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Review

Energy-Sufficiency for a Just Transition: A Systematic Review

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Abstract: Efforts to achieve an energy transition often neglect to account for the levelling of benefits realizable with higher levels of energy use, despite knowledge of a saturation effect and recognition of increasing harms of use. This research examines energy sufficiency as a maximum quantity of energy associated with improvements in human well-being to inform a recalibration of energy targets among high-energy societies. A systematic review of recent research was performed to identify the point at which increasing levels of energy use no longer correlate with meaningful increases in well-being. For selected studies (n = 18), energy sufficiency values range from 60–221 gigajoules per capita per year with a mean of 132 gigajoules per capita per year for associated measures of well-being. The review finds agreement in a pattern of saturation and provides a range of values for energy sufficiency maximums, suggesting that a relatively modest amount and a diverse quality of energy is needed to support high levels of human well-being. Beyond the conventional emphasis on energy efficiency and renewable energy, energy sufficiency therefore offers a necessary and complementary approach for supporting just and ecological energy transitions.

Keywords: energy consumption; energy sufficiency; just transition; renewable energy transition; societal well-being

1. Introduction: A Need for Maximum Energy Targets

At what level does increasing energy use no longer relate to improvements in human well-being, effectively shifting from enough energy to too much? While climate change and other environmental injustices compel dramatic and rapid reductions in the use of fossil fuels, these efforts typically center on improving energy efficiency and replacing fossil fuels with renewable energy systems including wind, solar, and hydroelectric power. Much of the focus on energy transitions thus simply projects current demand into the future, accounting for changes in efficiency and technology, yet failing to question the underlying need for this demand in terms of human well-being [1–3]. This narrow framing is problematic when accounting for extreme inequalities in levels of energy use worldwide and the unavoidable ecological harm associated with energy use of any form. Failing to understand the level at which higher rates of energy use no longer contribute to human well-being constrains our collective ability to respond to these complex and interrelated global priorities and achieve a just transition beyond fossil fuels.

Energy sufficiency offers a needed complementary approach for energy transition. The concept of energy sufficiency provides a lens for examining the relationship between energy use and well-being, a way for understanding the meaning of enough [4–6]. Energy sufficiency recognizes the necessity to achieve an absolute decrease in the total energy used for reaching high global levels of human development. As such, energy sufficiency relates to multiple concerns associated with energy use and just transitions [7,8]. First, energy sufficiency relates to both maximums and minimums, recognizing

that there can be levels at which there is not enough energy and levels at which there is too much. Secondly, energy sufficiency involves social and environmental thresholds, realizing that having too little or too much energy can only be determined in reference to desirable social and environmental outcomes. Energy sufficiency further relates to both individuals and society, as efforts to define and achieve sufficient levels of energy use are made through individual actions and behaviors as well as socially derived standards and collective agreements. Finally, energy sufficiency relates to but differs from more technical aspects of energy use including technology and efficiency, in the sense that having a desirable quantity and quality of energy relates to but differs from the procurement of that energy and the way it is used.

Energy sufficiency draws from previous work to theorize, identify, and implement energy maximum thresholds. The virtues of limiting or reducing consumption, especially among the wealthy, have been articulated since ancient times, while theories and concepts associated with sufficiency have been developed over the last half century [7,9]. These ideas include critical thresholds or ceilings [10], limits to growth [11,12] and limits to affluence [13,14], optimal scale [15,16], environmentally or strongly sustainable consumption [17,18], voluntary ecological behaviors and lifestyles [19,20], degrowth [21], safe and just operating space [22], and ecological intensity of well-being [23]. The associated perspectives on sufficiency broadly draw attention to the point at which further consumption does more harm than good, urging a shift to living well on less as an important element for just transitions. The starting point for energy sufficiency, then, requires attention to human needs and well-being rather than energy technologies [24].

The presence of energy maximum thresholds is supported by a pattern of saturation or decoupling [2,25–28]. Relatively small increases of non-metabolic energy use at lower levels may relate to sizable leaps in human development, depending on the source of energy used. However, higher levels of use exhibit little or no corresponding improvements—the benefits level off at a certain threshold, the point where human development decouples from energy use. This pattern suggests that ever increasing levels of energy use may not bring additional benefit to the already energy-advantaged, while higher levels of human well-being can be achieved at relatively modest levels of energy use. The only assured outcome of increasing energy use is increasing ecological degradation [27,29,30], if not social inequity [10], suggesting that at some point, any advantages gained from higher energy use will be overwhelmed by the social and environmental harms.

