Population-Density Bounds for 100% Domestic Renewable Energy Generation

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The long-running discussion on the global theoretical and practical potential of renewable energy is strongly affected by the size and connectivity of power networks. Small regional and national networks driven predominantly by intermittent and variable energy sources will require significantly more back-up power than continental networks containing a variety of weather zones. Thus, large networks will require less back-up but this comes with the drawback that some nations or regions rely on import from others. For example, in Europe in 2022, energy dependence on gas imports from Russia led to energy shortages and escalating prices. In this work, we estimate the limits of primary energy supply based on renewables, mainly solar photovoltaic (PV) sources and wind, in this setting. Taking as a starting point an average of 14 European countries, we find the mean energy consumption per unit time in what we argue is sufficient and necessary power per capita to maintain a sustainable life. The required energy generation is then translated into an area of energy production that, together with estimated area requirements for biological diversity, food, and infrastructure, constitutes a given fraction of the land area. When compared with typical human population densities, we find that before reaching one person per hectare, the area requirements exceed what is available. The results support the part of the scientific community that claims that a 100% renewable global power supply is unrealistic, especially as the world population steadily grows toward 10×10^9 people.

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I. INTRODUCTION

The outbreak of the war in Ukraine in 2022 became a strong reminder for Europe that energy dependency on foreign nations is compromising energy security [1]. The future build-up of large renewable-energy plants outside the border of any country implies dependency on the host nation and may lead to a lower degree of energy security. Should the host country decide to stop delivery, the dependent country will face energy shortages and escalating prices. To the extent that energy shortages in the receiver country become dramatic, a conflict with the potential outbreak of war may follow. A number of future conflicts following this scenario can be imagined as the trend of increased global oil consumption continues toward a period of peak oil [2].

The world population is at present growing toward 10×10^9 people, distributed unevenly in countries with population densities from a handful of persons per square kilometer (km^2) to densely populated regions with more than 500 persons per km^2 [3]. On average, the population density going into the second part of this century is expected to be around 75 people per km^2 of livable surface area. When subtracting 30% of the world surface area allocated for biological diversity [4], the average population density within the remaining area approaches 110 people per km^2. Both population growth and the United Nations (UN) plan for biological diversity may lead to competition with areas allocated for renewable energy generation. The latter has recently been estimated to approach 10×10^6 km^2 in 2050 [5], approximately 10% of the global livable land area.

In contrast to a rather extensive literature on the global potential of renewable energy, we focus here on a more restricted, but important, question: To what extent can individual countries provide their primary energy supply solely from renewable energy sources? This question is a subset of the more general question of whether the world population as a whole can live on renewables in the sense that the latter pays no regard to where the power is generated. A number of authors conclude that it can be done

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[6–10], while others arrive at the opposite conclusion [11–13]. Even when restricting the renewable energy production to be within each country, there is scientific literature that concludes that a 100% renewable energy supply is possible everywhere [14]. This stands in sharp contrast to Sir David MacKay's conclusion in his book *Renewable Energy—without the Hot Air* [15]: "Let's be realistic. Just like Britain, Europe can't live on its own renewables. So if the aim is to get off fossil fuels, Europe needs nuclear power, or solar power in other people's deserts."

MacKay's conclusion rests on a large number of energy estimates broken down to per person averages from the period around the years 2006–2008. The numbers have not changed significantly 15 years later: the present global energy consumption is around 530 EJ/year, corresponding to a power of about 17 TW, giving an average of 2.1 kW per person (pp) [16]. When disregarding nuclear energy in a transition away from fossil energy, biomass, wind, and solar energy must be the major sources, since they are mature and capable of delivering at a global (TW) scale. Biomass for energy production is found to be possible in a range as large as 1–36 TW [17]. The global (economic) potential of wind energy falls in the range of 1–10 TW [18] and published work concludes that wind energy is capable of becoming a substitute for all of today's fossil fuel consumption [19]. Finally, solar energy has a resource potential beyond several tens of terawatts [20]. We remark that hydropower already deliver at the terawatt level globally but we disregard this energy source as well due to its limited continued expansion potential.

In this work, we will analyze the energy requirements and land impact in what we coin a "one-hectare country" (OHC): population densities across countries lead to the order of one (0.1–10) persons per hectare (10^4 m^2). We estimate area requirements for energy production and other vital area needs in order to provide a worldwide general standard of living, as defined by the power consumption in an OHC. In Sec. II, we derive the model and discuss our assumptions. We then consider different population densities and distribute the required land use onto the available area. Our analysis leads us to the conclusion that countries with population densities approaching 1 in the OHC, corresponding to a population density of 100 persons per km^2 in a real country, simply do not have enough space! We note that at present, about 60% of the world population lives in countries in which this critical population density is exceeded.

