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Renewable export cost index as an indicator of global renewable energy trade potential

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Renewable energy resources are widely available, yet they are unevenly distributed globally. In a renewable future, countries lacking high-quality renewable resources may choose to import energy from other countries. To assess the resource-dependent and techno-economic basis for global renewable energy trade and identify potential importers and exporters, this study introduces two new metrics: Renewable Export Cost Index (*Cost Index*) and Renewable Export Volume Index (*Volume Index*). These metrics are computed based on regional resource potential, domestic energy demand and varying financial costs across countries, without the need for any energy system modeling. By applying these two metrics to 165 countries/regions, we identify countries with significant potential for exporting renewable energy (e.g., the US, China) and those that lack the domestic resources to satisfy demand (e.g., South Korea, Japan). The *Cost Index* and *Volume Index* are validated through a separate analysis, employing a comprehensive energy system model for each country/region.

Limiting the increase in global average temperature to "well below" 2 °C entails an energy transition towards nearly zero or even negative CO_2 emissions by mid-century[1,2]. Electrification of transportation, heating and industrial sectors, directly or via electricity-derived fuels, will require a substantial increase in electricity supply[3,4]. Following sustained cost reductions and rapid diffusion into the power generation mix, renewable energy technologies such as wind power and solar photovoltaic (PV) may serve as the cornerstone for the future low-carbon electricity system[3,5–7]. Though renewable resources are broadly available, they are unevenly distributed globally[8,9]. Therefore, similar to other natural resources, some countries have more potential than others to meet their energy demands using domestic resources. In a decarbonized future, countries that lack sufficient high-quality renewable resources to meet their domestic demand can either invest in nuclear power, deploy carbon capture and storage (CCS) with fossil fuel power plants or import energy from other countries. Decarbonizing some end-use sectors may also increase demand for hydrogen and synthetic fuels produced using renewable electricity as a "feedstock"[3,10]. Thus, countries whose renewable energy production exceeds domestic demand could become energy supply nodes both for electricity and for electricity-derived fuels[11,12]. In this study, we evaluate the global potential of renewable energy and identify countries that could serve as potential importers or exporters. To accomplish this, we introduce two novel metrics: **Renewable Export Cost Index** and **Renewable Export Volume Index**. Throughout the remainder of this study, these two metrics will be referred to as *Cost Index* and *Volume Index*, respectively. Our analysis considers regional resource endowments, land availability for wind and solar power installations, domestic energy demand and country-specific discount rates, which reflect the heterogeneous financial costs across countries[13]. As climate mitigation scenarios anticipate significant expansion in wind and solar energy[14], and our primary objective is to elucidate concepts rather than predict the eventual winners among technologies, this study primarily focuses on wind and solar energy, in addition to existing hydropower, for the sake of simplicity.

Numerous studies have explored wind and solar energy potential[8,9,15–24], with some delving into global aspects beyond pure technical potential. While these studies[8,9,15–24] focused on the renewable resources themselves, other studies complemented the physical and economic potential analyses with other factors to identify potential importers and exporters of hydrogen. Notably, Pflugmann and De Blasio[25] incorporated factors such as domestic energy demand, freshwater availability for hydrogen production and infrastructure capabilities into their analysis, and proposed that the US and Australia have the potential to become leading hydrogen exporters. In addition to the factors considered in ref. 25, Tonelli et al.[26] considered the water footprint of wind, solar and electrolyzer infrastructures in their analysis, and identified Southern Africa, South America, Canada and Australia as promising leaders in hydrogen export. The IRENA report[27] took a further step by accounting for heterogeneous financial costs when estimating hydrogen supply costs and potential. Based on a survey

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with experts in the field, Hjeij et al.[28] developed a hydrogen export competitiveness indicator that integrated resource availability and potential, economic and financial potential, political and regulatory status and industrial knowledge. Their analysis identified the US, Australia, Canada and China as the most competitive countries in hydrogen export. Other studies employed complex energy system models to estimate regional hydrogen supply curves for Europe[29] and the Middle East and North Africa[30]. Additionally, some other studies[31–34] applied a global energy system optimization model to investigate potential electricity or hydrogen trade between countries[31–34].

Unlike previous studies that primarily focused on the heterogeneity of the renewable energy resource itself[8,9,15–24], this study also recognizes national differences with respect to the financial ability to develop the resources, as well as variations in domestic energy demand. While these aspects are to some extent accounted for in global energy system models[35,36], these models can also create barriers to understanding as they rely on numerous assumptions that influence the results. Additionally, they are not well-suited for predicting trade patterns, as factors like Armington elasticities[37] are not considered. Furthermore, the modeling results tend to show a limited number of trade routes or partnerships, whereas, in reality, many more possibilities exist[31–34]. Finally, global energy system modeling analyses typically focus on aggregated geographical regions rather than individual countries[31–33]. In contrast, our study provides a more transparent and straightforward method for estimating the renewable energy potential of each country for export. We achieve this by incorporating the diverse resource endowments (solar insolation and wind speed) and socio-economic realities (financial costs and energy demands) across the world into two metrics to assess the resource quality and quantity for trade. Our metrics are relatively simple compared to detailed energy system models[29,30,34] and the more complex indicators introduced by refs. 25–28. Still, they capture the factors that Hjeij et al.[28] proposed as the most influential. Moreover, our study does not narrow the analysis to focus solely on the vagaries of trade in, e.g., hydrogen, like in refs. 34,38. On the contrary, the *Cost Index* and *Volume Index* are agnostic to the specific form of energy trade. Therefore, they are more generic indicators for assessing energy trade potential than the hydrogen export competitiveness indicators developed in refs. 25–28. Overall, our approach offers a global techno-economic backdrop against which further socio-political analysis can be conducted to identify potential trade partners.

This study offers three key contributions. First, from a methodological perspective, we introduce two new metrics: Renewable Export Cost Index and Renewable Export Volume Index. These metrics serve as comprehensive indicators for the potential future trade of renewable energy, and they are easy to compute since they do not require any energy system modeling. Second, by applying the *Cost Index* and *Volume Index* to 165 countries/regions in the world, we provide a global view of the relative competitiveness of national renewable energy exports between countries. Third, compared with previous hydrogen export competitiveness indicators[25–28], we validate the utility of the *Cost Index* and *Volume Index* by comparing them with the marginal hydrogen cost and potential hydrogen export volume for each country, calculated using a comprehensive energy system model.

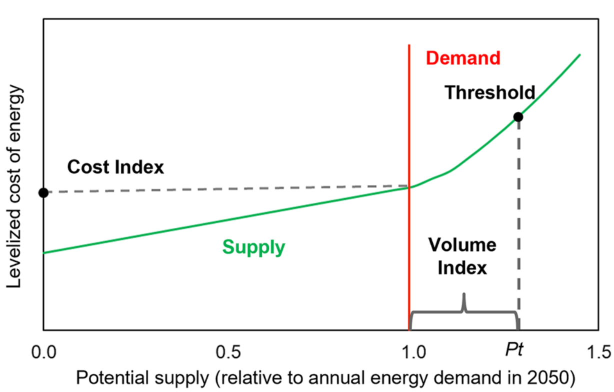

Fig. 1 | A schematic diagram for estimating the *Cost Index* and *Volume Index*. The x-axis represents the renewable energy supply potential relative to the estimated annual energy demand in 2050.

Results

We start by outlining the method for calculating the *Cost Index* and *Volume Index*, and we present the estimates of their values for different countries/regions in the world. Next, we illustrate the influence of diverse financial costs on both the *Cost Index* and *Volume Index*. Finally, we validate the utility of these two metrics by comparing them with the results obtained from country-specific, techno-economic energy system modeling analyses.

