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Solar and wind energy potential under land-resource constrained conditions in the Group of Twenty (G20)

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ABSTRACT

The Group of Twenty (G20) represents the world's largest economies, accounted for 86 % of global final electricity demand and 87 % of global energy-related CO_2 emissions in 2020. The success of the Paris Agreement will be heavily dependent on successful energy transitions in G20 countries. This is the first comparative study to assess the potential for solar and onshore wind energy generation across the G20 using a comprehensive and consistent approach. A GIS-based spatial analysis was conducted to identify geographical areas with potential for solar and onshore wind energy generation, and assessed the renewable electricity generation potential of individual G20 member states against the modelled electricity demands for 2050. The results confirmed that the G20's renewable energy potential is high enough to supply projected global electricity demand in 2050. A total of 33.6 million km^2 of land within the G20 was identified as solar energy potential areas, which could provide 923,322 TWh/year of electricity. The results also indicated that 31.1 million km^2 of land was suitable for onshore wind energy, with the potential to generate 466,925 TWh/year of electricity. These areas are sufficient to generate over 42 times (solar) or 21 times (onshore wind) global electricity demand in 2020, or 14 (solar) or seven times (onshore wind) the projected global electricity demand in 2050. The results also highlight significantly variance in opportunities and barriers by country. Despite the political challenges, further commitments by G20 leaders are expected to lead to faster energy transitions and greater international cooperation.

1. Introduction

The success of limiting global warming to 1.5 °C, will be dependent on the successful energy transition in the Group of Twenty (G20) countries. The G20 represents the world's largest economies, energy users, and producers of energy-related CO_2 emissions. In 2020, the final energy demand of the G20 was estimated to be 19,025 TWh/year, constituting 86 % of global demand [1]. In the same year, the G20 was responsible for 87 % of global energy-related CO_2 emissions (28,133 Mt CO_2) [1]. Based on both historic emissions (1750–2019) and modelled 1.5 °C pathway emissions (2020–2050), the G20 (1,570 Gt CO_2) is responsible for 75 % of total global carbon emissions (2,091 Gt CO_2) [2].

The G20 includes 19 countries (Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, the Republic of Korea [South Korea], Mexico, Russia, Saudi Arabia, South Africa, Türkiye, the United Kingdom and the United States of America [the United States]), and the European Union (EU). The African Union (AU) joined the G20 in September 2023, while this study covers only the original member countries of the G20. The original members (i.e. the 19 member countries plus the EU) cover over 80 million square kilometres (km^2) of land area and contained 62 % of the global population (4.8 billion people) in 2021 [3]. Together, they represent 85 % of the global GDP and over 75 % of international trade [4].

The leaders of the G20 countries have started to take actions in pursuit of a transition to renewable energy, sharing the common goal of meeting the objectives of the Paris Agreement. In the Bali Compact of 2022, G20 leaders agreed to make increased efforts to further a global energy transition and thereby achieve the global goal of net zero. Renewable energy adoption became a priority agenda item at the G20's New Delhi Summit in September 2023. The G20 leaders agreed at the end of the summit to pursue a tripling of renewable energy capacity globally by 2030, which the International Renewable Energy Agency (IRENA) recommended as a way of maintaining the possibility of limiting global warming to 1.5 °C [5,6]. All countries face similar challenges, including the need to ensure secure and affordable electricity supplies following the impact of the Russia-Ukraine War on the supply and cost of fossil fuels, and the need to meet energy demand while remaining in line with both international and national net zero targets.

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Abbreviations

G20 The Group of Twenty
OECM One Earth Climate Model

Units
TWh/year Terawatt hour(s) per year

However, there are significant differences between G20 countries in terms of their progress towards renewable energy transitions. While studies have found different results depending on their particular methodologies and considerations, EU countries (specifically northern European countries) generally rank highly in existing global energy transition indices and studies, including the Energy Transition Index [7] and the GeGaLo index [8]. Conversely, lower values are found for fossil fuel dependent and/or less energy secure countries [7–9]. Recent policy research and modelling work under the One Earth Climate Model (OECM) project calculated that the G20's renewable electricity share constituted 26 % of final electricity generation in 2020 on average. Progress varied among different countries; for example, Brazil had the highest renewable energy share (84.7 %) in 2020 due to its utilisation of large-scale hydropower, while Saudi Arabia had the lowest share of renewable energy (0.1 %) [1] (Table 1).