II. INTRODUCING THE "ONE-HECTARE COUNTRY" (OHC)

The starting point is an argument for a given average necessary renewable energy production per person per unit time, which will later be translated into land-area requirements. A useful unit is kilowatts per person, since the numerical values then lies in the range of 1–10 for almost any country in the world. As seen in Fig. 1, the total human power consumption scales remarkably well with population, implying an almost constant power per person close to 2 kW over the past 50 years. The correlation is in fact beyond 99%. The figure shows the total global power consumption without adjustments and the contributions from the main energy sources. The current power per person for the world and for a number of selected countries is shown in the lower part of Fig. 1, together with the average weighted power per person of 14 selected European countries where energy data are available. It is observed that the world average power is almost a factor of 2 lower than the power per person of the selected European countries (3.7 kW per person). Given an expected population of 10×10^9 people in 2050, it is therefore likely that a global "welfare society" at the European level requires a doubling of the power generation, or a total of around 1000 EJ/year in 2050. On top of that, a full replacement of fossils by intermittent and variable resources requires additional energy production for storage.

A. Energy requirements

While the global power consumption average just exceeds 2 kW per person (pp), some countries are far below this number, while some consume up to a factor of 4 more. Considering a cross section of 14 European countries, we find at an average energy consumption of 3.8 kW pp for these countries and a population density of 1.21 per hectare. The selection of countries is in reasonable parity with the European Union (EU) as a whole, regarding power consumption, population density, and gross domestic product (GDP).

Globally, the power per person of the selected countries has been relatively stable throughout the present century and so has the political situation. The past two decades also expose a weak decrease in Europe and North America, in Europe around 8%. Improved energy efficiency in general and in industrial processes, political measures promoting and encouraging lower energy consumption within the private sector, and the dramatic growth of the industrial sector in China are some of the factors that explain the trend. In the absence of near-future global recessions following international conflicts or pandemic outbreaks, it is likely that the trend will continue, with an increased energy consumption per year at the low end of the consumption spectrum and a decrease at the high end. The gain from energy efficiency may, however, play a smaller role in the second part of the period toward 2050 as compared to the first part. This is supported by the historical and predicted efficiency of thermal reactors, discussed in Ref. [16]. In 2023, as well as in 2020, all developing regions are seen to have an average power per capita well below 3 kW per person, while the opposite is true for

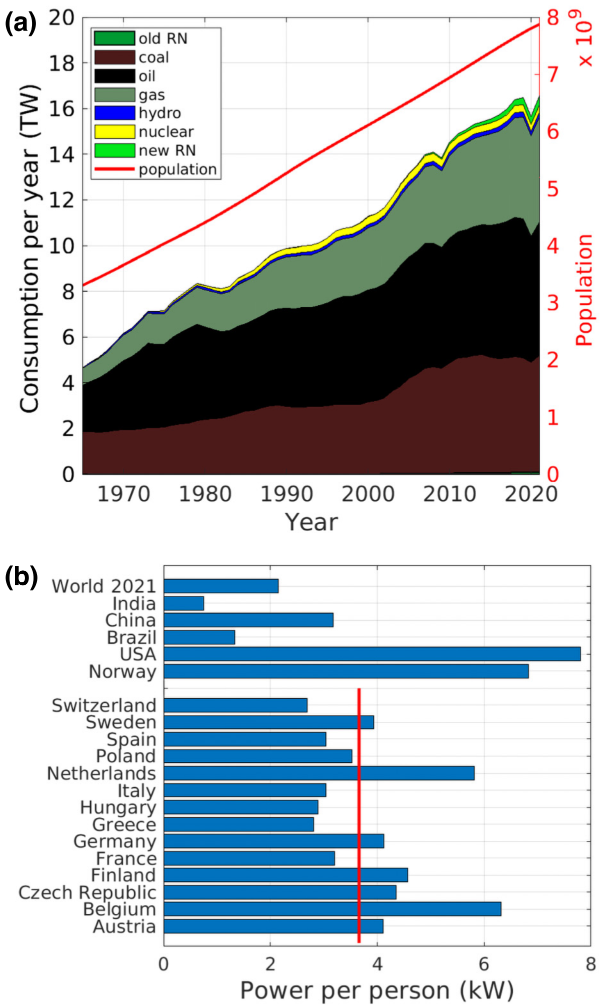

FIG. 1. (a) The global total power (energy per year) per capita as function of time (years) with color-coded contributions from all main energy sources. The red line (with the y axis to the right) shows the global population for the same time period. (b) The power per capita of some selected countries around the world and in 14 selected European countries. The average power consumption per capita of the 14 selected European countries is shown by a red vertical line. The data are from Refs. [3,16]. The real power contribution (the direct method) from nonfossil energy sources has been used, i.e. a factor of 0.4 of the adjusted values in Ref. [16]. RN, renewable bioenergy.

