water and energy are both critical resources for human life. Use of these resources does not inherently represent a socioenvironmental impact, but their use is closely linked to socioenvironmental impacts that vary widely based on context. At least to first approximation, both resources are also conserved, which makes clear definitions of use or consumption challenging (Grubert et al., 2020). As with energy use for human purposes, water use for human purposes ranges from benign to harmful from a socioenvironmental perspective. Also, just as energy use is associated with multiple types of energy (i.e. fuels), water use is associated with multiple types of water with different quality and accessibility characteristics. For example, ocean water is distinct from fresh groundwater, just as solar energy is distinct from oil. For both resources, human use induces changes in availability and quality; the effort required to acquire the resource is highly variable; and the impact of acquiring and using the resource varies based on context.

From a sustainability metrics perspective, data availability is one major difference between energy and water. Data about certain types of energy use are widely available (BP, 2019; EIA, 2018, 2019b), while data about water use are scarce (Chini & Stillwell, 2018; Grubert & Sanders, 2018). One possible explanation is that tracked energy flows tend to be associated with markets and trade, but water is not subject to the same financialization processes. One result of this dichotomy is that energy data tend to focus heavily on market-relevant forms of energy, while water data tend to be more inclusive about the definition of water. For example, EIA data do not include passive solar inputs, and official estimates of primary energy use of costless fuels are based on assumptions with no physical basis (Energy Information Administration, 2019). The high quality of market-relevant data can often obscure the large data gap associated with noncommercial energy resources.

Possibly due to the lack of anchoring on financially bounded available data, the water resources assessment community has tended to take a more expansive view of what counts as a water resource than the energy resources assessment community does with energy resources. Although language and definitions related to water use remain imprecise and inconsistently applied (Grubert et al., 2020), water footprinting has developed a more formalized approach to quantifying highly differentiated meanings of the idea of water use than has energy footprinting. Despite ongoing challenges with definitions and precision in water footprinting (Fereres et al., 2017), this article argues that energy footprinting should adopt the general structure of the water footprint. The remainder of this section explains current water footprinting practice.

Water footprinting distinguishes among three categories of water use. Although specific definitions become important during application, at an intuitive level, green water is locationally bound water that is available without an engineering intervention (essentially, soil moisture); blue water is water that requires an engineering intervention for use (essentially, surface and groundwater), and grey water is the hypothetical volume of water that would be necessary to dilute pollutants to an acceptable level (Hoekstra et al., 2011). Formally, the Water Footprint Network defines green water as “water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants”, blue water as “water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time”, and grey water as “the amount of fresh water required to assimilate pollutants to meet specific water quality standards” (Water Footprint Network, 2011). Thus, the water footprint distinguishes across two water quantity metrics and one water quality metric (Fig. 3).

The concepts of green water and blue water were introduced as early as 1994 by Falkenmark and Mikulski in the context of distinguishing across types of human vulnerability to freshwater scarcity (Falkenmark & Mikulski, 1994), then further elaborated and extended over time (Falkenmark & Rockström, 2006; Hoekstra, 2002, 2017; Hoekstra et al., 2011; Mekonnen & Hoekstra, 2011). One major application of the water footprint, including the grey water footprint as an indicator of environmental impact in the form of water pollution, has been to assess virtual water bound up in trade networks (Chapagain & Hoekstra, 2008; Chini et al., 2018; Hoekstra, 2002)—an issue that is also relevant for energy analysis in the context of globalization (Chen et al., 2018; Hong et al., 2007; Wiedmann, 2009).