Efforts to increase renewable energy capacity require land, which is becoming an increasing valuable resource [8]. As a result, an increasing number of studies have been conducted to investigate and/or assess potential areas for large-scale renewable energy projects and the energy generation potentials of different geographical locations. Most of these studies have integrated spatial analysis or modelling using Geographic Information Systems (GIS). GIS is a powerful tool that enables users to collect, store, manage, calculate, analyse, evaluate, manipulate and map geospatial data, which are generally collected by field survey and/or generated from remote sensing imagery. A number of GIS-integrated spatial analyses have been conducted to assess the suitability of areas within the boundaries of the G20 for solar (see Table 2 in Section 2) and onshore wind energy generation (Table 3 in Section 2). The geographic scope of these studies varies significantly, ranging from the continental (e.g., Africa [10], the EU [11,12]) to the national and sub-national scales (e.g., state, province, or any area of interest). In a global scale study, Jung and Schindler developed an onshore wind farm potential index (WPI) map to quantify site suitability and compare the potential use, effectiveness and efficiency of wind power in different countries [13]. However, no spatial assessments of renewable energy potential have been conducted specifically for the G20 countries.

Table 1
Share of renewables in projected electricity generation under 1.5 °C pathway emission scenarios (2030, 2040, 2050) (Unit: %).

	2020	2030	2040	2050
Argentina	25.2	63.7	88.6	100.0
Australia	20.0	83.6	98.9	100.0
Brazil	84.7	91.8	97.7	100.0
Canada	70.0	87.8	99.9	100.0
China	27.6	69.8	93.3	99.3
EU27	34.4	75.9	95.3	99.4
France	20.0	78.2	99.8	100.0
Germany	39.1	78.9	96.6	100.0
Italy	37.2	84.5	95.8	100.0
India	16.5	73.1	88.1	99.1
Indonesia	18.3	56.0	86.5	99.9
Japan	17.8	49.8	85.7	100.0
Mexico	19.8	69.7	92.5	100.0
Republic of Korea	4.9	43.0	77.0	100.0
Russia	20.0	66.0	94.5	99.4
Saudi Arabia	0.1	66.4	90.8	100.0
South Africa	4.4	57.5	89.3	100.0
Türkiye	41.8	76.6	96.8	98.6
United Kingdom	48.1	67.5	95.5	99.4
United States	17.0	64.7	99.5	100.0
G20 total	**25.7**	**69.1**	**93.6**	**99.6**

(Source) Teske et al., 2023 [1].

This study aims to inform key policy makers, the industry leaders and the research communities in the G20 about renewable energy potentials, as well as to support the acceleration of the renewable energy transition discussion both globally and regionally. A number of global-level analyses have been conducted of the strengths and weaknesses of countries from the perspective of energy security, geopolitics, competition around renewable energy, and the energy transition [7,8,14]. The outcomes of the present study will contribute to existing knowledge, helping to refine current understandings and strategies relating to the energy transition and geopolitical dynamics. This paper has two main objectives.

- To identify solar and onshore wind energy potential across the G20 under land resource-constrained conditions by using GIS-based spatial analysis and mapping, and to calculate available land resources that are suitable for these uses.
- To assess whether the solar and onshore wind energy potential of G20 countries is sufficient to decarbonise the energy supply by 2050.