Two simple metrics to measure renewable export potential: Renewable Export Cost Index and Renewable Export Volume Index

The *Cost Index* represents the cost of providing an additional unit of energy for export after annual domestic energy demand is met. We first calculate the *LCOE* of renewable energy for every grid cell ($0.01° \times 0.01°$) in each country. Subsequently, we arrange the *LCOE* in ascending order to generate the national renewable energy supply curve (Fig. 1). Then, we identify the annual domestic energy demand (including both electricity and hydrogen demands), indicated by the red line at 1.0 on the x-axis in Fig. 1. Hydrogen can be used both directly (e.g., in industry) or as a feedstock to produce synthetic fuels. The intersection point of the annual supply and annual demand on the supply curve represents the ***Cost Index***. Hence, the *Cost Index* measures the cost at which surplus energy beyond domestic demand may be exported, as well as the marginal cost for a country to supply its entire energy demand using only domestic solar, wind and hydro resources (see "Methods" "Renewable Export Cost Index (*Cost Index*) and Renewable Export Volume Index (*Volume Index*)" for further details). The *Cost Index* takes into account, in addition to wind and solar conditions and country-specific discount rates, demographic factors (energy demand and available land for wind and solar power installations) and the contribution from existing hydropower. Similar to the regular *LCOE*, the *Cost Index* is not the actual energy cost in the energy market. Instead, it reflects the investment and operational costs linked to the energy generation technology required to produce an additional unit of energy for export once the annual domestic demand has been met. Therefore, it should not be interpreted as the marginal cost to produce electricity or hydrogen, which encompasses additional costs (see Section 2.3 and Discussion). By setting a threshold on the national renewable energy supply curve, it is possible to estimate the total renewable energy production (*Pt*) under the threshold (Fig. 1). Subtracting the domestic energy demand from *Pt* gives us the ***Volume Index***. Overall, the *Cost Index* reflects the quality of renewable energy export potential, while the *Volume Index* assesses the quantity of export potential. Together, the *Cost Index* and *Volume Index* provide a more holistic view of national renewable energy export competitiveness. Given the uncertainties in estimating future global renewable energy costs, the absolute values of the *Cost Index* and *Volume Index* are less important than the relative ranking of countries based on these indices.

We estimate the *Cost Index* at the country level for small and medium-sized countries, or at the subnational level for some large countries (see Fig. 2). Saudi Arabia, Chile, Morocco and the majority of the US, China, Mexico, Brazil and Australia show relatively low values for the *Cost Index*, thus being potential exporters of renewable energy. The export possibilities are particularly favorable for China, as neighboring countries exhibit high *Cost Index* values, or, in the case of Japan and South Korea, are unable to meet their demands using domestic resources. Due to unfavorably high financial costs, some African and Latin American countries exhibit relatively high *Cost Index* values. These values are on par with those of Central or even Northern European countries, despite the latter having significantly less favorable solar conditions.

Africa is sometimes cited as a continent that may rely on distributed rather than centralized power, since the solar resource is abundant and

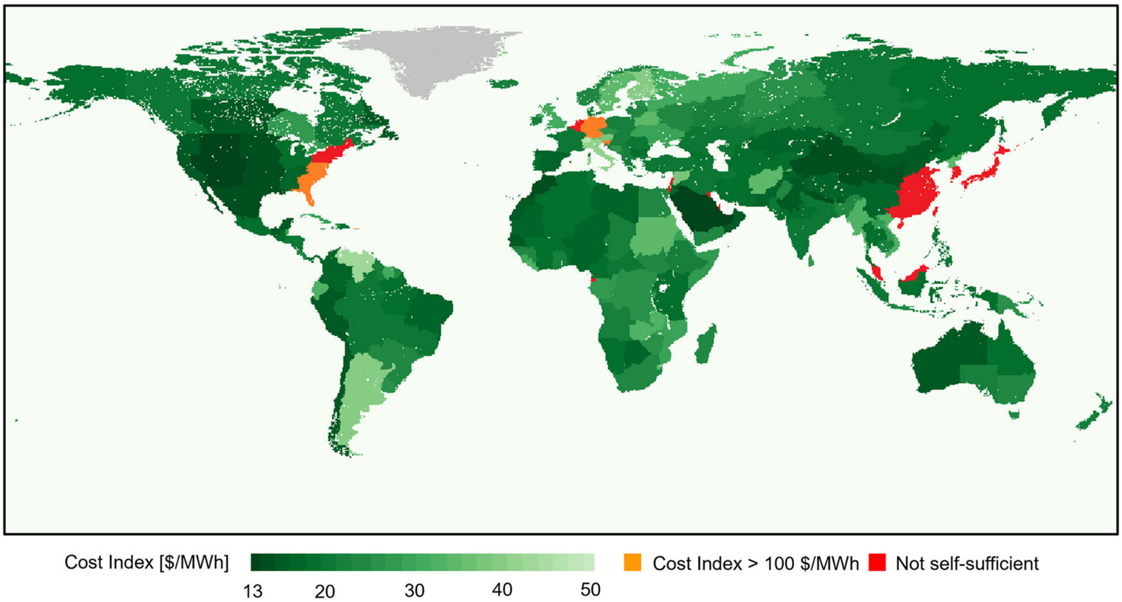

Fig. 2 | *Cost Index* for 2050. The *Cost Index* is estimated for most countries/regions in the world based on projected energy demand in 2050 and using current country-specific discount rates. The darker the green color, the lower the *Cost Index* value. Orange indicates a *Cost Index* value greater than $100/MWh, while red represents regions that are not self-sufficient with domestic renewable resources.

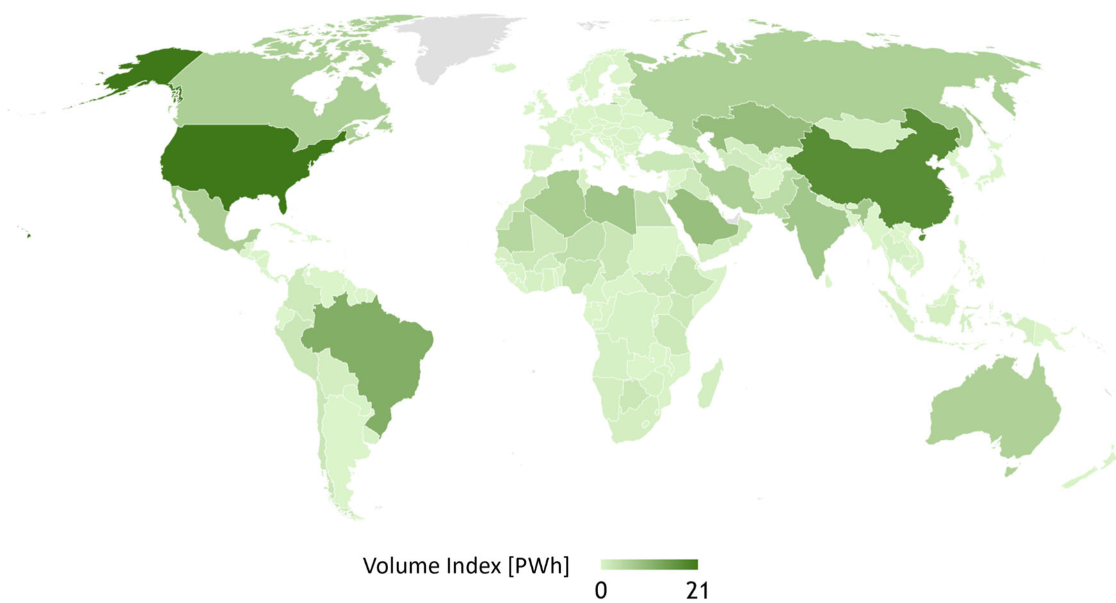

Fig. 3 | *Volume index* for 2050. The *Volume Index* is calculated under a threshold of 30 $/MWh on the national renewable energy supply curve.

evenly distributed[39]. However, Fig. 2 shows considerable heterogeneity within the continent, with several North African countries displaying a low *Cost Index* value, while the costs for some countries in the central part are notably high. Such uneven *Cost Index* values may provide incentives for developing long-distance power transmission grids for electricity trade. The heterogeneity in *Cost Index* values is also observed within large countries such as the US and China. For many countries, the *Cost Index* value is below 20 $/MWh, with the lowest cost reaching 13 $/MWh (Fig. 2). In stark contrast, around 30% of the countries are not self-sufficient or have a *Cost Index* value greater than 30 $/MWh. The large number of countries with comparably low *Cost Index* values may offer plenty of energy trade options for countries with insufficient renewable resources.