As a contribution to active research on just energy transitions, this review addresses the need to recognize and account for the point at which increasing levels of energy use no longer meaningfully relate to improvements in human well-being. This paper defines energy sufficiency as: (1) the maximum quantity of energy use; (2) associated with improvements to human well-being; (3) measured at the aggregate societal level; and (4) a necessary complement to existing efforts to advance renewable energy and energy efficiency for just transitions. First, regarding quantities of use, minimums and maximums are related yet not necessarily the same [7], therefore both deserve attention. There is broad agreement that justice requires a minimal level of energy use such that basic needs are met. However, justice also requires maximum consumption levels given that unnecessarily high levels of energy generate environmental and arguably social harms that make everyone worse off. While the threshold for societal well-being is addressed here, ecological measures must also be accounted for and compared when examining energy sufficiency maximums. Further, higher levels of energy use cannot be extended to the majority of the world without disastrous consequences and will reduce the energy and materials available for developing renewable energy systems.

Second, considering well-being, it is widely understood that energy use and energy services are a means for achieving human well-being and not an end in themselves. Energy sufficiency in this context is therefore linked to the level of demand of modern energy services necessary to lead a "good life" measured in physical and/or subjective quality-of-life variables [9,27].

Additionally, this paper takes a societal perspective. While energy sufficiency can be used to refer to changes in individual behaviors that lower energy demand [31,32], achieving overall reductions in demand requires collective action beyond the responsibility of individuals [7]. Indeed, Smil has asserted that the choice to limit the use of energy may be one of humanity's most important collective choices, offering a new chapter in human history [30]. The well-being of individuals is thus considered here in the broader context of society, providing a maximum per capita target for societal orientation [7] and allowing a focus on the social and political institutions that enable human well-being [9].

Lastly, while contentious and less well-developed than energy efficiency and renewable energy [4], energy sufficiency serves as a necessary complement [8,27,33]. Energy sufficiency is needed to support energy efficiency measures by emphasizing absolute reductions in technically supplied energy use [18,24]. This is not to say that energy efficiency is not required, yet as a practical matter, energy efficiency alone does not reliably achieve these absolute reductions and may actually enable increases in total energy use, exhibiting a rebound effect [5,34–38]. Similarly, reducing aggregate levels of energy use without reducing the share of fossil fuels and dirty biofuels is clearly undesirable [39]. However, because any technology carries an environmental impact and cannot be extended indefinitely, sufficiency as the maximum provides a necessary approach for constraining levels of environmental impact of any future energy mix [7]. Lacking this complementary approach, the effects of energy efficiency and renewable energy as climate solutions are unduly constrained and may deflect attention from possibilities available through an energy sufficiency approach. The three agendas must work together, yet energy sufficiency remains poorly understood and rarely implemented.

The objective of this paper is to further the development of targets for just energy consumption maximums for societies and communities. Using a review of recent research investigating the relationship between energy use and human well-being, the paper provides an update on the latest progress made in identifying the levels of energy use as associated with indicators of high quality of life. An active line of inquiry demonstrates the timeliness of such a review, to allow for a recalibration of energy targets among high-energy societies. Specifically, in response to the well-known effect of saturation, the paper aims to identify and compare the range of values of energy sufficiency maximums as the level of per capita energy use beyond which there is little to no associated increase in quality of life. Figure 1 frames and specifies the present inquiry within this well-documented pattern of saturation, delineating specific points along this curve in order to identify the possibility for reductions of energy use without corresponding reductions in quality of life measures. As with eco-sufficiency [20], this energy sufficiency threshold represents an upper bound of technically supplied energy use which should not be exceeded without clear justification for improving well-being [40]. Moreover, increases in energy use beyond this range of energy sufficiency are not easily justifiable given negligible gains and unavoidable harms and inequities.

The next section describes the procedures used for the review, followed by the results. These results are then discussed in the context of earlier (pre-2010) research on the relationship of energy use and human well-being, with further discussion on policy and implementation, and limitations and directions for further research. The results support the claim that a relatively modest amount and diverse quality of energy is needed to support high levels of human well-being, and that the goals for energy transition can be usefully organized accordingly.