North America and Europe. Our basic assumption is therefore that a necessary, not sufficient, power generation for a sustainable-welfare country is an energy consumption per year well above 3 kW per person. We therefore take the average power consumption of the selected 14 European countries as a basic unit of the constant energy supply required for sustainability.

The first task is then to compute what is needed in terms of primary energy per person when the energy supply of the selected countries is transformed into a fully renewable energy supply. This is essentially the same as removing and adding the energy needed for conversion when replacing all of the fossil-based energy supply with nonfossil sources. For coal and gas, it is simple: 60% of the energy is lost when generating electricity from heat and at present about 60% of the coal consumption and 40% of natural gas consumption are used to generate electricity. When replacing coal and gas with renewables that deliver electricity directly, the power consumption goes down to around 60–70% of its present level. Oil has diverse areas of application and only a certain fraction of those areas can be replaced by electricity directly. Thus, phasing out oil and replacing it with renewable electricity reduces the energy use in some applications while it increases the energy use in others (with regard to oil replacement, see Fig. 2).

In the EU, the total consumption is around 500 Mtoe. 69% is used for transport (49% for road and 20% for nonroad transport), 5% is used for energy purposes in the industrial sector, 14% is used for nonenergy purposes, 9% is used in private households, and the remaining 3% for other uses [21,22]. Electricity is a higher-quality form of energy than oil, meaning that there is a potential reduction of energy losses in nonheat energy applications when transitioning from oil to electricity generated directly from renewable energy sources. There are, however, areas where it is highly questionable if electrification is technically feasible, implying that switching from oil to electricity demands that a fuel is to be synthesized using electricity as energy input, leading to an increased energy loss. For example, replacing the 300×10^6 t of heavy fuel oil used annually by international shipping via green ammonia will require 2.7 times the entire EU power production but it constitutes only 3% of climate gas emissions. Hence, the decarbonization of fuels is very difficult. It is therefore favorable to electrify as much as possible and use synthetic fuel only when electrification is not feasible. The production of products that are currently made from an oil feedstock also requires more energy than the combustion energy of oil.

Half of the oil used for transport is used for passenger cars and light transporters, corresponding to 35% of the total oil consumption. 14% of the total oil consumption is used for heavy road transport. The remaining 20%, used for nonroad transport, is used primarily for air and marine. Based on current technology, it is a reasonable estimate that it is feasible to electrify all cars and light transporters and short- and medium-haul trucks and buses, while long-haul trucks, air traffic, and the vast majority of marine transport will rely on synthetic fuel. The assumption of electrification of half of the heavy road transport means that 60% of all transport (accounting for 41% of total oil use) can be electrified, leading to reduced energy use, while 40% (accounting for 28% of total oil use) will need synthetic fuel, leading to increased energy use. If we assume an overall efficiency of 35% when using a fossil fuel in a combustion engine to generate kinetic energy