Apart from assessing the relative cost-competitiveness of exporting renewable energy, we also analyze the potential export volume (in PWh) after meeting each country's domestic energy needs. This analysis assumes a threshold on the national renewable energy supply curves, under which there is a demand from other countries to import energy (see Fig. 1). With a threshold of 30 $/MWh, the countries exhibiting the highest *Volume Index* values are the US, China, Brazil, Kazakhstan and Saudi Arabia (Fig. 3). Given the uncertainties surrounding the threshold value, we also calculate the *Volume Index* using different thresholds (Fig. S1). Overall, large countries like the US and China consistently emerge as the leading potential exporters (Fig. S1). These countries possess favorable wind and solar resources and display low financial costs for investments. This advantageous combination allows them to produce a significant amount of low-cost renewable energy that surpasses their domestic demand. Unsurprisingly, the *Volume Index* increases as the value of the threshold on the supply curve rises (Fig. S1).

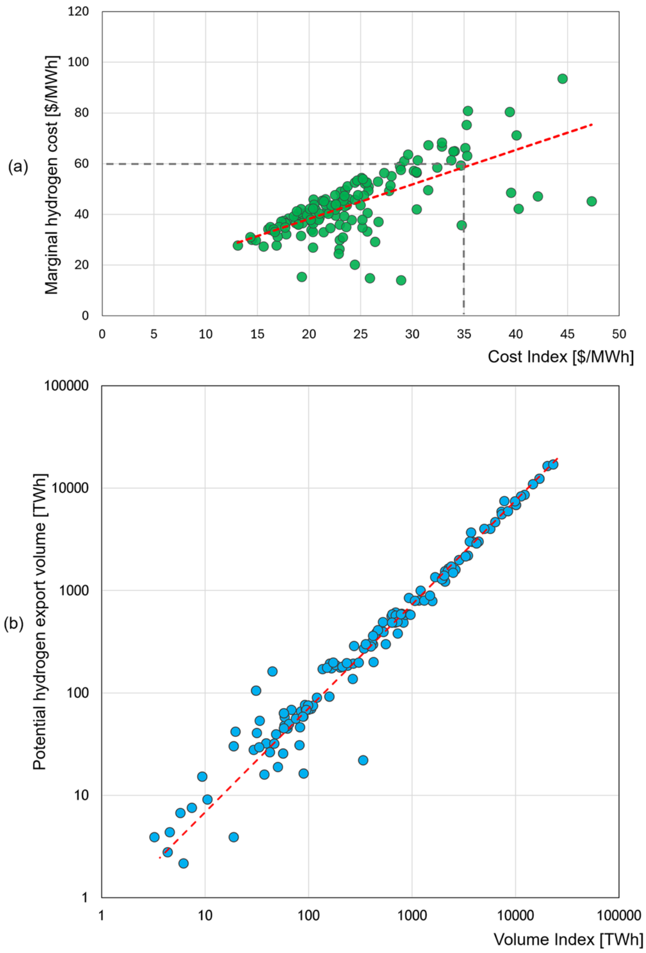

Fig. 4 | Validation of the *Cost Index* and *Volume Index* using marginal hydrogen cost and potential hydrogen export volume. **a** The relationship between the marginal hydrogen cost and the *Cost Index*. To enhance visualization clarity, countries that are not self-sufficient or exhibit exceptionally high costs due to land constraints are excluded. Only countries with a *Cost Index* value below 50 $/MWh are considered. The calculation of the *Volume Index* and the potential hydrogen export volume is carried out for countries located within the rectangle marked by the gray dashed lines. **b** The relationship between the potential hydrogen export volume and the *Volume Index*. Both the x-axis and the y-axis are displayed using a logarithmic scale.

Validation of the *Cost Index* and *Volume Index*: the cost to produce hydrogen and the potential hydrogen export volume

The *LCOE* of renewable energy, upon which the *Cost Index* and *Volume Index* are based, does not account for additional system costs associated with variation management for wind and solar power[40,41], nor does it factor in the expenses related to producing electricity-derived fuels, such as the investment costs of electrolyzers. To evaluate whether the inclusion of variation management and hydrogen production costs might affect the conclusions about potential importers and exporters based on the *Cost Index* and *Volume Index* analysis, we employ a detailed techno-economic cost optimization model[42] for capacity investment and dispatch to model each country covered in our study (see "Methods" "Marginal hydrogen cost and potential hydrogen export volume"). Since it remains unknown whether future energy trade will involve electricity or electricity-derived fuels like hydrogen, we validate the *Cost Index* results by comparing them with marginal hydrogen cost and average electricity price for each country. The marginal hydrogen cost reflects the cost of producing an additional unit of hydrogen for export after the domestic hydrogen demand has been met. Unlike the simple *Cost Index*, the marginal hydrogen cost and average electricity price represent the costs for hydrogen and electricity at the exporting node.

Figure 4a shows the relationship between the marginal hydrogen cost and the *Cost Index* for most countries in the world. The marginal hydrogen cost exhibits a high degree of correlation with the *Cost Index*, as indicated by a Spearman correlation coefficient of 0.7 (Fig. 4a). Furthermore, the relationship between the *Cost Index* and marginal hydrogen cost exhibits a similar pattern across countries, with the marginal hydrogen cost being approximately twice that of the *Cost Index* value (Fig. 4a). This relationship is consistent with the findings of other studies regarding the proportion of electricity generation cost in the total hydrogen cost[43–45]. Therefore, the relative cost-competitiveness of hydrogen export among countries based on the *Cost Index* analysis remains valid even when factoring in system integration costs and the expenses associated with producing a specific quantity of hydrogen. For further explanation of Fig. 4a, please refer to Supplementary Information 2,.1. Similar to the marginal hydrogen cost, the average electricity price is positively correlated with the *Cost Index*, with a Spearman correlation coefficient of 0.61 (Fig. S2). Thus, the *Cost Index* can indeed serve as a valuable indicator for comparing energy export costs across different countries and identifying potential importers and exporters.

We also validate the *Volume Index* by comparing it with the potential hydrogen export volume estimated with a detailed energy system model (see "Methods" "Marginal hydrogen cost and potential hydrogen export volume"). Figure 4b illustrates the relationship between the potential hydrogen export volume and the *Volume Index*. We evaluate the hydrogen export volume per country for a marginal hydrogen cost below 60 $/MWh and the *Volume Index* for a *Cost Index* value below 35 $/MWh, see the marked rectangle area in Fig. 4a. The threshold value for the marginal hydrogen cost was chosen based on the trendline in Fig. 4a, where a *Cost Index* value of 35 $/MWh corresponds to a marginal hydrogen cost of 60 $/MWh. The potential hydrogen export volume shows a positive correlation with the *Volume Index*, with a remarkably high Spearman correlation coefficient of 0.97 (Fig. 4b). This finding further emphasizes that the *Cost Index* and *Volume Index* together are valuable, not only for comparing energy export costs but also for assessing the volumes of export across different countries. Note that the *Cost Index* and *Volume Index* are agnostic to the form of energy trade. Our modeling analysis of hydrogen serves as an example to validate their effectiveness.