Blue, green, and grey water footprints are all defined by two characteristics: 1) what the water is and 2) what it is used for. This focus on both resource type and resource fate is instructive for the energy footprint, particularly because it directly addresses the definitional problems that arise when talking about use or consumption of a nonconsumable resource. Specifically, defining use *of* some specific type of resource *for* some specific

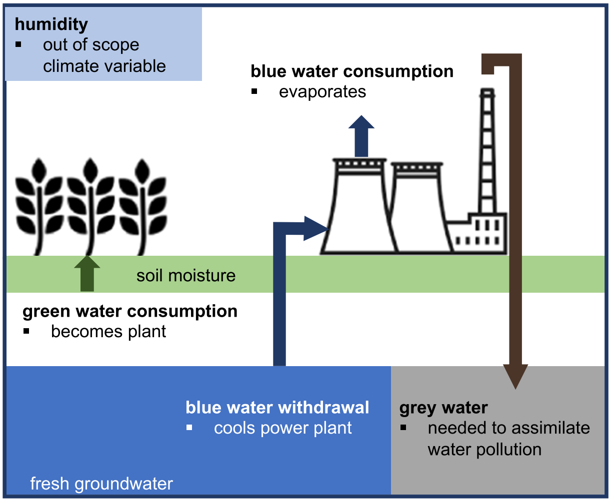

Fig. 3 Elements of the water footprint. Green water is consumed soil moisture, blue water is consumed or withdrawn fresh surface and groundwater, and grey water is a volume needed to assimilate pollution

purpose enables quantification. Although it is not a formal element of the water footprint as defined by the Water Footprint Network, blue water footprints can be further described by type of use—namely, withdrawal (where water is removed from a blue water source whether or not it is returned) or consumption (where water is removed from a blue water source and not returned) (Fig. 3). This distinction in use type is somewhat analogous to the concepts of primary energy (an amount of energy prior to human conversion) and secondary energy (an amount of energy post-human conversion). Another nuance is that although the Water Footprint Network only considers freshwater, water can be further distinguished by salinity, which is somewhat analogous to specifying fuels for energy. A final relevant analogy is that the water footprint excludes large volumes of water that exist outside the context of what most would consider to be usable resources: namely, the climate variable humidity reflects the fact that water is ambiently available, just as the climate variable temperature reflects ambient energy availability. Although it could be argued that both water in humidity and energy in temperature are harnessable resources, the intuitive understanding of what a footprint should be would not consider these to be part of a footprint until some explicit technological capture is undertaken.

4 Extending the energy footprint

Given a goal of extending current practice in energy footprinting to enable a wide variety of analyses that retain intuitive meaning during a period of major transition in the energy sector, extending the energy footprint beyond its typical meaning of cumulative commercial energy demand is likely needed. One value of using water footprint as a blueprint for energy footprinting is that it can inform expansion of the energy footprint in a manner that has already been tested with a resource—water—that has many similarities with energy. Recognizing that there are several different types of analyses that the energy footprint informs can help reveal the need to modify the focus of data collection from traditionally engineered systems (i.e. conventional, commercial energy, or blue water) to a broader suite of qualitatively different subsets of energy resource. The water footprint identifies three analytically distinct categories of water, two focused on quantity and one focused on quality: "free" water (green), "expensive" water (blue), and "cleaning" water (grey). This article proposes that the categories are similar for energy. "Free" energy includes resources like solar heat and light captured for a building or converted to a bioenergy crop. "Expensive" energy is the commercial energy sector and corresponds to the energy typically accounted for in current energy footprinting practice. "Cleaning" energy, as with water, must be expended to correct pollution and thus represents a quality-related cost.

To parallel the green, blue, and grey water footprint framework, this article suggests intuitive terminology of yellow (essentially, natural flow resource) energy, red (essentially, commercial) energy, and brown (pollution control) energy. Table 1 presents proposed definitions for yellow, red, and brown energy alongside green, blue, and grey water definitions, and Fig. 4 illustrates these definitions. These proposals account for the fact that distinguishing between primary and secondary energy remains important for commercial (essentially, red) energy in particular, just as distinguishing between withdrawals and consumptions is relevant for blue water. As with the exclusion of humidity from the water balance from a human footprinting perspective, these definitions also intentionally exclude baseline temperature (and daylight not being intentionally captured) as an energy input. Intentionality of human use is here defined as a use for which