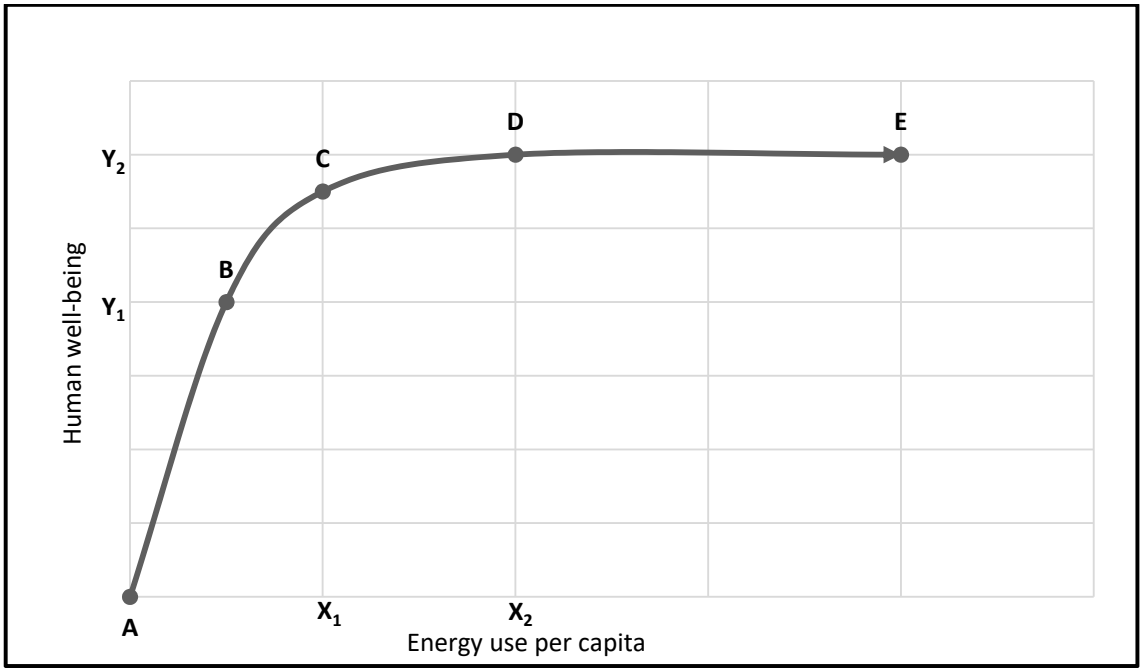

Figure 1. Energy sufficiency saturation curve. The value Y_1 represents the lowest acceptable level of human well-being while Y_2 represents the highest level of well-being attainable, as related to energy use. Line segments $\overline{AB}$ represent energy poverty, $\overline{BD}$ as energy sufficiency, and $\overline{DE}$ as energy excess. Energy sufficiency further includes a minimum range $\overline{BC}$ and a maximum range $\overline{CD}$. This paper seeks to identify a range of values of energy use per capita X_1 to X_2 for the energy sufficiency maximum $\overline{CD}$.

2. Materials and Methods

A systematic review of existing research was performed to identify the levels of energy use associated with a high quality of life, meaning a threshold level after which increases in the energy variable translate into only marginal or no increase in well-being. Typically, this research takes country-level variables and applies statistical techniques to relate energy use and human well-being [9]. Measurement of the level of energy use associated with high levels of human well-being requires specification of indicators.

Various measures are commonly used to describe the levels of per capita energy use. At the country level, popular indicators include the total primary energy supply (TPES) or demand (TPED) and the total final consumption (TFC). While TFC accounts for only the final consumption by end users, TPES additionally accounts for the use of energy within the energy sector and the losses associated with transforming and distributing this energy. TPES in this sense provides a more complete perspective on the quantity of energy needed to meet demand. Globally, trends indicate that the TFC typically ranges around 70 percent of the TPES. While the TPES and TFC are both production-based measures, additional work has sought to develop consumption-based measures that account for the global energy requirements of users of goods and services (i.e., the energy embodied in imported goods and services). These measures refer to the energy footprint, operationalized as the total primary energy footprint (TPEF) [41,42]. The energy footprint provides a more accurate measure of energy requirements of a country, especially avoiding underestimating the values of high-energy countries. However, the TPES can be measured more directly and transparently [42] and data on TPES values are available for most countries over longer periods of time.

Similarly, multiple indicators exist for measuring human well-being. Despite well-known deficiencies, the gross domestic product (GDP) is still often used as a proxy for human development, for example, in measuring energy intensity as the total energy consumption of a country divided by its GDP. The human development index (HDI), developed by the United Nations Environment

Program, indicates the average achievement of each country as aggregated for life expectancy at birth, adult literacy and school enrollment, and standard of living as measured by per capita GDP. The HDI uses a scale from zero to one, with high levels of development understood as around 0.8 on the HDI. Other indicators used in this research include various composite (following Ribas et al. [43] (p. 436), composite or aggregate indicators include those that combine and often weigh individual indicators or variables related to dimensions of human well-being) and disaggregated quality-of-life (QoL) measures, most frequently life expectancy at birth (LEB), access to safe drinking water, infant mortality rates, mean years of schooling, and malnutrition [27,44], measures of subjective well-being (SWB) and life satisfaction [45], and attainment of sustainable development goals (SDG) [46].

The systematic review proceeded as follows. Sources of interest included peer-reviewed, English-language, academic literature and referenced books or book chapters published from 2010 to 2019. Potential sources were first identified through the process of literature review on context and background of energy sufficiency for this review (n = 10), followed by a systematic search. Search for sources were performed in December 2019 for Web of Science, Google Scholar, and ScienceDirect. To illustrate the search strategy, for Web of Science, the topic was specified as ((“energy consumption” or “energy use” or “energy demand” or “energy conservation” or “energy sufficiency”) and (“human need” or “human wellbeing” or “human well-being” or “human development” or “longevity” or “lifespan”)). Potential sources identified through the initial review (n = 10) were added to those identified through Web of Science (n = 450), in addition to the top 150 returns when sorted by relevance for Google Scholar (n = 150) and ScienceDirect (n = 150). Initial screening for relevance to the research objectives and removal of duplicates left a set of full-text articles (n = 96) to be assessed for inclusion in the study.