How much do financial costs matter? - Impact of heterogeneous discount rates on renewable export potential

To investigate the impact of heterogeneity in financial costs on the quality and quantity of renewable energy trade, we compare the *Cost Index* and *Volume Index* using both country-specific and uniform discount rates. The country-specific discount rates are obtained by adding the country-specific risk premiums[46] to a "risk-free" baseline discount rate (5%). As illustrated in Fig. 5a, in an optimistic future where all countries are harmonized to the same discount rate (5%), the *Cost Index* values for countries with the highest discount rates today decrease significantly (by more than 60%) compared to the values calculated with country-specific discount rates. Notably, the *Cost Index* values for Sudan and Venezuela are more than halved, indicating a substantial reduction in the cost of exporting renewable energy if these countries were to experience improved socio-political conditions and lower financial costs. In addition to reducing the *Cost Index* value, a lower discount rate also increases the *Volume Index* value. This is because the *Volume Index* measures the surplus energy exceeding domestic demand and having an *LCOE* below 30 $/MWh. This effect is particularly pronounced for countries with large geographical areas, such as Mongolia and Chad, where the *Volume Index* value more than doubles (Fig. 5b). These countries possess abundant high-quality renewable resources, but their renewable energy development may be hindered by high financial costs. Overall, we see that the assumption on discount rate significantly influences the assessment of both the quality and quantity of renewable energy potential. For potential implications, please refer to the Discussion section.

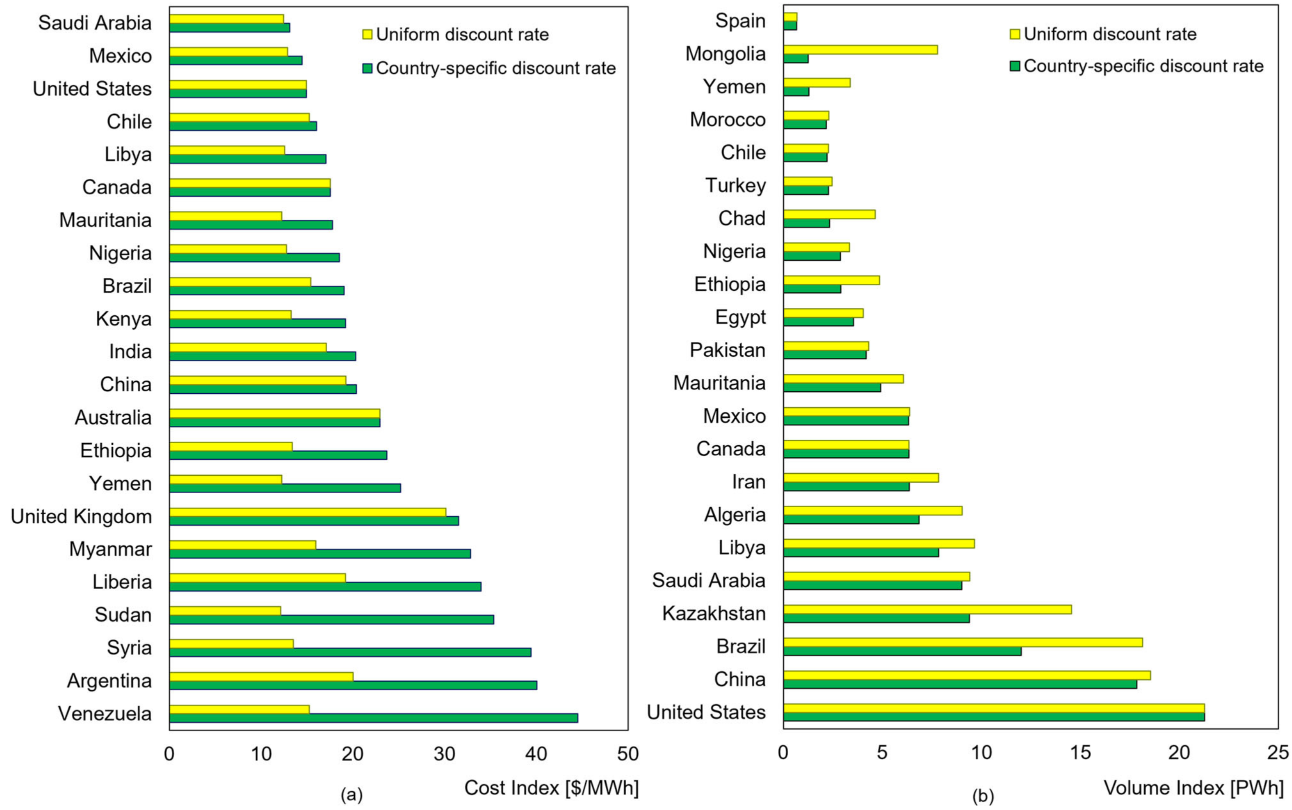

Fig. 5 | Impact of heterogeneous discount rates on the *Cost Index* and *Volume Index*. The *Cost Index* (**a**) and *Volume Index* under a threshold of 30 $/MWh (**b**) estimated with country-specific (green) and uniform (yellow) discount rates for some selected countries.

Sensitivity analysis: double electricity and hydrogen demands

To account for potential large-scale electrification and the production of electricity-derived fuels for energy sectors beyond the electricity system, we conduct sensitivity analyses by doubling the electricity and hydrogen demands, one at a time. Doubling the electricity demand does not affect the *Cost Index* significantly for most of the countries, except for countries with a high population density. Some of these countries are no longer self-sufficient, see Figs. S3, S4. In particular, a substantial impact is observed in European countries due to the change in electricity demand assumptions. The United Kingdom, Italy, Austria and the Czech Republic exhibit *Cost Index* values exceeding 200 $/MWh, while Germany, Switzerland and Slovenia are no longer self-sufficient with domestic renewable resources (Fig. S4). As for hydrogen, if the demand is doubled, the marginal hydrogen cost correlates better with the *Cost Index*, with a Spearman correlation coefficient reaching 0.9 (Fig. S5), compared to the correlation coefficient of 0.7 with the original assumption on hydrogen demand (Fig. 4a). This suggests that an increased domestic hydrogen demand does not diminish the validity of *Cost Index* as a metric for assessing the cost-competitiveness of hydrogen exports between countries.

Discussion

This study introduces two new metrics, the *Cost Index* and *Volume Index*, to comprehensively evaluate the quality and quantity of renewable energy exports worldwide. These metrics take into account regional renewable energy resource (wind, solar and hydro) endowments, country-specific discount rates, land availability for wind and solar power installations and domestic energy demand. These metrics are easy to compute using openly available data, without the need for complicated energy system models. By applying the *Cost Index* and *Volume Index* metrics to most countries in the world, we offer a comprehensive global perspective on the relative competitiveness of national renewable energy exports across countries.

The *Cost Index* and *Volume Index* extend beyond the mere physical potential studies[24] as they assess the availability of energy for export after fulfilling domestic energy requirements, regardless of the potential energy trade form. These two metrics offer a broader scope than other comprehensive indices developed by Hjeij et al.[28] and the IRENA report[27] for evaluating the competitiveness of hydrogen exports. Like the indices in Hjeij et al.[28] and the IRENA report[27], they provide a simple and transparent approach for deriving insights about the potential for global renewable energy trade, and they do not require a full-scale global energy system modeling analysis like in refs. 31–34. Unlike Hjeij et al.[28], the IRENA report[27] and Tonelli et al.[26], we validate the utility of our metrics with a comprehensive energy system modeling analysis of all 165 countries/regions included in our study.