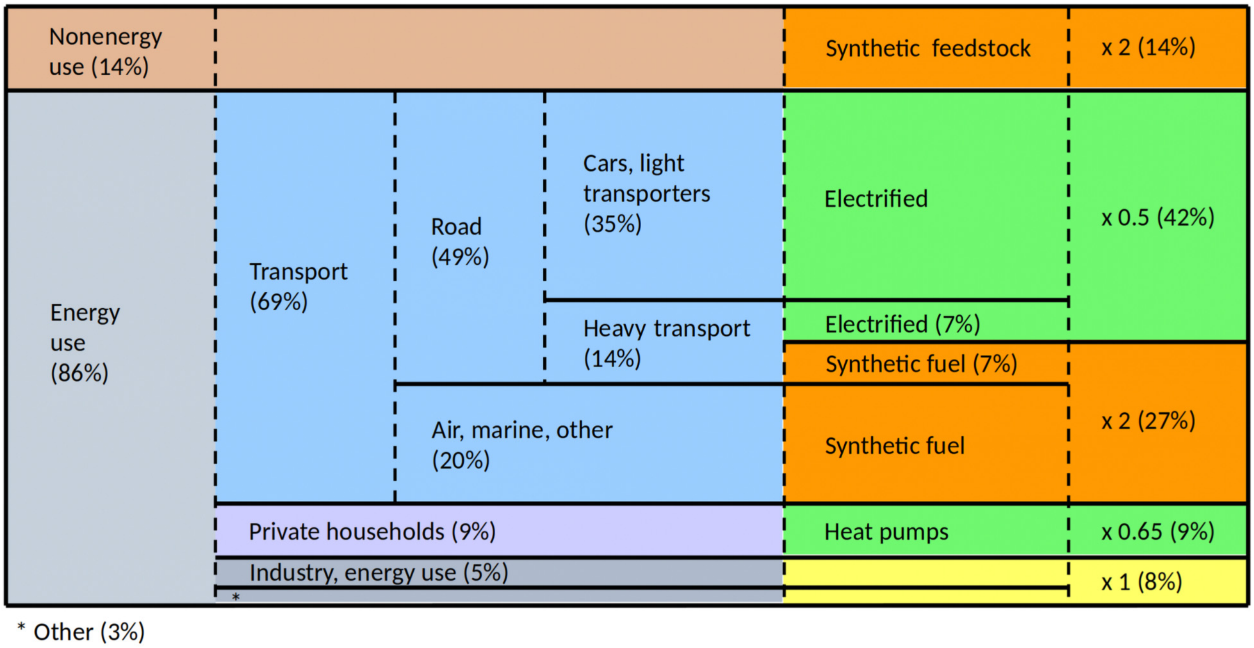

FIG. 2. A graphical representation of the replacement of oil based on the distribution of total oil use in different applications in the EU region. The colors on the left-hand side indicate different areas of application [brown, nonenergy uses; light gray: energy uses divided into transport (blue), private households (purple), and industry and other energy uses (dark gray)]. The colors on the right-hand side indicate decreased energy consumption (green), increased energy consumption (orange), and unchanged energy consumption (yellow).

of an average vehicle in the current fleet, an overall efficiency of 70% when using electricity from a solar panel to generate kinetic energy in an electrically driven vehicle, and an overall efficiency of 17% using electricity from a solar panel to synthesize fuel and use the fuel in a combustion engine instead of fossil fuel, the energy use is halved compared to the current use when switching from the oil–internal-combustion engine to the electricity-electrical engine and the use is doubled when switching from the oil–internal combustion engine to the electricity–internal combustion engine via synthetic fuel.

The majority of the oil used for energy uses other than transport is used for heating. Half of it, 9% of the total oil consumption, is used in households, primarily for heating (62% for space heating, 15% for water heating, and 6% for cooking [21]. The efficiency of oil for heating is very high. With present technology, an air-to-air heat pump reduces the electricity use to approximately 65% and heat pumps for the supply of hot water are reaching similar efficiencies. Taking into account the technological energy savings on currently electrified appliances in the households, an overall energy reduction to 65% of the current level is estimated in households when transferring from oil to electricity. The remaining 8% of the total oil consumption stems from energy use in industry and other uses, e.g., services, and is for simplicity assumed to be unchanged when replacing oil with electricity. For the nonenergy uses, it is assumed that a similar feedstock is to be synthesized, assuming an energy cost similar to that of synthesizing synthetic fuel. Adding all of this together, the amount of electricity, E_e, needed to replace the current exergy in oil, E_o, is therefore given by $E_e = 1.17E_o$.

The transformation of the consumption data of Fig. 1 into power consumption per capita based on a 100% renewable energy supply is shown in Fig. 3. From the outlined transformation procedure, the average power per person is only reduced by a few percent, from 3.7 kW to 3.5 kW pp, and with minor changes up or down for each country depending on their present energy mix. Next, we need to consider the challenges caused by intermittency and variability of the power production, also from a national perspective.

B. Effective load-carrying capacity

For national energy networks, it is apparent that a 100% renewable production system will require substantial amounts of additional stored balance and back-up power [23]. A way of quantifying this is through the effective load-carrying capacity (ELCC), which defines the extra load that can be added to the system once the production capacity is installed without degrading the stability of the power system. Estimates of the ELCC will depend on the size of the power system (including the transmission losses driven by size), the renewable-energy mix, the solar and wind resources, and the fraction of renewables in the

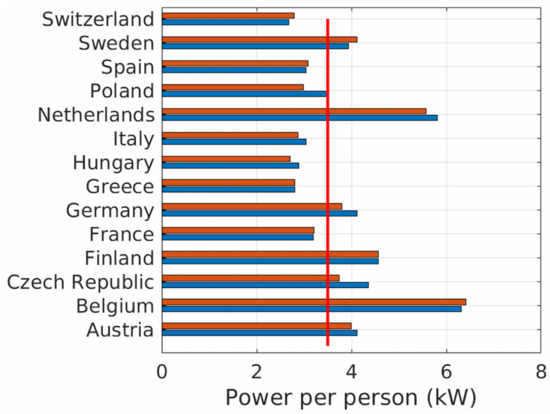

FIG. 3. The power per capita as from Fig. 1 (blue bars) and as calculated following the result of the above discussion for transforming energy production to 100% renewable for the group of 14 selected European countries as discussed in the text (orange bars).

total energy supply. In general, the ELCC goes down as this fraction increases and numbers around the world for a 50%-50% wind-solar energy system will vary as much as from 10% to 70%. In Ref. [24], it is found that 90% renewable electricity production requires 64% of the peak load capacity for storage. Thus, it is not surprising that Zappa *et al.* [25] find that the energy production in a full European integrated renewable power system would require almost a doubling of the peak generation capacity, from 1 TW to 1.9 TW. Translated into the topic of the current work, we argue that the extra power capacity to ensure a stable power supply will at least be of the order of two. This implies that the average number displayed in Fig. 3, of about 3.5 kW pp, should be increased to at least 8 kW pp. We take this number as a starting point for estimating area needs in Sec. II C.