This study was conducted in accordance with the One Earth Climate Model (OECM) [2,15,16]. The OECM is an integrated energy assessment model to develop decarbonisation pathways for sectors, countries, and regions, and also at a global level. The OECM has been applied to around 50 countries and regions since 2017. In this research project, a literature review was conducted to understand the current status and progress of existing research on the relevant topic within the G20. A spatial analysis was then conducted to identify areas with potential for solar and onshore wind energy generation within the G20 countries, taking into account key land-resource constraint factors identified in the literature review, namely land use, slope/topography, protected areas, solar irradiation (DNI) and wind speed. This spatial analysis was combined with high-resolution mapping of areas with potential for solar or onshore wind energy generation using the Renewable Energy Potential under Space Constraint Conditions ([R]E Space) approach [17–19]. The installed capacity and the electricity that could potentially be generated from solar and onshore wind energy were estimated from the land areas obtained in the spatial analysis. Lastly, the outcomes were compared with our projection of final electricity demand in 2050, which was obtained from the results of the OECM [58]. The results of this study highlight countries with high levels of land-based renewable energy potential, and specifically those which have the greatest potential capacity to achieve 100 % renewable energy by 2050.

This study makes multiple contributions to the existing literature. The use of [R]E Space to identify and assess renewable energy potentials produces novel findings regarding the G20's ability to transition to renewable energy systems. The results provide a better picture of global, regional and national renewable energy potential by integrating spatial analysis and the energy assessment model. This is the first comparative study to inform solar energy and onshore wind energy potential based on a spatial analysis and mapping across the G20 countries using a comprehensive and consistent approach, and presents an initial comparison of the renewable energy potential of individual G20 member states against projected electricity demands for 2050 based on the OECM. The results flag opportunities and challenges for renewable energy development under the land-constrained conditions of each G20 country and the EU. As solar and onshore wind energy generation requires both land and favourable climate and geographic conditions, opportunities are not equal between all countries: this may result in dynamic changes and resource competition. To date, few studies have assessed the renewable energy potential of the G20 countries, and so the findings of this study will inform policy making and analysis of the energy transition and decarbonisation processes, as well as of the energy security and geopolitical dynamics of the G20 countries.

Table 2
Existing solar potential/suitability assessments.