The *Cost Index* and *Volume Index* focus solely on the costs associated with power generation assets. A large part of the cost to satisfy demand in a system based on variable renewables consists of the cost to provide the so-called system integration[40,41], namely variation management, including storage and backup capacity to address the intermittency of wind and solar power production[6,7,47]. Additionally, the decarbonization of certain end-use sectors is likely to drive an increased demand for electricity-derived fuels like hydrogen. To investigate whether the inclusion of additional system integration costs for wind and solar power, as well as hydrogen production, could influence the conclusions regarding potential importers and exporters based on the *Cost Index* and *Volume Index* analysis, we use a detailed techno-economic cost optimization model for capacity investment and dispatch[42] to model each country covered in our study (see "Methods" "Marginal hydrogen cost and potential hydrogen export volume"). We find that the *Cost Index* is indeed highly correlated with the marginal cost to produce hydrogen at future predictions for hydrogen demand (correlation coefficient 0.7, Fig. 4a). The marginal cost of hydrogen is approximately double that of the *Cost Index* value across the countries (Fig. 4, S5). Additionally, we observe a strong correlation between the *Volume Index* and the potential hydrogen export volume (correlation coefficient of 0.97, Fig. 4b). This reinforces the value of *Cost Index* and *Volume Index* as effective tools for assessing the competitiveness of renewable energy exports across different countries.

In contrast to the comprehensive hydrogen export competitiveness index developed by Hjeij et al.[28], which considers resource availability and potential, economic and financial potential, political and regulatory status and industrial knowledge, this study places a greater emphasis on renewable resource potential and economic factors of each country. This choice hinges partly on the perspective regarding future hydrogen or other electricity-derived fuels as predicated on, but by no means determined only by, the physical resource endowment[48]. This perspective aligns partially with the methodology employed in Hjeij et al. [28], where they assigned importance to factors related to resource availability and financial stability, accounting for roughly 75% of their index. The *Cost Index* and *Volume Index* do not incorporate certain factors such as freshwater scarcity, as emphasized in refs. 25,26, which can be addressed through alternatives like desalination at a relatively cheap cost compared to the total cost of hydrogen production for regions not significantly far from the coast[49]. However, it is important to note that in countries where both freshwater and seawater are scarce, the approach employed in our study may overestimate the potential of hydrogen. Last but not least, compared to the energy systems literature[31–33], we incorporate country-specific discount rates in our calculations to account for the varying financial costs across countries.

Our results show that some countries possess both the physical and financial potential to meet their domestic energy needs and have the potential to further export significant amounts of renewable energy at a low cost (Fig. 3). For instance, the analysis suggests that the US and China, currently the top two oil-importing countries[50], have an export potential of renewable energy at a production cost below 30 $/MWh around 20 PWh, respectively. For context, this number is comparable to the current electricity consumption for the entire world[51]. Other countries that we identify as potential exporters include Saudi Arabia, Brazil and Kazakhstan. Our results regarding potential large exporters are in line with the main findings of Hjeij et al.[28] and the IRENA report[34], where big countries such as the US, China, Australia and Saudi Arabia emerge as the top contenders in the future hydrogen market. Australia does not rank within the top five countries in our study because we exclude remote sites located more than 200 km away from regions with grid access. This could change if Australia were to extend its grid to enable the development of these resources for export. Our results also indicate that some countries, such as Japan, South Korea, Belgium, the Netherlands and Germany, may not be self-sufficient with domestic renewable energy or can do so only at an extremely high cost. Such conditions could prompt them to explore other low-carbon technologies, like nuclear power and CCS, or encourage them to import from low-cost countries with substantial potential. Even for countries that are potentially self-sufficient, but at a relatively high cost, importing electricity or electricity-derived fuels may be an attractive option, thereby stimulating trade. The ability of most countries to meet domestic demands with domestic resources offers them a choice between low-cost imports or securing higher-cost domestic supplies, which represents a marked contrast to the fossil economy, where energy self-sufficiency is impractical for most countries[52]. In a renewable future, some countries that are now large importers of fossil fuels can become exporters. Such shifts in energy imports and exports may have implications for foreign policy in the US[53] and China[54]. It is an open question whether the significant potential held by these two giants in comparison to the rest of the world (Fig. 3) would result in a dominant position in the energy trade, akin to the current dominance of countries rich in oil resources.

In addition to the identification of potential importers and exporters, our findings also underscore the significant impacts of heterogeneous financial costs on both the *Cost Index* and *Volume Index*. These results highlight the need to address financial obstacles, rather than technical challenges, to facilitate the development of renewable energy in certain countries effectively. For example, using North Africa to tap solar resources, as previously suggested by refs. 11,12, is perhaps not as economically attractive as the solar radiation data alone might suggest. Our findings regarding the impacts of heterogenous financial costs are consistent with the conclusions of refs. 35,55–57, where renewable energy is less competitive in high-risk countries (Fig. 5, S7).

In this study, we do not focus on the specific trade patterns between countries. We intentionally maintain a neutral stance regarding the nature of future energy trade, seeking only to highlight the potential for spatial arbitrage, subject to the costs of closing the arbitrage (i.e., trade). We also remain purposefully agnostic about future energy trade relationships. While our primary focus is on the potential for energy cost arbitrage, it's important to note that trade relationships are influenced by many other factors, including the availability of trading infrastructure (such as pipelines or import/export terminals), the cost of the trade itself and geopolitical relationships. The differences in renewable potential, here embodied using the *Cost Index* and *Volume Index*, between different countries create incentives and opportunities for international energy trade, but we acknowledge that this information alone does not predict what future trade patterns might look like. The energy trade, either through transmission grids or via some electricity-derived fuels such as ammonia, will come with a cost for transport, which is not included in our analysis. Therefore, the gap between one country's self-sufficiency margin and the export cost from another country (*Cost Index*), will partly be narrowed by the transport cost. Although we have not explicitly evaluated this cost, it seems that, at least for electricity, heterogeneity in resources does result in trade being an efficient way to decrease electricity system costs, at least within continents (by 10%–30%[6,58–60]). As the distances become even longer, this effect diminishes. For instance, the reduction in electricity system costs resulting from intercontinental electricity trade is less than <5%[33,36]. As for hydrogen, a recent study conducted by Hampp et al.[61] showed that, even when factoring in transport costs, it is still more cost-effective to import hydrogen, methane, methanol and ammonia produced from other countries than domestically producing them in Germany. We also conducted a simple calculation of the levelized cost of hydrogen exported to Germany from Spain, Morocco and Saudi Arabia based on the cost parameters outlined in Hampp et al.[61]. The levelized cost of hydrogen exported from Spain, Morocco and Saudi Arabia is 21%, 19 % and 16% cheaper, respectively, compared to domestic hydrogen production in Germany. This example serves as further evidence that the heterogeneity of energy costs between countries can create an incentive for international energy trade. Notably, existing hydrogen trade agreements between Chile and Australia with Germany, Japan and the Netherlands[62] further highlight the growing trend of countries engaging in energy trade to capitalize on energy cost disparities.

We do not explore the impact of land availability for wind and solar power installation on the *Cost Index* and *Volume Index*. Lower land availability has an impact that is comparable to a higher electricity demand, as discussed in "Results" "Sensitivity analysis: double electricity and hydrogen demands". For the country-specific discount rate, we use a value that reflects the present financial risk level for each country. The discount rate is particularly high for countries that experience political and social unrest today, which explains the high values in, e.g., Venezuela and Sudan (see Fig. S7). However, these values can change. Countries that are unstable today may become stable in the future, while countries with a low-risk premium today may fall into socio-political unrest. We acknowledge this uncertainty and, thus, agree with the critique in Bogdanov et al.[63] about whether today's risk premiums accurately reflect a 2050 world. Addressing this uncertainty may require multiple scenarios of political stability and financial risk. Although outside the scope of this work, we welcome such efforts for future research. Furthermore, the discount rate varies not only between countries but also across different sectors, technologies and projects[64,65]. Due to the project-specific nature of renewable energy technologies, we acknowledge the extreme difficulty of estimating the discount rates for every technology in each country. Instead, our focus is directed towards assessing how regional disparities in discount rates affect the potential for national renewable energy exports.