It should be noted that in a real-life case, a 90% level of renewable energy sources is not possible due to either resource constraints (biomass) or the fact that wind and solar power are not synchronous energy sources. Ireland is the present record holder of renewable power penetration in a complete synchronous grid, with up to 70% wind-power penetration at 15-min resolution. This can theoretically be increased using power electronics but at great cost and risk. Also, the ELCC is actually on the optimistic side of reality. Consider Fig. 4, where we have aggregated the hourly production data for all the wind farms in Europe, ignoring bottlenecks and other practical obstacles. The hour with the highest production is shown to the left and the hour with the least production is shown to the right. The figure contains data for 2016–2019, when the wind-power capacity grew by 26%, yet we see that there are always hours (to the right) where the production volume is abysmally low. The true ELCC for wind power is therefore potentially much lower than the ELCC, leading to 8 kW pp. The key factor(s) behind this situation originate from the fact that weather patterns are correlated over large distances, resulting in overproduction or lack of production.

C. Area requirements

The area needed for energy production in an OHC to generate 8 kW pp depends on the location, energy mix, and efficiency of each energy source. Regarding energy sources we continue to restrict the alternatives to a combination of bioenergy, wind, and solar energy.

Figure 4 shows that wind energy in Europe delivers about 2.7 W/m^2. For the United Kingdom, offshore wind-energy production so far has resulted in only 1.4 W/m^2 even though the capacity factors offshore are larger [27] than onshore. However, the use of offshore wind-energy production does not diminish the available OHC land area. However, relatively few countries have access to waters available for massive offshore wind-energy development. In 2022, the fraction of offshore installed capacity was thereby only about 6% of the onshore installed capacity [28]. A global offshore wind capacity of 370 GW is expected by 2030, corresponding to about 10% of the total capacity. From these figures, we compute the delivered wind intensity of the OHC as

$$I_{\text{wind}} = \frac{C_{\text{onshore}} + C_{\text{offshore}}}{C_{\text{onshore}}} \times 2.7\text{W/m}^2 \simeq 3\text{W/m}^2, \quad (1)$$

where C denotes the installed onshore and offshore installed capacities. Note also that the typical European average wind speed is around 6 m/s, while close to the Equator it is about 3–4 m/s, which will reduce the intensity of the wind by a factor 3 relative to Europe.

Regarding the delivered intensity from solar PV farms, one may assume that it is significantly larger close to the Equator compared to in Europe, given the average incoming radiation of about 300 W/m^2 at the Equator and typical nameplate efficiencies for solar panels at about 20%. However, the real delivered power turns out to be much less: the largest and most modern solar PV farms in, e.g., India [29], Egypt [30], and the United States [31] deliver electricity at about 10–14 W/m^2, while at higher latitudes it is typically around 5–6 W/m^2 [32]. In Europe, bioenergy delivers electrical power output at only about 0.5 W/m^2 [15]. In tropical regions, we can expect about 2 times more, which is still significantly below what is delivered from wind and solar energy production per unit area. Thus, it could be tempting to neglect bioenergy due to its lower intensity. It does, however, compare more favorably with wind and solar for nonelectrical energy needs and it comes with a higher degree of production predictability. We therefore include a small amount of biomass energy amounting to 10% of the OHC energy mix.