Study area	Source	Summary of results	Method
Solar PV suitability or potential studies			
Australia (east coast: NEM)	[46]	**Capacity:** 24,100 GW (utility)	GIS
Australia (Far North Queensland)	[47]	**Area:** 70 % of studied region (57,705 km^2) **Capacity:** 5,956 GW	GIS multi-criteria
Brazil (Rio Grande do Sul state)	[48]	**Area:** 1,823 km^2 (about 30 % of the total area).	GIS MCDM
Brazil (Pernambuco state)	[49]	**Area:** 22 and 40 % of the study area has the very high and high potential.	GIS fuzzy AHP
Canada	[50]	**Potential:** 329 TWh/year (excluded areas for potential wind development)	GIS
Canada (Toronto)	[51]	**Potential:** 3,718 MWh/year from rooftop PV	GIS
China	[20]	**Area:** 300 million km^2 (31 % of national area) **Capacity:** 108.22 TW **Potential:** 150.73 PWh/year	GIS MCDM
	[21]	**Area:** 993,000 km^2 **Potential:** 131.942 PWh/year	GIS MCDM (AHP)
	[22]	**Area:** 1,020,000 km^2 (CSP) **Capacity:** 2.45–5.4 TW (CSP) **Potential:** 64.6–185 TWh/year	GIS
	[23]	**Capacity:** 3,250 GW **Potential:** 5,200 TWh/year	GIS based scenario analysis
	[24]	**Capacity:** 45.6 TW **Potential:** 66.5 PWh/year	GIS based modelling
	[25]	**Area:** large area suitable in the north western regions, several hot-spots for large-scale PV installations	GIS MCDM
EU28	[11]	**Capacity:** 10,000 GW **Potential:** 11,000 TWh	GIS modelling
	[12]	**Outcome:** A European suitability map for the solar energy (PV) systems deployment	GIS MCDM
India	[52]	**Area:** 606,472 km^2 **Capacity:** 16,846 GW	GIS MCDM
Indonesia (West Kalimantan Province)	[53]	**Area:** 46.6–108.58 km^2 **Capacity:** 2,034 - 4,785 MW	GIS MCDA (AHP)
Italy	[54]	**Area for Agrivoltaics** (land use that combines crops and PV systems): 10.7 million ha **Capacity potential:** 6435 GW	GIS/MCDM (AHP)
Japan	[55]	**Capacity:** 166 GW (competing area), 64 GW (non-competing area)	GIS
Japan (Fukushima prefecture)	[56]	**Potential:** 2,124 TWh/year	GIS constraints
Japan (Kansai region)	[57]	**Potential:** 4,564 GWh/year from Agrivoltaics	GIS
Mexico (Desert of Chihuahua)	[58]	**Area:** 4,983 km^2 (AHP) vs. 1,237 km^2 (RM)	GIS MCDM (AHP & rank based method (RM))
Russia (Krasnodar region)	[59]	**Area:**55,000 km^2 (72 % of the region) **Potential:** 24 GWh/year	GIS MCDM
Saudi Arabia	[35]	Site suitability map was generated as part of the assessment to select the suitable locations for renewable energy in Saudi Arabia.	GIS MCDM (AHP)
	[28]	**Area:** 376,623 km^2 (suitable area)	GIS MCDM (Fuzzy AHP)
	[29]	**Area:** 16 % (300,000 km^2) of the country is suitable for deploying utility-size PV power plants while the most suitable areas in the north and northwest of the Saudi Arabia.	GIS MCDM (AHP)
	[30]	**Area:** 15 % and 8.2 % of the study areas show high and moderate suitability **Potential:** 8,330,807 GWh/year (only 10 % was the highly suitable land)	GIS MCDM (AHP)
Saudi Arabia (Al-Qassim region)	[31]	**Area:** the most suitable' and 'suitable' areas represent about 17.53 % of the study area	GIS MCDM (AHP)
Saudi Arabia (Riyadh region)	[32]	**Area:** 16,748 km^2 and an 80 % suitability degree in the north and northwest of the region	GIS MCDM (AHP)
South Africa	[36]	<u>**Solar CSP**</u> **Area:** 104 billion m^2 **Capacity:** 11,000 TWh/year	GIS
South Africa (Africa)	[10]	<u>**Solar**</u> <u>**CSP**</u> 43 275 TWh/year <u>**Solar**</u> <u>**PV**</u> 42 243 TWh/year	GIS
	[37]	**Area:** very high investment potential sites located in the western part of South Africa	GIS MCDM (AHP)
Türkiye (Besni)	[39]	**Area:** 510 ha for 300 MW in the study area	GIS MCDM (AHP)
Türkiye (Antalya)	[40]	**Area:** 24 % of the study area were suitable for solar farms, while 731,094 ha (36.3 %) were less suitable.	GIS MCDM (AHP)
Türkiye (Kayseri province)	[41]	Verified and compared different MCDM methods	GIS MCDM (RM and AHP)
Türkiye (Erzurum province)	[42]	**Area:** 25,065 km^2	GIS MCDM (intuitionistic fuzzy)
Türkiye (East Mediterranean region)	[43]	**Area:** 8 % (3.42 km2) of the total study area	GIS modelling (MaxEnt)
Türkiye (Malatya Province)	[44]	**Area:** 34 suitable areas	GIS MCDM (AHP)
Türkiye (Istanbul)	[45]	**Outcome:** Istanbul province solar plants site selection availability map	GIS MCDM (AHP)
United Kingdom (South Central England)	[60]	**Area:** 18.6 % of South-central England (3714 km^2)	GIS MCDM (AHP)
United Kingdom	[61]	**Capacity:** 4041 GW	GIS MCDM (AHP)

(*continued on next page*)

Table 2 (*continued*)

Study area	Source	Summary of results	Method
United States	[62]	**Urban utility-scale PV**: **Capacity:** 1,200 GW **Potential:** 2,200 TWh. **Rural utility-scale PV:** **Capacity:** 153,000 GW **Potential:** 280,600 TWh **Rooftop PV:** **Capacity:** 664 GW **Potential:** 800 TWh	GIS
United States (New York State)	[63]	**Theoretical Area:** 46 % of (57,969 m^2) study area**. Theoretical solar potential:** 2,235 GW **Area with good & medium suitability**: 24,167 km^2 with a **solar potential** of: 931 GW	GIS MCDA

(Note) Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP).