We argue that the *Cost Index* and *Volume Index* provide a solid basis for further scientific analysis of trade relations, thus removing the necessity for researchers to employ complex energy system models for such analysis. In addition, this work highlights the importance of a country's financial circumstances, alongside the renewable resource endowments, for its self-sufficiency and export potential of renewable energy. While we leave it to others to go deeper into the possible geopolitical scenarios that may be the consequence of the renewable energy cost reality, we hope that this paper can provide the basis for analyzing self-sufficiency and trade patterns for renewable electricity and electricity-derived fuels.

Methods

The approach for assessing the comparative competitiveness of countries in renewable energy exports consists of two parts: introducing the *Cost Index* and *Volume Index* and validating them using an energy system model. The development of the *Cost Index* and *Volume Index* involves two fundamental aspects: sourcing and processing data concerning wind, solar and hydropower output (Section "Renewable *LCOE* (*RLCOE*)"), and assessing the financial costs linked to renewable energy in each country (Section "Renewable *LCOE* with country-specific discount rate"). For details about validating the *Cost Index* and *Volume Index*, an introduction to the energy system model and the cost assumptions for various energy technologies, please refer to Section "Marginal hydrogen cost and potential hydrogen export volume".

Renewable *LCOE* (*RLCOE*)

We first calculate the cost of supplying one unit of wind or solar energy from a grid cell 0.01° × 0.01° (approximately 1 km × 1 km at the equator) based on the ERA5 reanalysis data (hourly wind speed, direct and diffuse solar insolation)[66], annual average wind speed from Global Wind Atlas (GWA)[67] and a uniform discount rate of 5%. The *RLCOE* for global onshore wind and solar resources is illustrated in Fig. S7.

Wind capacity factor. The wind profile, which represents the hour-to-hour variation in wind speed, and the annual average wind speed are the two key parameters for assessing the wind power potential. The ERA5 data provides an accurate estimate of the wind profile[68]. However, its low spatial resolution (31 km × 31 km) means that it is not well-suited for assessing the annual average wind speed given the potential heterogeneity in wind speed within a small geographical area[69]. The annual average wind speed is accurately documented in the GWA[67]. Thus, we combine the ERA5 data set (wind profile) and the GWA dataset (annual average wind speed) with the methodology from Mattson et al.[69]. Each small pixel (with a size same as that in GWA, 1 km × 1 km) is provided with the wind profile from the corresponding larger pixel in ERA5, and the wind profile is then scaled using the average wind speed in GWA. By doing so, we obtain an hourly time series of wind speed that captures geographical variations in wind output caused by local differences in topography and land cover at a spatial resolution of 1 km (compared to 31 km for ERA5). The instantaneous wind speeds are then converted into capacity factors using the output profile of the 3 MW Vestas V112 wind turbine, including wake losses and Gaussian smoothing to account for wind variations within a park (Fig. S9)[69]. The annual mean wind power capacity factor is calculated by averaging the hourly wind power capacity factor over one year.

Solar capacity factor. The solar capacity factor is estimated based on the ERA5 "surface solar radiation downwards" (SSRD) and "total sky direct solar radiation at surface" (FDIR)[66]. In addition to these two ERA5 variables for diffuse and direct insolation, we also need top-of-atmosphere solar insolation (TOA) variations over the year. This variable is calculated as below[70]:

$$\mathrm{TOA} = I_0\left(1 + 0.034\cos\frac{2\pi n}{365.25}\right)$$

where I_0 is the solar constant (1361 W/m2) and n is the ordinal of the day in the year.

The total insolation striking a tilted solar PV panel is the Global Tilted Irradiance (GTI):

$$\mathrm{GTI} = I_{direct}^{sun} + I_{diffuse}^{sky} + I_{diffuse}^{ground}$$

where I_{direct}^{sun} is direct beam radiation from the sun, $I_{diffuse}^{sky}$ is diffuse radiation from the sky and $I_{diffuse}^{ground}$ is diffuse reflected radiation from the ground. I_{direct}^{sun} can be directly calculated from the ERA5 FDIR variable using the solar position. $I_{diffuse}^{ground}$ is also straightforward assuming a constant uniform ground albedo. We use the Hay-Davies model which includes an isotropic component and circumsolar diffuse radiation to take into account that the sky is brighter nearer to the sun. The resulting equations are:

$$I_{direct}^{sun} = \mathrm{FDIR}\cdot R_b = \mathrm{FDIR}\cdot\frac{\cos\mathrm{AOI}}{\cos z} = \mathrm{DNI.}\cos AOI$$

$$I_{diffue}^{sky} = \mathrm{DHI}\cdot\mathrm{AI}\cdot R_b + \mathrm{DHI}\cdot(1-\mathrm{AI})\cdot\frac{1+\cos\beta}{2}$$

$$I_{diffue}^{ground} = \mathrm{GHI}\cdot\rho\cdot\frac{1-\cos\beta}{2}$$

where R_b is the ratio of tilted and horizontal solar beam irradiance, AOI is the angle of incidence of the sun on the PV panel, z is the solar zenith angle, DNI is direct normal irradiance, DHI is diffuse horizontal irradiance, AI is the anisotropic index (a measure of nonuniformity of sky brightness), β is the tilt angle of the PV panel and ρ is ground albedo, which is assumed to be 0.2 everywhere. The variables are further related by:

$$\mathrm{DHI} = \mathrm{SSRD}, \mathrm{DNI} = \frac{\mathrm{FDIR}}{\cos z}, \mathrm{AI} = \frac{\mathrm{DNI}}{TOA}, \quad R_b = \frac{\cos\mathrm{AOI}}{\cos z}$$

$$\cos\mathrm{AOI} = \cos z\cos\beta + \sin z\sin\beta\cos(\alpha_{sun} - \alpha_{PV})$$

Here α_{sun} is the azimuth angle of the sun and α_{PV} is the azimuth angle of the PV panel (assumed zero), with azimuth measured with zero due south and positive direction toward west. ERA5 radiation variables are documented in Hogan[71].

In clear-sky weather, the optimal tilt angle of a PV module for a given location is the latitude of the panel. However, if conditions are often cloudy, more diffuse sky radiation can be captured if the tilt angle is smaller than its latitude. Therefore, the optimal tilt angle is location specific. For simplicity, we use the fitted third degree polynomials from Jacobson et al. [72] to get near optimal tilt as a function of latitude and we do not consider tracking solar PV systems.

Given that solar radiation is rather stable within a certain geographical area (compared with the heterogeneity in wind speed), the calculated solar capacity factor based on ERA5 for each large pixel (31 km) is then provided to the corresponding small pixels (1 km). In this way, we get a map for the solar capacity factor with the same resolution as the wind capacity factor.

Cost assumptions. The costs for wind and solar in 2050 are based on the estimates from IRENA[73,74]. We do not explicitly consider learning rates, meaning that we do not have endogenous learning in the analysis. Instead, we assume that the cost declines implied in the IRENA estimates for 2050 adequately capture the combined effects of local and global learning for a level of deployment sufficient to achieve a 100% renewables-based energy system. For more discussion about cost assumptions, please refer to Supplementary Information 3.1. All the cost assumptions and technical parameter values are summarized in Table 1. Note that most utility-scale PV and onshore wind projects do not own the land on which the PV panels and wind turbines are placed. The land lease

Table 1 | Cost data and technical parameters

Technology	Investment cost [$/kW]	Variable O&M costs [$/MWh]	Fixed O&M costs [$/kW/yr][a]	Lifetime [years]
Onshore wind	825[b]	0	33	25
Offshore wind	1500[b]	0	55	25
Solar PV	323[c]	0	8	25
Solar rooftop	423[c]	0	6	25

[a] Akar et al. [88]
[b] IRENA[73]
[c] IRENA[74]

cost consists of a minor share of the total cost for the solar and wind power project[75,76].