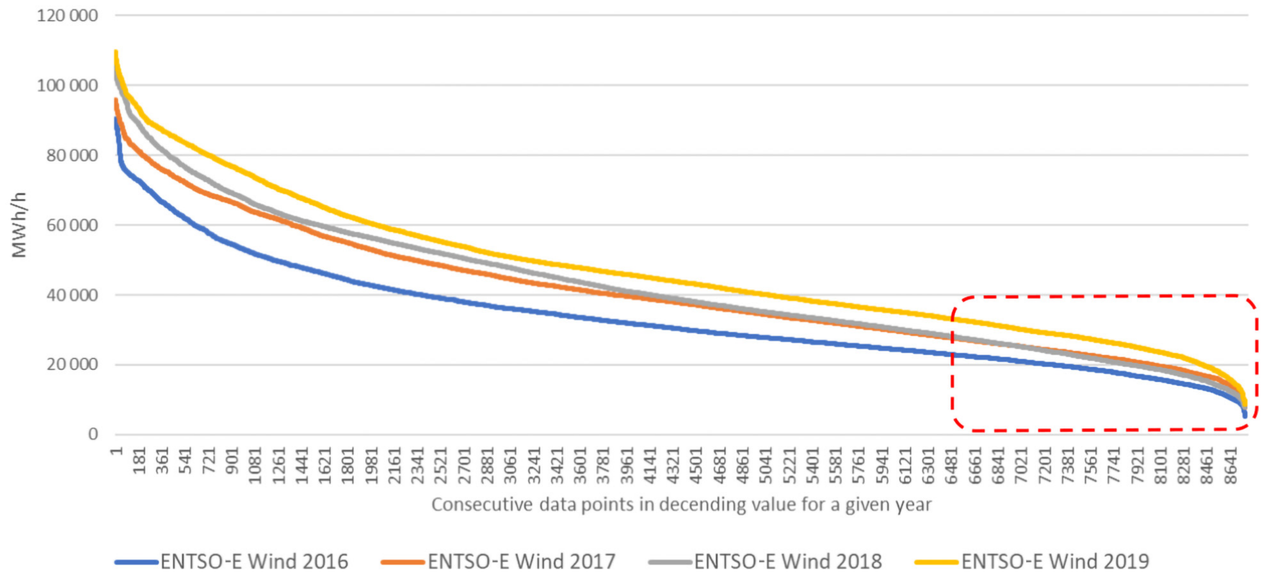

FIG. 4. The hourly production of wind power covering the 15 largest countries in the European association for the cooperation of transmission system operators for electricity (ENTSO-E) for the period 2016–2019. The data are organized according to descending hourly production from the left to right, so that the hours with the least production are found to the right, as highlighted with the dotted box. Authors' calculations based on [26].

In Fig. 5, we plot the area requirements for energy generation as a function of the fraction of solar energy in the OHC energy mix, keeping the contribution from bioenergy fixed at 10% and with wind energy covering the rest. In the temperate region (blue curves), we observe a modest variation between 3000 m^2 and 4000 m^2 for the required area. This is due to the relatively small difference in the average delivered power per area between solar and wind energy in these regions. In the tropical region, a much stronger variation is observed, since wind energy is here far less intense than solar. The figure also suggests that an optimal energy mix in terms of land use would be roughly equal contributions from wind and solar within the temperate zone, while it would be dominated by solar power at around 75–80% in the tropical region.

In summary, an optimal renewable-energy mix will clearly depend on location, e.g., the latitude of the OHC. In Europe, there is a cold, generally more windy and less sunny, winter period. During summer, the energy needs are lower, which implies that solar energy is out of phase with peak energy needs. A reasonable replacement in an OHC in this region could be 10% bioenergy, 45% solar, and 45% wind. This gives an area requirement for the average energy production of about 3500 m^2 (35%). In tropical regions, the fraction of solar energy should dominate, e.g., 80% solar and 10% wind, thereby requiring an area of 2200 m^2 in an OHC.

The order-of-magnitude requirements for nonenergy purposes are even more demanding, in particular if high-density regions should aim to follow the signed UN ambition for biological diversity, which requires 30% of the area to be assigned to this category. The area demands for food production are no less: globally, about 46% of the habitable land area is used for this purpose and at the same time some one billion people suffer starvation or nonsustainable nutrition [33]. Therefore, the pressure for more arable land will likely increase with increased population. Some degree of increased efficiency may be expected but it is questionable whether that can compensate for increased average welfare and population. Another option can be reduced livestock

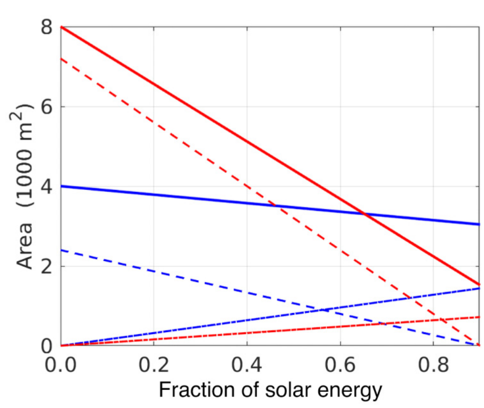

FIG. 5. The area requirements in an OHC using intensities as discussed in the text, as a function of the fraction of solar PV energy in the system and with a constant 10% contribution from bioenergy . The blue curves refer to a temperate region (e.g., Europe) and the red curves refer to an OHC in a tropical region. The dash-dotted lines refer to the area required for solar energy while the broken lines refer to the wind-energy area.