Table 1 Definitions for green, blue, and grey water and proposed definitions for yellow, red, and brown energy

Footprint Water	Use metric	Type	Fate	Examples	Footprint Energy	Use metric	Type	Fate	Examples
Blue water	Withdrawn	Ground or surface fresh-water	Removed from source, whether or not it is returned	Lake water used to cool a power plant	Red energy	Primary	Energy embodied in a renewable or nonrenewable stock resource that has not yet been subjected to engineered conversion processes. Typically[a] purchased as a fuel	Transformed into a different energy carrier, loss, or energy service via a process for which the energy return on energy invested (EROI) is finite	1 MJ of coal converted to electricity or heat
Blue water	Consumed	Ground or surface fresh-water	Removed from source and not returned, e.g. via evaporation, incorporation into a product, or discharge to a different water body	Portion of lake water used to cool a power plant that evaporates	Red energy	Secondary[b]	Energy embodied in an energy carrier derived from some other form of energy via an engineered conversion process, typically purchased[a]	Transformed into a different energy carrier, loss, or energy service via a process for which the energy return on energy invested (EROI) is finite	1 MJ of electricity converted to heat

Table 1 (continued)

Footprint	Use metric	Type	Fate	Examples	Footprint	Use metric	Type	Fate	Examples
Water					Energy				
Green water	Consumed	Precipitation-derived freshwater stored in root zone	Evaporated, transpired, or incorporated by plants	Rainfed soil moisture used to grow corn	Yellow energy	Primary	Energy embodied in renewable flow resource that has not yet been subjected to engineered conversion processes	Transformed into a different energy carrier, loss, or energy service via a process for which the energy return on energy invested (EROI) is finite	1 MJ of sunlight converted to electricity or light
Grey water	Theoretically required volume undergoing specified quality change	Freshwater	Would be needed to assimilate pollutants to meet specific water quality standards	Lake water used to dilute a chemical released from a factory	Brown energy	Theoretically required delivered energy to mitigate environmental quality change	Delivered energy	Required to remove pollutant to acceptable concentration	1 MJ of electricity used for direct air capture of carbon dioxide

[a] Major exceptions: noncommercial biomass, stored water behind a dam

[b] Refers to energy carriers after any number of engineered conversions. Some analysts refer to, e.g. tertiary energy instead