Renewable *LCOE* with country-specific discount rate

The *RLCOE* is first calculated with a uniform discount rate of 5% for the entire world, similar to the common practice in other studies, see Fig. S6a & c. By contrast, Renewable *LCOE* with country-specific discount rate ($RLCOE_r$) takes into account the different circumstances for investment in different countries, see Fig. S6b & d. The fixed investment costs for renewable power plants can be characterized using an overnight capital cost (OCC), potentially modified by a cost of capital during construction, which is depreciated over the economic lifetime of a project using a weighted average cost of capital (WACC). Both OCC and WACC can vary regionally. For instance, the IEA's World Energy Outlook 2021 used 600 $/kW as OCC for solar PV in India and 1100 $/kW in the US[77]. Additionally, it applied a WACC of 3%–6% for solar PV and onshore wind projects[77]. OCC can even vary significantly within a single country. In the Annual Energy Outlook 2023, the US EIA employed OCC for onshore wind that varies from 1566 to 3458 $/kW across the 25 regions modeled in the United States[78].

OCC includes the costs of materials, equipment and labor, and can also include the cost of land acquisition, grid interconnection, permitting and other professional services. Regional differences can be driven by the costs of both skilled and unskilled labor, remoteness of the site and the regulatory environment in which a project is developed, among other factors, each of which can vary over time as well. WACC incorporates the financing structure of a specific project, including the costs of equity and debt financing, along with any government support, such as guarantees, subsidies, favorable tax, royalty treatment or direct financial contributions. These items can vary from project to project, across companies and industries, and are dependent on the priorities of national and local governments, which can sometimes change abruptly.

In the present study, we emphasize the impacts of regional differences in levelized capital costs on the deployment potential of wind and solar energy, as well as the corresponding impacts on the national competitiveness of renewable energy exports. Levelized capital costs can vary due to differences in resource quality, capital costs or WACC. Due to the project-specific nature of many of the capital cost drivers, we recognize the futility of trying to estimate average capital costs from a bottom-up analysis of their constituent components. Instead of estimating regional OCC and WACC separately, we take a different, top-down approach to estimate differences in levelized capital costs. Our approach modifies a uniform capital cost baseline using a country-specific hurdle rate that captures the overall difficulty of doing business in a country. We are unaware of any comprehensive global studies about the country-specific variations in wind and solar PV capital costs. In addition, we anticipate that idiosyncratic capital cost differences across individual renewable energy projects would become less pronounced under the type of large-scale building program encompassing many individual projects that would be required under a low-carbon energy transition. We therefore assume for the sake of illustration that the levelized capital cost differences for wind and solar are dominated primarily by the quality of the resource and the cost of capital (i.e., WACC). We assume a common capital cost (unmodified OCC) for all projects, and levelize it over the lifetime of the asset using country-specific discount rates that incorporate risk premium estimates from Damodaran[46]. These estimates are available for most countries and are given in the form of an additional hurdle rate above a common global risk-free yield. They are based on objective financial measures (e.g., credit default swap spreads from sovereign bond yields), where available, and subjective sovereign credit risk ratings from Moody's or Standard & Poor's where government bonds are not widely traded[46]. While such country risk premiums technically correspond only to sovereign default risk, the ability of a government to support a multi-decadal, large-scale infrastructure program depends on many of the same drivers, such as macroeconomic and political stability. We add the country risk premiums to the uniform discount rate (5%) to obtain the country-specific discount rates that are employed in calculating the $RLCOE_r$ for each country in this study. Note that the financial costs of an individual project may differ significantly from the country-specific discount rates. For more discussion about the individual project's financial costs, please refer to Supplementary Information 3,.2.

Renewable Export Cost Index (*Cost Index*) and Renewable Export Volume Index (*Volume Index*)

We estimate the **Renewable Export Cost Index** (*Cost Index*) for most countries in the world. It measures the marginal cost for a country to supply its entire energy demand using only domestic renewable resources (wind, solar and existing hydropower) (Fig. 1). Here, the energy demand includes both electricity demand and hydrogen demand. Our initial step involves arranging the $RLCOE_r$ in ascending order to construct the national renewable energy supply curve (Fig. 1). Subsequently, we pinpoint the annual domestic energy demand marked by the red line at 1.0 on the x-axis in Fig. 1. The point of intersection between the annual supply and annual demand on the supply curve represents the *Cost Index*. For instance, if a country has an annual energy demand of 100 TWh and an annual hydropower generation of 20 TWh, the *Cost Index* is determined by sorting $RLCOE_r$ for all the grid cells within that country until the total generation reaches 80 TWh. The *Cost Index* corresponds to the $RLCOE_r$ of the last grid cell required to achieve a generation equal to the annual demand.

The *Cost Index* is estimated at the country level or subnational level for some big countries. Figure S10 illustrates the national renewable energy supply curves for a random selection of countries. Remote solar and wind power plants that are far from regions with grid access may require additional investments in transmission grids. Therefore, we add 200 $/kW as extra investments in transmission grids for remote solar PV and wind power plants[69]. As for the hydropower potential, we obtain the data from refs. 79–81. The *Cost Index* thus assesses the renewable energy potential in relation to the energy demand of the country. It is a metric that hints at the national self-sufficiency potential (if the *Cost Index* value < certain reasonable cost), as well as the export potential (If the *Cost Index* value is very low, there is likely an export potential of electricity or electricity-derived fuels). It takes into account, in addition to the country-specific discount rate, the available land for renewable energy in relation to the domestic energy demand.

Taking into consideration a threshold on the national renewable energy supply curve, it is possible to estimate the overall renewable energy production (*Pt*) within the specified threshold (Fig. 1). By deducting the domestic energy demand from *Pt*, we derive the Renewable Export Volume Index (*Volume Index*, in PWh) (Figs. 1, 3). The *Volume Index* serves as an approximation of the amount of renewable energy that could be economically produced and traded in different countries in a renewable future. For more discussions about the methodology, please refer to Supplementary Information 3.3.

It is important to note that all renewable energy resources, including wind, solar, hydro, biomass and geothermal, along with other power generation technologies like nuclear power and CCS, can be integrated as energy supply technologies for the estimation of the *Cost Index* and *Volume Index*. The reason why we concentrate on wind and solar for energy supply is twofold. First, these resources are abundant, widely available, and the technologies harnessing them are becoming increasingly cost-competitive compared to other power generation methods. Second, our primary goal is to elucidate concepts rather than predict eventual winners among technologies. For simplicity, we primarily focus on wind and solar energy, along with existing hydropower. Additionally, both the *Cost Index* and *Volume Index* are agnostic to the nature of future energy trade. These metrics serve as generic indicators for evaluating energy trade, irrespective of the energy carrier. For a more detailed discussion on the format of future energy trade, please refer to Supplementary Information 3,.4.

Energy demand. The annual electricity consumption for each country in 2050 is estimated by extrapolating the annual demand in 2016[82]. This extrapolation is based on the regional demand growth between 2016 and 2050 in the Shared Socioeconomic Pathway 2 scenario outlined in the IPCC report[14]. We then estimate the hourly demand profile based on a machine learning approach which adopts historical demand profiles for 44 countries as input to a gradient boosting regression model[83] to calculate the hourly demand profile. The regression model takes into account the calendar effects (e.g., hour of day, weekday and weekend), temperature (e.g., hourly temperature in the most populated areas of each region), and economic indicators (e.g., local GDP per capita). Finally, the hourly demand series is scaled to match the annual electricity demand for each region in 2050. As for hydrogen demand, we assume the annual demand for hydrogen equals half the annual electricity demand, which is consistent with the magnitude of projected hydrogen demand for 2050 outlined in the European Commission's long-term strategic vision[84].