Eligible sources (n = 18) included those reporting energy use figures based on either historical data and/or projections for total primary energy supply/demand or total final consumption per capita as associated with a specified measure of human well-being. Different measures of well-being were allowed as there is presently no standardized measurement for this research. Ineligible articles (n = 78) were those that did not report TPES (e.g., reporting electricity supply, residential/household end use, or energy footprint), did not directly address the relationship between higher energy use levels and human well-being (e.g., energy use and greenhouse gas emissions or economic growth), or reported on studies already included within the sample or published prior to 2010.

The included studies (n = 18) were reviewed to collect data on the average annual energy use per person, stated in or converted to gigajoules per capita per year ($GJ \cdot cap^{-1} \cdot yr^{-1}$) for a given year. This value was defined as the energy sufficiency value, corresponding to the range of values of energy use per capita associated with the energy sufficiency maximum ($\overline{CD}$ of Figure 1). The analytical approach was based on correlations and graphs and does not provide evidence for causal relations. Energy sufficiency minimums, meaning levels of use just beyond energy poverty (point B of Figure 1), do not represent the threshold of interest to this review, and thus were not included. Additional values for other energy use measures including energy footprint and energy return on investment were also beyond the focus of this review.

The review selected only one value per source, using the higher value in the case of multiple indicators of well-being, and selecting observed rather than projected values when available. If studies provided only the plots of correlations or saturation curves and did not otherwise specify a relevant level of energy use, the energy sufficiency value was estimated based on a point of correlation with a high level of human well-being as defined within the given source. When studies categorized findings according to groups of nations, findings were retrieved for values for the “energy-advantaged” or “developed” countries. Additional data collected included article information (author, date, title, type), retrieval date, evidence of relevance, time period for energy use observation or projection, and indicator(s) of well-being used, as well as explanatory notes, as studies varied in terms of countries included, years reported, and type and level of measure of well-being used. TFC values were converted to TPES values using the ratio of World TPES to World TFC for the relevant year(s) as available through International Energy Agency data <https://www.iea.org/data-and-statistics>.

3. Results

The results are presented here first for the retrieved energy sufficiency values across the studies, followed by qualifications accounting for differences, and finally reporting on factors that might explain saturation, and implications for future energy use. Energy sufficiency values ranged from 60 GJ · cap^{-1} · yr^{-1} (based on 2005 and HDI) to 221 GJ · cap^{-1} · yr^{-1} (based on 2005–2013 and QoL), with a mean energy sufficiency value for all studies (n = 18) of 132 GJ · cap^{-1} · yr^{-1} across all selected years and measures of well-being. Following Arto et al. [42] (p. 3), Table 1 summarizes the relevant findings of the selected set of studies.

Table 1. Energy sufficiency values (lowest to highest) and well-being indicator(s) per source.

Energy Sufficiency (GJ · cap^{-1} · yr^{-1})	Well-Being Indicator(s)	Source
60 (2005)	HDI	[28] (p. 430)
71 * (2000)	Basic needs access and LEB	[47] (pp. 16–17)
77 (2030)	SDG	[46] (p. 212)
84 (2 toe) (2008)	HDI and SWB	[48] (p. 4671)
110 (2006)	HDI, infant mortality, female LEB and malnutrition	[27] (pp. 722–724)
110 (3.5 kWpc) (2009)	LEB	[49] (pp. 102–103)
116 (2050)	Inclusive Wealth Indicator	[43] (p. 448)
126 (4 kWpc) (2008)	HDI	[50] (p. 893)
126 (3000 kgoe) * (2013)	HDI	[51](p. 786)
138 (3287 kgoe) (2005–2013)	QoL indicator	[52] (p. 678)
144 (40 MWh) (2006)	LEB	[40] (p. 2570)
146 (2010)	HDI	[53] (p. 55)
150 (2012)	HDI, children underweight and Gender Inequality Index	[54] (pp. 158–161)
150 * (2015)	HDI and Education Index	[55] (pp. 1358–1360)
158 (5 kWpc) (2005)	Improved water access, LEB, infant mortality, mean years of schooling	[44] (pp. 469–470)
176 (2008)	HDI	[42] (p. 6)
209 (5000 kgoe) (2000–2009)	SWB	[45] (p. 4)
221 (5273 kgoe) (2005–2013)	QoL indicator	[56] (p. 2963)

Notes. (1) GJ · cap^{-1} · yr^{-1}: gigajoules per capita per year. (2) HDI: human development index. (3) LEB: life expectancy at birth. (4) SDG: sustainable development goals. (5) SWB: subjective well-being. (6) QoL: quality-of-life. (7) * Value estimated based on plot of correlation of energy use and well-being rather than reported directly.