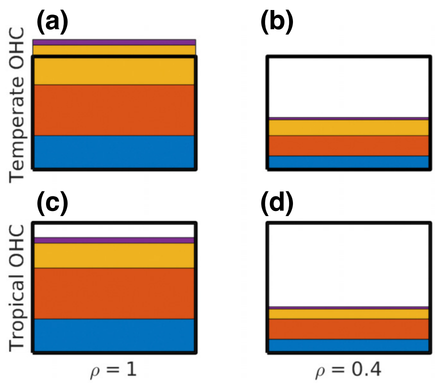

FIG. 6. A visualization of the area requirements for sustainable life with 100% national renewable energy generation in countries with population densities of (a),(c) 1 pp hectare and (b),(d) 0.4 pp hectare; (a),(b) a region in the temperate zone, (c),(d) the area requirements in a tropical region. The colors are for biological diversity (blue), food production (dark orange), primary energy generation (yellow), and infrastructure (purple).

production and increased marine food production [34]. However, the willingness of nations to invest in marine food production and the marked acceptance of marine food is uncertain. Thus, it seems reasonable to allocate an area in the OHC for food production, which corresponds to the current agricultural area use, i.e., 45%.

Finally, infrastructure is a smaller, but also significant, part of the land area. Here, we put everything in one bag: public services, buildings, cities, gardens, fresh water, parks and leisure regions, industrial complexes, etc. While the urban land and freshwater areas are each only about 1% of the Earth's habitable land area, we will assume that 5% is needed for this sector, to account for, e.g., extra areas around connectivity infrastructure such as power transmission lines, roads, and railways.

This adds up to 80% of the OHC area before the area needed for energy generation is allocated. In the regions near the Equator, where only 2200 m^2 is needed, we see that the OHC is just about large enough to accommodate everything. In regions further from the Equator, the OHC is simply too small. Some illustrative examples are given in Fig. 6, where the area requirements in an OHC with population densities of 1 and 0.4 (corresponding to 100 and 40 people per km^2, respectively) are displayed. From this figure, we conclude that countries with population densities up to about 50 people per km^2 may cover their energy needs and have a sustainable society based on a dominant fraction of renewable energy, with all energy production made on their home ground. Above 50 pp km^2, this becomes increasingly difficult and above 100 pp km^2, it becomes physically impossible.

It is also worth noting that our analysis has excluded well-known weather anomalies such as the Dunkelflaute [35] during the winter, when the weather is cold, dark, and without any wind. In 2021, the Dunkelflaute in northern Europe lasted for more then 14 days. Therefore, we remark that there clearly exist large error bars connected to each area estimate and that these are difficult to quantify. They will depend on seasonal and annual weather fluctuations, amongst others. Thus, by taking a safe margin of a factor of 2 for energy production in all countries, the upper bound for 100% renewable energy supply is lowered to about 40–50 people per km^2. In closing, with reference to the energy trilemma [36], we note that an energy supply involving nuclear energy, and some degree of continued fossil energy production, would immediately solve the area constraints everywhere.

III. CONCLUDING REMARKS

In this paper, we have estimated the possibilities for countries to provide a sustainable standard of of living based on 100% domestic renewable energy production. The estimates are based on the present energy consumption and mixture of 14 European countries, a selection of EU member states that reflects the EU reasonably well. Considering the historical increase of energy consumption in countries with low energy consumption and the decreasing energy-efficiency improvement rates in countries with high energy consumption, we have found that the average current energy use per person in the selected countries is a reasonable estimate of the required energy supply for sustainability. With these assumptions, we have introduced the concept of the one-hectare country (OHC), where the energy and other area requirements fill the available area.

Despite uncertainty in numbers and the restrictive assumption of national production of the entire energy consumption, it is shown that a population density of any country higher than 50 people per km^2 will face challenges in attempting to function using renewable energy only. This conclusion is reached not based on the area needs for renewable energy production alone but for the total area needs of everything that factors into human civilization. For countries well above the density of 50 people per km^2, it is unrealistic to achieve 100% renewable energy production and at the same time maintain the standard of living assumed in this work. At the other end of the density scale, for countries well below 50 pp km^2, the conclusion is the opposite. Unfortunately, only a very small fraction, less than 20% of the world's population, lives in such countries.

[1] A. Cherp and J. Jewell, The concept of energy security: Beyond the four As, Energy Policy **75**, 415 (2014).
[2] U. Bardi, Peak oil, 20 years later: Failed prediction or useful insight?, Energy Res. Social Sci. **48**, 257 (2019).
[3] World population prospects, https://population.un.org/wpp/ (2022), accessed on May 1, 2023.

[4] A new global framework for managing nature through 2030: 1st detailed draft, https://www.un.org/sustainabledevelopment/blog/2021/07/ (2021), accessed on May 1, 2023.

[5] J. Lovering, M. Swain, L. Blomqvist, and R. Hernandez, Land-use intensity of electricity production and tomorrow's energy landscape, PLoS ONE **17**, e0270155 (2022).

[6] M. Hoogwijk and W. Graus, *Global Potential of Renewable Energy Sources: A Literature Assessment*, Background report prepared by order of REN21. Ecofys, PEC-SNL072975 (2008).