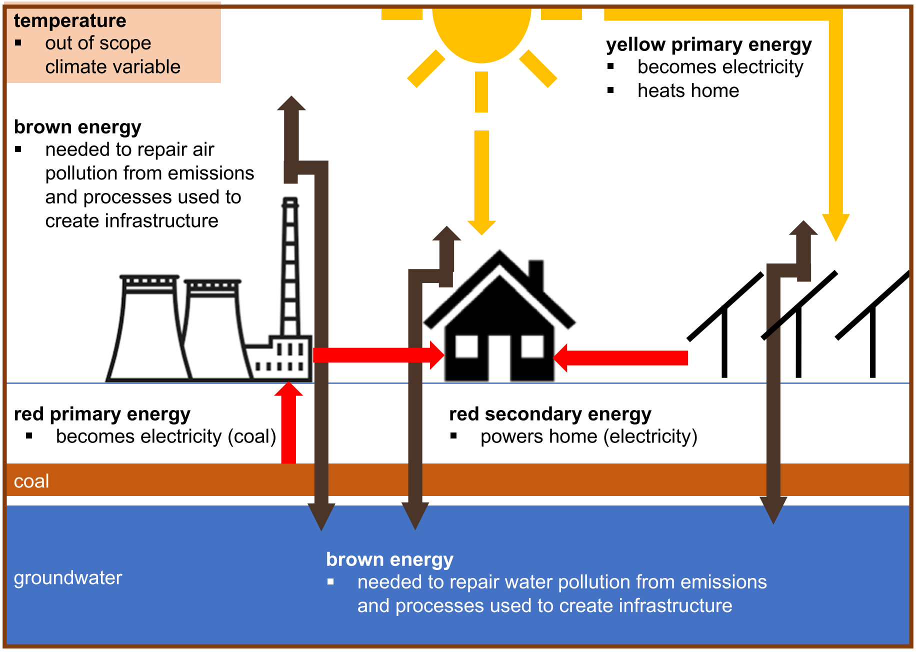

Fig. 4 Elements of the proposed yellow–red–brown energy footprint. Yellow energy is primary captured energy flows, red energy is primary stock resources and secondary engineered resources, and brown energy is delivered energy needed to mitigate pollution

the energy return on energy invested (EROI) is finite—that is, some energy was invested into energy capture, whether in the form of a window, a power plant, a bioenergy crop, or some other mechanic.

One of the rationales for distinguishing between blue and green water is that although both can be used in ways that preclude other uses, blue water is generally scarcer, and using blue water carries higher opportunity cost (Hoekstra et al., 2011). This rationale also applies to the concept of yellow and red energy proposed here: just as abstracting water from a river and transporting it to irrigate a crop typically incurs greater opportunity cost than planting a crop in a location with available soil moisture, mining coal, converting it to electricity, and transmitting it to a house for heating typically incurs greater opportunity cost than orienting the building to receive solar heat. Similarly, both green water and yellow energy are location-locked, which contributes to the typically higher competition for more portable blue water and red energy resources. As Hoekstra et al. argue, tracking green water (or by analogy, yellow energy) is important because it has historically been undervalued as a potential productive input in the face of a traditional engineering emphasis on blue water (or by analogy, red energy) (Hoekstra et al., 2011). Measuring green water or yellow energy inputs can reveal opportunities for currently unconventional system designs that take advantage of these resources.

Characterizing grey water as volumetric has been controversial (Ridoutt & Pfister, 2013), but the fundamental idea of describing "pollution in terms of the claim it puts on scarce freshwater resources" (Hoekstra, 2017) is instructive when considering pollution from an energy resource management perspective. As with grey water, focusing on brown energy—the energy that would be required to return an environmental state to a defined acceptable condition—emphasizes the relevance of environmental damage through a highly evocative metric. Brown energy is in principle similar to an alternative early definition of the energy footprint as the amount of land required to assimilate specific energy-related pollutants (Ferng, 2002; Wackernagel & Rees, 1997), though more focused on a management-relevant indicator in the form of energy requirements. In general, both grey water and brown energy provide a way to both acknowledge and quantify the point that resource management analyses focus on both quantity and quality issues, which are fundamentally different. When analyses require more detail about impacts, the idea of brown energy does not prevent more traditional assessment of pollution impacts via the linking of socioenvironmental intensity metrics with energy use metrics.

As Hoekstra writes in a retrospective look at 15 years of water footprinting, the four major motivators of water footprint assessment are 1) the global dimension of water management due to trade; 2) the limited renewal rates of freshwater; 3) the value of supply chain thinking in informing sustainable resource use; and 4) the need to consider not just traditional water resources (blue water) but also the management implications of location-based, freely available water (green water) and water quality threats (grey water) (Hoekstra, 2017). All four of these drivers also apply to energy. It is largely for this reason that this work proposes an extension of the energy footprint concept based on water footprinting. Unlike socioenvironmental outcome-based footprints (e.g. carbon footprints), the water footprint is fundamentally focused on resource management with attention to externalities rather than on precisely accounting for the externalities themselves. Modelling energy footprints after the water footprint rather than after externality footprints is thus likely to enable more nuanced and more management-relevant analyses because of the recognition that not all energy (or water) is the same.

The remainder of this section describes yellow, red, and brown energy in more detail.