Contextualizing these values, most studies (n = 11) identified energy sufficiency levels between 100 and 150 GJ · cap^{-1} · yr^{-1}, with modal values (n = 2) at 110, 126, and 150. Fifteen studies used data and reported values for the TPES while three studies used data and reported values for the TFC, which were then converted to TPES as previously explained. The time periods for values identified for this research ranged from observations from 2000 to 2015 and projections for 2030 and 2050, where values of three studies were derived from data on energy use averaged over multiple years while the remainder were derived based on a single year. Relevant values were selected for two studies as future targets or projections for 2030 and 2050, whereas all others were based on historic data. Well-being indicators varied as expected, with energy sufficiency values found for 15 studies using established indicators, two using uniquely constructed composite QoL indicators, and one using a combination of both. The HDI was used in nine of the studies, SWB in two, with the SDGs and the inclusive wealth indicator used in one each. Nine of the energy sufficiency values are identified using non-income measures. Sources largely drew from academic journals having a specific focus on energy (n = 12), including five published in the journal *Energy Policy*, while only one article was published in a journal focusing on QoL. A small but steady output of one to two sources per year for 2010 to 2019 was found through this search.

Regarding this range of values for energy sufficiency, the different objectives, data sources, and methods used across this collection of research deserve consideration. It should be noted, for example, that while for most articles included here the stated objective was to consider the relationship between energy use and well-being, for several articles including Dale and Ong [50]

and Steckel et al. [53], this relationship and the resulting value are not of primary concern to the article's aims. For data and methods, country-level data for energy use were largely derived from the International Energy Agency, or in a few cases, from the U.S. Energy Information Agency, whereas quality of life data were generally drawn from the World Bank and the United Nations Development Programme human development reports, for a given year or range of years. The World Database of Happiness provided data for SWB. An important difference related to the sample of countries included in each study, ranging from a smaller group of developed nations as in Arto et. al. [42] and Liu and Matsushima [55] to larger sets that included a high percentage of nations of the world as used in Dale and Ong [50], Mazur [40], Pasten and Santamarina [44], and Steckel et al. [53]. As to defining variables, the indicators of human well-being varied, as noted, as did the points identified as representing a high level of well-being for a given indicator. For example, high levels of human development as measured by HDI ranged from 0.75 [54] to 0.90 and above [27,48,51,53,55]. For energy use, values were converted from those using data on the TFC based on calculated ratios to the TPES for a given time period for Lamb and Rao [47], Nadimi and Tokimatsu [52], Nadimi et al. [56], and Steckel et al. [53]. Methods of analysis generally involved statistical techniques based on functions for correlation of variables for the energy-well-being relationship, often performed using simple linear regression as described by Liu and Matsushima [55] and Ribas et al. [43]. While the semi-logarithmic least square fit is commonly used to analyze these relationships [42], others including Lamb and Rao [47] and Steinberger and Roberts [28] favor a hyperbolic function over logistic or semi-logarithmic functions due to improved goodness of fit and distribution of residuals when modeling saturation curves.

The framing of the resulting values for each study also varied. As this review aims to identify a range of values of energy use per capita for the energy sufficiency maximum (the level of saturation described by $\overline{CD}$ in Figure 1), results are expected to vary across this range. For example, Jess [48] and Schwartzman [49] describe the values in terms similar to "the current minimum demand to reach a high status of development" [48] (p. 4671), which logically corresponds to the lower end of the range at point C, whereas others including Lambert et al. [54], Nadimi and Tokimatsu [52], and Smil [27] find values of energy use associated with the point at which "(t)here is little or no additional improvement in societal well-being" [54] (p. 164), corresponding to point D at the higher end of the range of values.

As to explanatory factors accounting for the saturation effect, there was agreement that correlations do not imply causation, yet the studies proposed various explanations for the decoupling of energy use from human well-being. The pattern was often explained in terms of reaching a point where basic human needs are met in industrial societies, beyond which no improvements in well-being can be attained, as in Mazur [40] and Okulicz-Kozaryn and Altman [45], for example. This possibility would address the levelling off of well-being indicators. Regarding mechanisms driving higher levels of energy use beyond this point, alternative explanations were offered. Given a bi-directional relationship between energy use and economic growth, a commitment to economic growth as policy would involve increases in energy use irrespective of improvements to well-being. Energy use may also continue to rise due to: the opportunity or necessity to generate profits; luxury or wasteful consumption that fails to satisfy needs; positional consumption driven by desire for relative increases; bounded rationality and an inability to predict the effects of increased consumption; the possibility that any gains are offset by harmful effects including pollution; and other country-specific factors. As another driver of increasing energy use, Ribas et al. [43] and Steckel et al. [53] underscore the importance of infrastructure, especially steel and cement, in that such investments require ever more energy use beyond the point at which the physical infrastructure contributes to well-being improvements.

While not directly the focus of this review, implications for future energy use are also worth noting. The studies varied in their estimations for future total world energy needs based on their targeted energy use values. Accounting for population growth, some authors concluded that current levels of use are sufficient for attaining well-being for all [28], while others saw the need for increases, ranging from relatively modest overall increases of 25%–30% [27], upwards closer to 50% [48,49], and as high as a doubling of current world consumption [50]. This range of estimations was dependent on assumptions

for a number of factors including the percentage and type of renewable energy, the efficiency gains realized, and the energy needs for such uncertainties including carbon sequestration, climate adaptation, and biosphere restoration [49].