[7] B. J. De Vries, D. P. Van Vuuren, and M. M. Hoogwijk, Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach, Energy Policy **35**, 2590 (2007).

[8] T. B. Johansson, K. McCormick, L. Neij, and W. C. Turkenburg, in *Renewable Energy* (Routledge, 2012), p. 43.

[9] C. Kleinschmitt, J. Fragoso Garca, K. Franke, D. Teza, L. Seidel, A. Ebner, and M. Baier, *Global Potential of Renewable Energy Sources*, Fraunhofer ISI (2022).

[10] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, The role of renewable energy in the global energy transformation, Energy Strategy Rev. **24**, 38 (2019).

[11] P. Moriarty and D. Honnery, What is the global potential for renewable energy?, Renewable and Sustainable Energy Rev. **16**, 244 (2012).

[12] P. Moriarty and D. Honnery, Can renewable energy power the future?, Energy Policy **93**, 3 (2016).

[13] C. T. M. e. a. Clack, Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar, Proc. Natl Acad. Sci. **114**, 6722 (2017).

[14] M. Z. Jacobson, The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected, Renewable Energy **179**, 1065 (2021).

[15] D. J. C. MacKay, *Sustainable Energy–without the Hot Air* (Bloomsbury Publishing, 2016), https://www.withouthotair.com/.

[16] BP statistical review of world energy June 2022, http://www.bp.com/statisticalreview (2022), accessed on May 1, 2023.

[17] M. Hoogwijk, A. Faaij, R. Van Den Broek, G. Berndes, D. Gielen, and W. Turkenburg, Exploration of the ranges of the global potential of biomass for energy, Biomass Bioenergy **25**, 119 (2003).

[18] C. De Castro, M. Mediavilla, L. J. Miguel, and F. Frechoso, Global wind power potential: Physical and technological limits, Energy Policy **39**, 6677 (2011).

[19] T. Haidi and B. Cheddadi, State of wind energy in the world: Evolution, impacts and perspectives, Int. J. Tech. Phys. Probl. Eng **41**, 347 (2022).

[20] World Energy Council, https://en.wikipedia.org/wiki/World˙Energy˙Council, accessed on May 1, 2023.

[21] Eurostat energy balances, https://ec.europa.eu/eurostat/cache/infographs/energy˙balances/enbal.html (2023), accessed on May 1, 2023.

[22] European Environment Agency, https://www.eea.europa.eu/data-and-maps/indicators (2023), accessed on May 1, 2023.

[23] I. Chernyakhovskiy, M. Joshi, D. Palchak, and A. Rose, *Energy Storage in South Asia: Understanding the Role of Grid-Connected Energy Storage in South Asia's Power Sector Transformation*, Tech. Rep. (National Renewable Energy Laboratory (NREL), Golden, Colorado, 2021).

[24] W.-P. Schill, Electricity storage and the renewable energy transition, Joule **4**, 2059 (2020).

[25] W. Zappa, M. Junginger, and M. Van Den Broek, Is a 100% renewable European power system feasible by 2050?, Appl. Energy **233**, 1027 (2019).

[26] Open power-system data, https://data.open-power-system-data.org/time˙series/2020-10-06 (2020), accessed on May 1, 2023.

[27] Energy numbers—UK offshore wind capacity factors, https://energynumbers.info/uk-offshore-wind-capacity-factors (2023), accessed on May 1, 2023.

[28] Global wind report 2022, https://gwec.net/global-wind-report-2022/ (2023), accessed on May 1, 2023.

[29] Kamuthi Solar Power Project, https://en.wikipedia.org/wiki/Kamuthi˙Solar˙Power˙Project (2023), accessed on May 1, 2023.

[30] Benban Solar Park, https://en.wikipedia.org/wiki/Benban˙Solar˙Park (2023), accessed on May 1, 2023.

[31] Solar Star, https://en.wikipedia.org/wiki/Solar˙Star (2023), accessed on May 1, 2023.

[32] D. J. MacKay, Solar energy in the context of energy use, energy transportation and energy storage, Philos. Trans. R. Soc. A: Math., Phys. Eng. Sci. **371**, 20110431 (2013).

[33] World hunger facts: What you need to know in 2022, https://concernusa.org/news/world-hunger-facts/ (2022), accessed on May 1, 2023.

[34] Food from the oceans, https://sapea.info/topic/food-from-the-oceans/ (2017), accessed on May 1, 2023.

[35] Dunkelflaute, https://en.wikipedia.org/wiki/Dunkelflaute (2023), accessed on May 1, 2023.

[36] J. Emblemsvaag and A. Österlund, How the energy trilemma can provide learning points between countries–the case for nuclear, Atw-Int. J. Nucl. Power **68**, 31 (2023).