2. Literature review: spatial assessments of solar and wind energy in the G20

This literature review was conducted prior to the performance of spatial analysis to better understand current progress in the assessment of renewable energy potential and suitable areas for renewable energy generation within the G20 countries, and also to review applicable methodologies, specifically by identifying key factors relating to land-resource constraints in the context of solar energy projects and onshore wind energy projects.

A keyword search was performed using the Scopus search engine, with combinations of keywords such as “GIS” and “wind energy” and “(country names)”, or “GIS” and “solar energy” and “(country name)”. This resulted in 526 articles on solar energy and 453 on wind energy. In the next step, duplicate articles, those outside the scope of the study (e.g. those dealing with offshore wind) and local site-specific land suitability studies or assessments were eliminated. The articles were screened and filtered for relevance, and grey literature (e.g. reports or policy documents) was added to the collection using a “snowball” technique.

This literature review confirmed that to date no spatial assessments specifically for the G20 that consider future opportunities for renewable energy development across these countries and the regions have been published. However, there have been a number of GIS-integrated spatial analysis and assessments conducted within the G20 boundaries regarding suitable areas for solar energy and onshore wind energy. Ultimately, 42 studies were selected for this review as assessments of the potential or suitability of land for solar power generation (Table 2), and 30 studies were selected as assessments of the potential or suitability of land for onshore wind power generation (Table 3). Significant differences were found between these studies in terms of their research aims, the GIS methods they used (e.g., various modelling, multi-criteria decision-making (MCDM), analytical hierarchy process (AHP), and ranking-based approaches), and the land-resource constraint factors and other locally-varying criteria considered in the assessments (e.g., policy).

2.1. Solar potential/suitability assessments

This review identified varied number of studies by country, which may reflect political aspirations and motivation to pursue the renewable energy transition on the part of both government and industry in these countries. Specifically, over the past few years numerous assessments have been published for China [20–27], Saudi Arabia [28–35], and South Africa [10,36–38] for both solar and onshore wind potentials, and for Türkiye [39–45] mostly regarding solar potential. Notably, these countries have the existing advantages of large areas of available land and abundant solar irradiation. This indicates that the governments of these countries are strongly motivated to pursue a rapid renewable energy transition and use large-scale investments to capitalise on the economic opportunities presented by increasing demand for energy. The installation of solar photovoltaic (PV) technology has additional advantages for developing countries due to its flexibility, cost competitiveness and higher electricity outputs, along with recent technological innovations [41].

Recent studies have identified huge areas with potential for electricity generation using solar PV in some countries. For example, China has land with the potential to generate 66.5–150.73 PWh (PWh) per year, especially in the northwest of the country [20,21,24], and South Africa has land with the potential to generate 11 PWh/year [36] to 42 PWh/year [10], particularly in the western part of the country. Over 300,000 km^2 of land has been identified as suitable for large-scale solar deployment in Saudi Arabia [28,29]; this land is located in the north and northwest of the country [35].

2.2. Onshore wind potential/suitability assessments

Estimates of onshore wind potential are generally more conservative than estimates for solar due to the greater geographical restrictions imposed on wind turbines in many countries. These include restrictions on certain land use types (e.g. buildings, infrastructure, water), proximity to certain areas (e.g., settlements, airports) [53,64–66], environmentally sensitive areas (e.g. forests, wetlands) and ecological considerations (e.g., bird migration channels) [33,67,68]. As in the case of solar energy potential, substantial opportunities for wind energy have been found in countries with strong aspirations to transition to renewable energy combined with large land availability. This includes China (15 PWh/year [23], installed capacity of 4.1 TW [27]) and South Africa (1.5–41 PWh/year) [10]. The United States has also accelerated its rate of wind power installation in recent years. Von Krauland et al. [66] identified significant potential for wind energy (2,539,000 km^2, or 32 TW) in the United States, especially in inland states such as Alaska, Texas, Montana, Nebraska and South Dakota [66].