4.1 Yellow energy

As with green water, yellow energy is more easily intuited than precisely defined. Green water is not exactly rain, and yellow energy is not exactly solar, wind, and other renewable energy flows. This article posits that a good definition reflects the core idea that yellow energy is an intentionally captured renewable energy flow resource that is used to provide an energy service of some kind. A few examples can help illustrate desired definitional boundaries. Solar energy collected through a window for daylighting in a building should be yellow energy, but biomass harvested and burned to provide lighting should not. Geothermal energy collected with a circulating fluid or solar energy collected with thermal mass to heat a building should be yellow energy, but ambient temperatures outdoors should not. Solar energy captured and converted to create alternative energy carriers, like biomass via a tree farm or electricity via a solar panel, should be yellow energy, but solar energy inputs to natural forests that are never harvested should not. Based on these intuitions, and based on a desire to connect the concept of yellow energy to existing energy use evaluation metrics, this article proposes the following definition: yellow energy is the amount of energy embodied in a renewable flow resource that has not been subjected to an engineered conversion process that is transformed into a different energy carrier, loss, or energy service via a process for which the EROI is finite (Table 1).

Stock resources (like biomass) are excluded even when renewable because they are generally subjected to some engineered processes to enable use in a conversion process before use, which often means that the fuels themselves are associated with financial and socioenvironmental footprints. For example, wood needs to be harvested, transported, and pelletized before it can be fed into a boiler for conversion, whereas sunlight requires no further processing before it enters a conversion process by hitting a photovoltaic panel. Note that this definition also helps to clarify a common and somewhat confusing distinction drawn about water resources for power generation: hydropower associated with run-of-river systems is often considered among the modern class of renewables, while hydropower associated with dam-and-reservoir systems is not. Damming a river converts a flow water resource, where kinetic energy is extracted, to a stock water resource, where potential energy is extracted.

Another definitional challenge that the introduction of yellow energy helps address is the question of how to usefully define energy efficiency associated with resources like wind and solar energy. Generally, conserving energy is less of a priority when the impacts of use are low or zero (Scheraga, 1994). Currently, the EIA defines the conversion efficiency of renewable flow resources in power plants to be equal to the annual average of that at fossil-fuel fired power plants (Energy Information Administration, 2019). This choice reflects the point that conversion efficiency for renewable flow resource plants is not linked to environmental impacts except via the infrastructures required for conversion, so allowing the often low first-law conversion efficiencies of renewable resources to affect aggregated metrics leads to incorrect conclusions when analysts expect efficiency to be linked to direct fuel-related outcomes. Distinguishing between yellow and red energy clarifies this confusing choice to ignore the actual conversion efficiency for infrastructure using yellow energy: yellow energy fuel use is not environmentally or financially meaningful at first order, but red energy fuel use is.

As with green water, yellow energy use does not carry socioenvironmental impacts other than those associated with the infrastructure required to capture it. In a multicriteria impact assessment context, both green water and yellow energy might more usefully be described with respect to land occupation (Pfister et al., 2017). Thus, higher conversion efficiency is still often desirable, but the direct operational link between efficiency, fuel cost, and conversion impacts does not exist for yellow energy. Notably, however, just because the energy resource itself has minimal inherent impact does not release the overall fuel cycle from impacts (Arent et al., 2014). For example, solar panel manufacturing can lead to serious environmental impacts (Hou et al., 2016). Land occupation and habitat disruption from capture facilities can also cause significant damage (Pruett et al., 2009; Turney & Fthenakis, 2011). These embedded impacts motivate the use of a metric of intentionality in the definition of yellow energy—that is, the energy (and other resources) invested to capture the fuel.

From a management perspective, as with green water, tracking yellow energy can also be useful because it can reveal opportunities to shift energy demand from red to yellow energy. For example, recognizing the role that different equipment in a building can play in harnessing yellow energy for light and heat can lead to substantive design changes that enable similar delivery of energy services with much lower dependence on red energy (Chen et al., 2015; He et al., 2018). Yellow energy is often excluded from consideration (Wang, 2005), so developing a way to include it while still recognizing the decision-relevant differences between yellow and red energy is likely to clarify discussions and reveal opportunities.