4. Discussion

That energy sufficiency levels would vary across sources is unsurprising, yet what is crucial is the conformity of views that such a level exists, and the range of values within which this level is found. This range of values may be understood as a first estimate of energy sufficiency maximums, meaning the levels of energy use associated with $\overline{CD}$ in Figure 1. With energy sufficiency values from this review ranging from 60 to 221 GJ · cap^{-1} · yr^{-1}, and most studies finding levels between 100 to 150 GJ · cap^{-1} · yr^{-1}, the results can be compared to other efforts to identify the energy requirements for meeting human needs in modern industrial societies. An influential article by Goldemberg et al. [2] found only marginal increases in the physical quality of life beyond energy use rates of 32–38 GJ · cap^{-1} · yr^{-1}. The widely-known policy example in Switzerland targets a 2000-Watt (W) (63 GJ · cap^{-1} · yr^{-1}) society [31,39,57], while the UN Secretary General's Advisory Group on Energy and Climate Change suggested that modern needs could be met through an aggregate energy use of around 37 GJ · cap^{-1} · yr^{-1} (26 GJ · cap^{-1} · yr^{-1} final consumption) [58]. Martínez and Ebenhack [25] found that 120 GJ · cap^{-1} · yr^{-1} are needed to achieve the highest HDI values, while Smil [59] found no substantial gains across various indicators of high quality of life beyond about 105 GJ · cap^{-1} · yr^{-1}. Clearly these results do not offer any simple comparison as the measures and purposes across these studies vary considerably, reinforcing the need for the present study. The primary value in positioning the current results within this existing set of work is to suggest conformance regarding the phenomenon of saturation and its range of values.

To put these figures in context, based on data from the International Energy Agency <www.iea.org>, the world TPES was about 78 GJ per capita in 2017, ranging from an average of less than 56 GJ per capita for nations not included in the Organisation for Economic Co-operation and Development (OECD), to about 172 GJ per capita for OECD nations. Among the highest levels of energy use were the TPES in Canada, at 338 GJ per capita, and the TPES in the United States, at 284 GJ per capita, in 2018 (Figure 2). Meanwhile, measures of well-being vary considerably, for example, high levels of average life satisfaction (2010–2018) are found in nations using more moderate levels of energy use such as Mexico, Colombia, and Costa Rica, with the USA ranking 31st in life satisfaction [60] and 44th in LEB (2018) [61]. In finding a mean energy sufficiency value of 132 GJ · cap^{-1} · yr^{-1}, this review suggests that while previous targets and estimates may be toward the low end of energy sufficiency values (i.e., energy sufficiency minimums), there exists ample opportunity for reducing the highest levels of energy use while supporting a high quality of life. Such reductions would support a just transition by reducing the inevitable harms associated with energy use while enabling greater equity in levels and modes of energy use.

This opportunity then raises the question of how to effectively implement policy for energy sufficiency maximums. A full elaboration of policies is beyond the scope of this review, yet much has already been learned through research and practice about the means to achieve energy sufficiency. The most important first step is to create the social and political framework for sufficiency. This involves raising awareness of the empirical relationship between energy use and well-being, agreeing that ever-rising energy use is not viable, articulating the need to determine and realize energy sufficiency maximums, and including sufficiency in energy policies and planning scenarios [27,28,44–46,62,63]. The point here is to acknowledge that high levels of energy use cause more harm than good and that reductions in energy use from the highest levels are therefore desirable [17,27]. Through considered restructuring, energy-advantaged countries could use substantially less energy without measurable losses in human well-being [28]. In this way, sufficiency can serve as a key organizing principle for society [64].