The review also found that developed countries with land resource constraints are interested in further exploring potential for onshore wind energy. Germany and Japan are interested in onshore wind energy for their own reasons. Germany is a global leader in onshore wind deployment, with nearly 30,000 turbines, and the process of expanding onshore wind in the country is speeding up to meet EU emergency energy measures. Identification of the most suitable locations for wind turbines is becoming increasingly crucial to address a range of land use and environmental constraints, and to minimise potential impacts on local biodiversity [69]. An example of location identification methodology has been published by Tefarte et al. [65], who examined changes in onshore wind potential areas in Germany by testing different geographical criteria and assumed constraints, such as those relating to distance to settlements and the use of forest areas. Japan is similarly resource-constrained, and has been looking for replacements for its existing fossil fuel- and nuclear-based energy sources, especially since the Fukushima nuclear disaster in 2011 [56,70].

While these additional studies beyond those mentioned here examine solar energy potential (Table 2) and onshore energy wind potential (Table 3) in G20 member countries, there remains a need for a comprehensive and consistent discussion across the G20 that considers these countries’ increasing influence on global politics and the global economy in the coming decades.

Table 3
Existing onshore wind potential/suitability assessments.

Study area	Source	Summary of results	Method
Onshore wind suitability or potential studies			
Australia (East Coast: NEM)	[46]	**Capacity:** 879 GW	GIS
Australia (Far North Queensland)	[47]	**Area:** 71 % of studied region (58,483 km^2) **Capacity:** 421 GW	GIS MCDM
Canada	[50]	**Potential:** 1,380 TWh/year	GIS
China	[27]	**Capacity:** 4.1 TW (onshore) 0.5 TW (offshore)	GIS MCDM
	[24]	**Capacity:** 8.69 TW **Potential:** 21.4 PWh/year	GIS based modelling
	[23]	**Capacity:** 4,700 GW **Potential:** 15,000 TWh/year	GIS scenario analysis
	[26]	**Potential:** 2,560 TWh/year (no agricultural land)– 3,194 TWh/year (70 % agricultural land)	GIS based modelling
China (Wanfangdian)	[67]	**Area:** 30.2 % of studied region were suitable for installing the wind-power facilities	GIS interval (IAHP)
EU28	[11]	**Capacity:** 3,400 GW **Potential:** 8,400 TWh	GIS modelling
France (Southeast France)	[71]	**Area:** around 6.98 % of the research area, potential for 182.6–280.2 MW	GIS MCDM (AHP)
Germany	[65]	**Potential:** 171–785 TWh/year (depending on legal restrictions)	GIS modelling
Germany (Städteregion Aachen)	[64]	**Area:** 9.4 % of the study area is available for wind energy development (1.74 % of the region is high suitability)	GIS MCDM (AHP)
India	[52]	**Area:** 2,004,023 km^2 **Capacity:** 3,102 GW	GIS MCDM
	[72]	**Capacity:** 486.6 GW **Potential:** 1,057.9 TWh	GIS
Japan	[55]	**Capacity:** 25 GW (competing area)	GIS
Japan (Fukushima prefecture)	[70]	**Area:** 1,561 km^2	GIS MCDM (AHP)
Japan (Fukushima prefecture)	[56]	**Potential:** 2 TWh/year	GIS
South Korea	[73]	**Area:** around 20 % of total land area (wind class 2 and higher) **Theoretical potential:** 96 GW (wind class 2 and higher), 41 GW (wind class 3 and higher)	GIS
Russia (Krasnodar region)	[59]	**Area:** 12,000 km^2 (15.2 % of the region) **Potential:** 23 GWh/year	GIS MCDM
Saudi Arabia	[35]	Site suitability map was generated as part of the assessment to select the suitable locations for renewable energy in Saudi Arabia.	GIS MCDM (AHP)
	[33]	**Area:** 13,521.6 km^2 (suitable area)	GIS MCDM
	[34]	**Area:** 1.86 % of the total area classed under the most suitable area and 14.65 % classified under the next best area	GIS MCDM (AHP)
South Africa (Africa)	[10]	1,559–41,195 TWh/year	GIS
	[37]	**Area:** very high wind farm investment potential sites are located the southern and western coasts of South Africa	GIS MCDM (AHP)
South Africa	[38]	**Area:** 706,162 km^2 (grid restriction); 732,865km2 (no grid restriction) **Potential**: 6306.7 TWh/year (no grid restriction), 6040.7 TWh/year (grid restriction),	GIS
South Korea	[73]	**Capacity**:20.8–41.6 GW	GIS
Türkiye (East Mediterranean region)	[43]	**Area:** 3.39 % (1554 km^2) of the total study area	GIS modelling (MaxEnt)
United Kingdom (South Central England)	[60]	**Area:** 37.8 % of South-Central England (6,470 km^2)	GIS MCDM (AHP)
United States	[66]	**Area:** 2,539,000 km^2 **Capacity:** 32 TW	GIS
	[62]	**Capacity:** 11,000 GW **Potential:** 32,700 TWh	GIS
United States (Southeast)	[68]	**Area:** 99,310 km^2 **Capacity:** Up to 297 GW **Potential:** Up to 835 TWh	GIS