4.2 Red energy

The red energy footprint is intuitively equivalent to the energy footprint as it is currently used in practice—essentially, the cumulative energy demand or embodied energy in some analytical object of interest that is derived from marketed fuels. Tentatively, this work suggests formal definitions for primary and secondary red energy as follows. Primary red energy is the energy embodied in a stock resource that is transformed into a different energy carrier, loss, or energy service via a process for which the EROI is finite. Secondary red energy is the energy embodied in an energy carrier derived from some other form of energy via an engineered conversion process. Both types of red energy are typically purchased as fuels (Table 1). Although there are exceptions to the purchasing heuristic, such as for industrial use of fuel by the same organization that produced it (e.g. petcoke at a refinery), the intuition behind the heuristic is to separate use of materials as fuels from use of materials as feedstocks. For example, natural gas used as an input to plastics production rather than for energy supplying the plastics manufacturing process should likely not be considered as part of the energy footprint.

Just as the concepts of withdrawal and consumption as different forms of water use are only really meaningful for blue water, this work proposes that primary and secondary energy distinctions should only be applied to red energy. Thus, the proposed definition of secondary red energy would include electricity made from solar or wind, even though the primary energy is yellow energy. Again by analogy to water footprints, green water is consumed but not withdrawn, and yellow energy is primary but not secondary energy.

Separating yellow and red energy has a number of implications for energy footprinting practice that can improve clarity. One relatively common issue in the literature is that the use of yellow energy solutions for energy service provisioning, like daylighting and passive solar heating for buildings, is characterized as energy savings or energy efficiency (Li, 2010; Omer, 2008) when in fact it is substitution of yellow for red energy. Similarly, as currently used, energy footprints cannot reflect the general understanding that some highly energy inefficient processes, such as using electricity rather than natural gas for space heating, are a desired outcome if the electricity is produced using yellow primary energy (Zappa et al., 2019). Distinguishing between yellow and red energy resources helps avoid the use of widely understood but not physically realistic caveats and exceptions to definitions.

4.3 Brown energy

Including the burden of pollution in metrics associated with energy use can contribute to an environmental communication frame (Lakoff, 2010) that normalizes the need to consider pollution management in understanding implications of energy use. By analogy to the grey water footprint, the brown energy footprint can be tentatively defined as the amount of delivered energy required to remove a pollutant to an acceptable concentration (Table 1). The grey water footprint is "defined as the volume of freshwater that is required to assimilate a load of pollutants to a freshwater body, based on natural background concentrations and existing ambient water quality standards" (Franke et al., 2013)—essentially, the volume of water required to dilute the pollution to an acceptable level. This definition of the grey water footprint includes two main components instructive for defining a brown energy footprint: first, the footprint is defined as a hypothetical water volume directly interacting with the pollution; and second, the amount of water required depends on externally determined references for how clean the water needs to be. That is, the grey water footprint changes if water quality standards change. Similarly, this paper proposes that the brown energy footprint be expressed as hypothetical energy directly interacting with the pollutant—that is, delivered energy, like a kilowatt-hour of electricity used for a pump—and that it be defined in reference to an agreed acceptable level of contamination. That is, if some process results in the release of a contaminant to a water body that can be removed via an energy-intensive water treatment process, the brown energy footprint is the energy embodied in electricity required to return the water quality to compliant levels, not necessarily to remove every molecule of the contaminant. Depending on what the pollutant is, standards might be stricter. For example, the brown energy footprint of a process releasing greenhouse gases might indeed be the amount of delivered energy required to capture and sequester the entire greenhouse gas release.

The example of brown energy footprint of a greenhouse gas emission raises another relevant point, which is that unlike for a grey water footprint based strictly on dilution, the brown energy footprint may also change with technological availability, improved energy efficiency, and other conditions that mean some pollutant can be removed with less overall energy input. For example, if at some time the only way to completely remove greenhouse gases from the atmosphere is direct air capture (DAC) requiring 100 energy units per tonne carbon dioxide equivalent (CO_2e), but an alternative technology (or more efficient DAC process) later requires only 50 energy units to deliver the same service, the brown energy footprint would decrease.