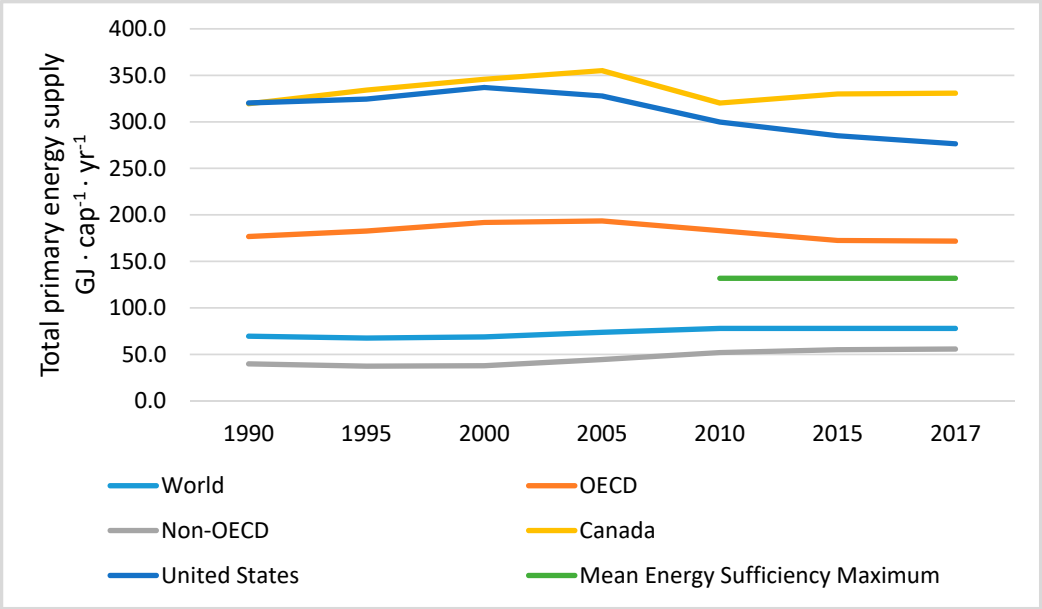

Figure 2. Comparison of energy sufficiency and energy use by country or region 1990–2017. GJ · cap^{-1} · yr^{-1}: gigajoules per capita per year; OECD: Organisation for Economic Co-operation and Development. Source of data: International Energy Agency data services <https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics>.

As applied to a just energy transition, this principle requires orienting the transition more directly toward a goal of meeting human needs and achieving collective well-being. In the context of the climate emergency, this point becomes ever more critical when recognizing that global warming may increase economic growth whereas reducing global warming may reduce economic growth [65], revealing the inability of the growth agenda to ensure ongoing well-being among high-energy societies. Moreover, the availability of renewable energy sources may be inadequate to meet higher levels of energy demand [66,67], while the emissions reductions achieved through a transition to renewables may be more than offset by the increase of emissions associated with economic growth [68]. Sufficiency therefore implies the application of alternative measures of prosperity and well-being other than high levels of energy use or its associated economic growth [4,20,63,69]. As demonstrated through this review, a variety of measures of well-being are available and in use for assessing the energy-well-being relationship.

Reorienting goals of energy transition toward this relationship clearly requires mechanisms for accounting for energy sufficiency maximums. Thus, in addition to existing acceptable minimum standards for energy access and use, there is a need to establish and implement maximum targeting reductions among the energy affluent to advance these goals. In accordance with this review, this means providing a maximum per capita target for societal orientation. As noted, a prominent example of implementation includes the vision of the 2000 W society, aiming to reduce energy demand among the relatively advantaged to an average of no more than 2000 W per person without lowering the living standard [39]. The point is not to monitor and narrowly contain individual energy use, rather to identify and target a desirable modal value at the societal level that can be attained over time [27].

The policies and approaches to attain these reductions in high-energy societies can and do take many forms. A host of policies are available including regulation, information and education, pricing and taxation, supply caps, allowances and rationing, energy descent planning, and changes in production and consumption patterns, jobs and livelihoods, use of time and work-time reductions, and so on, for all sectors and applications of energy use [4,8,34,63]. As different policies involve different functions, advantages, and limitations, a combination of measures within an integrated package is needed [24].

This is not to suggest a narrow focus on individual behavioral change and responsibility as consumers, although there is potential for change here as well [8,31,62,70]. Rather, the perspective taken in this review emphasizes the need for collective measures and institutions defined and organized by citizens, who agree that all are to be subjected to some forms of energy constraint, avoiding free riders and rebounds by marginal consumers [13,63]. Prioritizing collective actions then in turn enables the emergence of individual actions and shifting lifestyle priorities. The application of specific targets and measures will vary from place to place and must be developed in context relevant to the specific conditions of their implementation [71]. Likewise, because the relationships between energy use and quality of life indicators change over time [28], processes of implementation should be expected to require continual monitoring and adjustment across diverse measures of need, as well as political negotiation, as a form of "politics of sufficiency" [63]. Acceptance and adoption of quantitative measures of sufficiency depends on being able to demonstrate that quality of life can be maintained or improved [4,39]. Such is the reality of engaging with contentious questions of societal needs and collective sufficiency.

This emphasis on sufficiency in energy policy must not in itself become reduced to simple targets and measures, replicating the narrowness of much existing technically oriented policy. Energy sufficiency requires a distinct set of actions and policies that must be taken up in coordination with energy efficiency, a transition to renewable energy, carbon sequestration, ecological restoration, climate adaptation, and other policies and strategies, coordinated across locations to achieve more equitable distribution. Energy sufficiency maximums must also be considered relative to ecological thresholds, as the levels indicated here may still exceed those that the Earth can support, with disastrous consequences [43,48]. Lastly, the implementation of energy sufficiency aims to change both the quantity and quality of energy use, limiting energy demand while also seeking to satisfy needs in different ways [24]. The issue then is not simply a matter of limiting energy per capita, but also changing the qualitative relationship to the use of energy [1], meaning redirecting energy use toward activities with clear effects upon well-being, such as improved medical systems, increased energy access in communities of need, and the achievement of SDGs [43,46]. Taken together, the overall approach for achieving energy sufficiency is as Smil describes, to "put in place rational limits that guarantee a decent quality of life for an increasing proportion of humanity while preserving the integrity of the only biosphere our species will ever inhabit" [27] (p. 728).