The annual electricity demand and the annual hydrogen demand are combined to form the domestic energy demand used in the calculation for the *Cost Index* and *Volume Index*. Meanwhile, the hourly electricity demand profile and the annual hydrogen demand are utilized as inputs for an energy system model, which is employed to calculate the marginal hydrogen cost and the potential hydrogen export volume (see "Methods" "Marginal hydrogen cost and potential hydrogen export volume"). For sensitivity analysis, we double the electricity demand to account for large-scale electrification, which is consistent with the estimations from sector-coupling energy system studies[3,85]. For simplicity, we assume that the energy demand is inelastic. Please refer to Supplementary Information 3,.1 for more discussion about energy demand.

Assumptions about wind and solar capacity. A crucial parameter needed to estimate the *Cost Index* is how densely solar and wind power may be deployed in the landscape, and which types of land to exclude from potential wind and solar exploitation. Many different assumptions are made in the literature for wind power[23], and there is sparse empirical evidence for those assumptions[86]. The analysis in Hedenus et al.[86] suggests that wind turbines have been built on all kinds of land types, and up to 20% of all the land has been used for wind deployment in some counties in the US. Since institutional frameworks differ between countries, ideally, assumptions regarding restrictions on where to deploy solar and wind power should be dependent on each country. However, as such analyses have not yet been done, we here simply assume that wind power may be deployed on all types of land, but that a maximum of 10% of the land may be exploited for wind power purposes. As for offshore wind power, we assume it can be installed in areas with a maximum depth of less than 60 m, and a maximum of 10% of the area may be deployed for wind power. Given the limited knowledge about where and how much solar PV may be built, we make more conservative assumptions for solar PV. We exclude all land covered with forests and assume a maximum of 5% of the remaining land to be available for solar PV installations. For Rooftop solar PV, we assume that 5% of the urban areas can be utilized for its installations Table 2.

Marginal hydrogen cost and potential hydrogen export volume

The *Cost Index* and *Volume Index* focus only on the costs of power generation. The cost of energy in a renewable energy system consists of both generation costs and the costs to manage the variation of wind and solar[6]. To validate the comparative competitiveness of exports based on the *Cost Index* and *Volume Index* analysis and findings regarding potential importers and exporters, we employ a typical techno-economic cost optimization model (Supergrid) to investigate each country covered in our study[42,87]. The Supergrid model is a greenfield capacity expansion model with hourly time resolution, which optimizes the investment and dispatch for the electricity sector and hydrogen production with an overnight approach. The exception is hydropower, where existing hydropower plants are assumed to be still in operation in 2050 and the capacity is assumed to remain at the current level due to environmental regulations. In terms of the CO_2 emission target, we assume a nearly zero emission system with a global CO_2 emission cap of 1 g CO_2 per kWh of energy demand. The model is written in the Julia programming language using the JuMP optimization package. The model-specific code, input data and output data are available online to further enhance the transparency and reproducibility of the results. The cost assumptions and key parameters for technologies are summarized in Table 3. For a more detailed description of the model, see ref. 42.

We first calculate the marginal hydrogen cost for each country. The marginal hydrogen cost refers to the shadow price of the hydrogen balancing constraint. The marginal hydrogen cost represents the cost of producing an additional unit of hydrogen for export after the domestic energy demand has been met. Unlike the simple *Cost Index*, the marginal hydrogen cost represents the cost for hydrogen at the export node. By comparing the *Cost Index* results with the marginal hydrogen costs, we can assess whether our conclusions about the relative national competitiveness in exporting renewable energy, based on the *Cost Index* analysis, remain valid when accounting for system integration costs and hydrogen production.

By conducting a thorough analysis of the marginal cost of hydrogen at various hydrogen demand levels, we can generate a hydrogen supply curve for each country (Figs. S10, S11). By setting a threshold on the national hydrogen supply curve, we can calculate the potential total hydrogen production achievable at the designated threshold. Subtracting the domestic hydrogen demand from this total hydrogen production allows us to determine the potential hydrogen export volume. We then validate the partition of countries into those with a large export potential from those with a potential import demand by comparing the *Volume Index* results

Table 2 | Assumptions about the capacity limits of wind and solar PV

	Solar PV	Solar Rooftop	Onshore wind	Offshore wind
Density [W/m^2] [a]	45	45	5	5
Available land [%]	5%	5%	10%	10%

[a]The term 'Density' refers to the capacity assumed to be installed per unit area for a typical solar or wind farm.

Table 3 | Cost data and technical parameters

Technology	Investment cost [$/kW]	Variable O&M costs [$/MWh]	Fixed O&M costs [$/kW/yr]	Fuel costs [$/MWh fuel]	Lifetime [years]	Efficiency/Round-trip efficiency
Natural gas OCGT	500	1	10	22	30	0.35
Natural gas CCGT	800	1	16	22	30	0.6
Coal	1600	2	48	11	40	0.45
Biogas OCGT	500	1	10	37	30	0.35
Biogas CCGT	800	1	16	37	30	0.6
Onshore wind [a]	825	0	33	n/a	25	n/a
Offshore wind [a]	1500	0	55	n/a	25	n/a
Solar PV [b]	323	0	8	n/a	25	n/a
Solar Rooftop [b]	423	0	5.8	n/a	25	n/a
CSP	3746	2.9	56	n/a	30	n/a
Electrolyzer	250	0	5	n/a	25	0.66
Hydrogen storage	11 $/kWh	0	0	n/a	20	n/a
Fuel cell	800	0	40	n/a	10	0.5
Hydro	300[c]	0	25	n/a	80	1
Onshore Transmission[d]	400 $/MW/km	0	8 $/MWkm	n/a	40	0.035 loss per 1000 km[e]
Offshore Transmission[f]	470 $/MW/km	0	1.65 $/MWkm	n/a	40	0.035 loss per 1000 km[e]
Converter[d]	150	0	3.6	n/a	40	0.986[g]
Battery[h]	116 $/kWh	0	1.5 $/kWh	n/a	15	0.85
Demand response	0	1000	0	n/a	n/a	1

[a]IRENA[73]
[b]IRENA[74]
[c]Steffen[89], this cost refers to the expenses associated with the replacement of old mechanical and electrical machinery.
[d]Hagspiel et al.[90]
[e] Kalair et al.[91]
[f]Purvins et al.[92]
[g]Alassi et al.[93]
[h]Cole et al.[94], the parameters for battery are based on a 4-hour lithium-ion battery system.
O&M, operation and maintenance; OCGT, open-cycle gas turbine; CCGT, combined-cycle gas turbine; CSP, concentrating solar power.

with the potential hydrogen export volume. For the validation, we choose the threshold value for the marginal hydrogen cost based on the trendline in Fig. 4, where a *Cost Index* value of 35 $/MWh corresponds to a marginal hydrogen cost of 60 $/MWh.

Data availability
The data supporting the *Cost Index and Volume Index* metrics are available at the following links: https://github.com/xiaomingk/Global-renewable-potential and https://zenodo.org/records/6793266.

Code availability
The code for the *Cost Index and Volume Index* metrics can be accessed at: https://github.com/xiaomingk/Global-renewable-potential. The code for the Supergrid model is available at: https://github.com/xiaomingk/Supergrid.

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X.K.: Methodology, Formal analysis, Investigation, Writing—original draft, Writing—review & editing. F.H.: Conceptualization, Methodology, Writing—original draft, Writing—review & editing, Supervision, Funding acquisition. L.R.: Conceptualization, Methodology, Writing—original draft, Writing—review & editing, Supervision, Funding acquisition. D.D.: Conceptualization, Methodology, Writing—original draft, Writing—review & editing.

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