Defined thus, the brown energy footprint is crucially not an indicator of the relative importance of a particular impact. A major disadvantage of framing pollution in terms of required mitigation effort (e.g. energy demand) is that it implies that something more difficult to clean up is also a worse impact. Although this framing can contextualize the total pollution burden in a world where mitigation is expected, it cannot direct prioritization on its own. As with the "probability times consequence" model of risk, however, a brown energy metric can inform priorities using a model based on both relative importance and relative amount of required mitigation effort. Another major disadvantage of the brown energy metric as suggested in this work is that it does not address social impact other than that related to environmental pollution. Consideration of social impacts will likely continue to require use of contextualizing details and conversion factors associated with underlying impact drivers, including specific social context.

5 Conclusions

The sustainability assessment community needs to consider the underlying goals of energy footprinting as the energy system changes, specifically in the context of deep decarbonization. Particularly because of the historical value of cumulative energy demand as, effectively, a proxy for most major socioenvironmental impacts of interest, the decoupling of energy use from predictable, easily estimated impacts represents a major methodological challenge for life cycle assessment and similar methods. If the main value of energy footprinting is to describe energy consumption, expanding the energy footprint approach to account for the use of renewable inputs outside the electricity context will likely be necessary if energy footprints are to reflect energy demand. If the main value of energy footprinting is to describe energy's associated socioenvironmental impacts, clear means of assessing these impacts will be needed as the global energy system transitions away from a relatively stable mix of oil, coal, and natural gas. Especially given goals of using energy footprints in international contexts that reflect globalization and heavily interlinked trade relationships, the fact that fuel and associated impact mixes are likely to change unevenly in time and space also motivates investigation to more inclusive energy footprinting approaches. Following the lead of water footprinting in distinguishing among low-impact inputs that are primarily time and place dependent (green water, or yellow energy), higher-but-variable impact inputs that require explicit human intervention to secure and process (blue water, or red energy), and resources required to assimilate harms (grey water, or brown energy) could both harmonize energy footprints with other assessment approaches and enable energy footprints to better reflect important nuances of energy use and impact.

Case studies will need to be carried out to test the usefulness of the yellow, red, and brown energy footprint proposal. The call to expand energy footprinting from red-only to yellow, red, and brown, rather than completely redefine it, means that existing analytical practice remains valuable and consistent with proposed changes. Nonetheless, developing precise definitional approaches, collecting data, and advancing a collective methodological understanding pose nontrivial challenges. Water footprinting remains an area with active development and debate, and some data are inherently easier to gather than others. For energy, the very high-quality data for red energy footprints will likely always be more readily obtained and validated than data for yellow or brown energy footprints, which require assumptions and technological baselines to estimate given the lack of direct measurements. As with the green, blue, and grey water footprint, case studies can reveal the limits of definitions, suggest modifications, and map the universe of potential applications. Also as with the water footprint framework, this proposed energy footprint framework does not readily adapt to expressing social impacts—a weakness of sustainability quantification more broadly.

Moving toward a clearly communicated framework that differentiates among major categories of energy demand that preserve the value of energy footprints as a proxy for wider impact assessment is a worthwhile goal. Particularly as a global energy transition unfolds, with the expectation that different countries, industries, and supply chains will transition at different paces, being able to distinguish among yellow, red, and brown energy can aid in the communication of energy footprints as a sustainability metric. Each has different uses: for example, yellow energy can contribute to discussions of total energy intensity, red energy can communicate cost differences, and brown energy can serve as a proxy for environmental impact. Over time, making these metrics more precise, standardizing use, and identifying methods for better evaluating socioenvironmental impacts as part of an energy footprint could lead to wider use and more valuable insights from the energy footprinting community.

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