Several specific limitations recognized through this research can help guide future research on identifying energy sufficiency maximums. Surprisingly, the study was limited by an overall gap in attention to the relationship between high levels of energy use and human well-being, limiting the number of eligible studies and the associated mode of analysis, as well as its generalizability. Confirmation or clarification of the results would benefit from greater monitoring and analysis of this relationship over time, while the topic deserves considerably more attention in general. For measuring well-being, the use of HDI has advantages yet ultimately falls short of a reliable measure of well-being in relation to energy sufficiency maximums due to the strong influence that GDP has on HDI. GDP and energy use are closely associated (and neither are strongly correlated with well-being at higher levels), and thus any well-being measure for energy sufficiency should have greater independence from measures of income [43,44,49,55]. The issue of correlation across variables suggests a cautious use of composite measures of quality of life more broadly. Several objective indicators seem most relevant to creating some consistency across measures, including life expectancy and infant mortality. However, as relationships change over time and from place to place, and every indicator has its limitations, a diverse set of indicators of well-being are required for different contexts, and should be investigated [28,40,55]. The combination of subjective and objective measures of well-being appears promising [55]. For measures of energy use, final energy use provides a better perspective than TPES on actual energy needs, and both production and consumption measures would be usefully applied [27,28]. The review also exposes a range over which energy sufficiency may be realized (from points C to D in Figure 1), and the differences in these values deserve greater clarity for energy sufficiency research going

forward. For analyses of relationships, research could draw from comparisons over time and time-series rather than cross-sectional data, which may only weakly indicate the energy-well-being relationship or involve important time lags [25,40,45]. Similarly, sufficiency must be considered at different spatial scales, as any per capita country average will hide the important differences in energy use within a given country [9]. Certainly, more work could seek to understand the causal relationship between energy use and well-being [45], and specifically the macro- and micro-drivers of high levels of energy use [8], [13], while research centering on well-being could more productively contribute to this work.

The consideration of policy and implementation suggests a critical role for social scientists to engage with social practices to better understand and define human needs and well-being for different groups and contexts, and for future scenarios to include quantitative sufficiency levels and energy-sufficient lifestyles [32,62]. Additionally, advancing energy sufficiency would benefit from greater scholarly engagement with the issue of energy and well-being at least to the level of attention now given to the relationship between energy and economic growth. To better understand implementation, more work is needed to evaluate the multiple policy measures in combination, including voluntary and behavioral sufficiency approaches, as part of a more comprehensive policy package [8,20,62]. This work is sorely needed to move beyond the tendency to emphasize technical energy efficiency and energy supply in discussions and research on energy futures.

5. Conclusions

An overemphasis on technical matters of energy transition may limit the collective capacity to grapple with the contentious but necessary questions around the underlying need for modern forms of energy in the context of high-energy societies. Technical matters clearly hold great importance as responses to climate change, yet the social issues that drive high levels of energy use require at least as much attention. Given steep inequalities and unavoidable harms of energy use, energy sufficiency allows for a direct consideration of the relationship between energy use and well-being, enabling these societies to more readily recognize the level of use at which enough becomes too much. The existence of this phenomenon has previously been demonstrated in terms of a saturation effect.

This review contributes conceptually, theoretically, and methodologically to the research and practice of energy sufficiency as a societal goal. Conceptually, the paper clarifies and asserts the value in recognizing the energy sufficiency in terms of the level of per capita energy use beyond which there is little to no associated increase in quality of life. Contributing to theory of the energy-well-being relationship, a range of values for energy sufficiency was derived from recent literature quantifying this relationship across various measures of human well-being, stated in or converted to gigajoules per capita per year. Energy sufficiency values ranged from 60 to 221 GJ $\cdot$ cap^{-1} $\cdot$ yr^{-1}, with a mean value of 132 GJ $\cdot$ cap^{-1} $\cdot$ yr^{-1} across selected years and measures of well-being. Importantly, this review demonstrates the existence of a common perspective across these studies that such a point of saturation exists and provides an updated and systematic estimate of its range of values. These values can be compared to existing world and country-level data and guide the development and implementation of policies and policy frameworks for energy sufficiency and a just energy transition. Finally, this systematic review contributes to the method of energy sufficiency by identifying both commonalities and gaps in measurement and analysis. This work could be extended and strengthened through improved, systematic, and ongoing measurement and analysis of the energy-well-being relationship for different areas and time periods, and with greater focus among communities of researchers and practitioners on energy sufficiency planning and implementation.

Complementing existing technical efforts, the key opportunity of energy sufficiency is to reorient energy transition toward humans needs by identifying, implementing, and monitoring targeted reductions and qualitative changes in energy use among high-energy communities and societies. Energy sufficiency can thus contribute to creating and sustaining the necessary space for achieving more equitable collective well-being while preserving the Earth's ecological integrity.

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