(Note) Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP).

3. Methodology: GIS-based spatial analysis of solar and onshore wind energy potential using [R] E space

To identify and map areas with potential for renewable energy (hereafter referred to as 'solar energy potential areas' and 'onshore wind energy potential areas'), we employed the Renewable Energy Potential under Space Constraint Conditions ([R]E Space) approach. [R]E Space was developed as an important component of the OECM and has been upgraded over the past years, and has been applied in a number of contexts including global regions [17], Tanzania [74], Nepal [75] and Australia [76].

The current version of the [R]E Space methodology [19] incorporates the Boolean raster overlay approach, focusing on multiple land-resource constraint factors that can affect decisions about the locations of renewable energy projects. Individual criteria were set for each land-resource constraint factor so that multiple spatial data inputs on different themes could be combined into a single output raster, thereby generating maps of solar or onshore wind energy potential. Mapping was performed using the ESRI ArcMap 10.6.1 software and publicly available, global spatial data. Both maps were developed using the same method but with different constraint factors and criteria. The areas with potential for solar and onshore wind power generation were calculated and visualised by country using GIS.

3.1. Land-resource constraint factors and criteria

The review of existing GIS based renewable energy potential assessments (solar potential studies: n = 42; onshore wind potential studies: n = 30) highlighted the following land-resource constraint factors. The most critical land-resource constraint factors used in the reviewed literature were (1) slope (n = 42), (2) land use or land cover (n = 38), and (3) protected areas (n = 35). Almost all assessments of solar potential required inputs of (5) solar irradiance (n = 25), and (6) windspeed data was essential for all studies of onshore wind energy potential (n = 23) (Table 4). The present assessment thus considered these land-resource constraint factors (Table 5).

Distance from urban areas/settlements (n = 35), distance from (major) roads (n = 24), and distance from electricity transmission lines (n = 23) were also incorporated in the existing studies as additional land-resource constraint factors. These three factors are equally as

Table 4
Key land-resource constraint factors for solar and wind energy deployment considered in existing studies.

Land-resource constraint factors	Solar energy	Onshore wind energy
Slope	Australia [46,47]; Brazil [48]; China [20–25,67]; EU28 [12]; India [52]; Indonesia [53]; Italy [54]; Japan [55,56]; Mexico [58]; Russia [59]; Saudi Arabia [28–32,35]; South Africa [10,36,37]; Turkey [39, 42–44]; UK [60,61]; The U.S [62,63].	Australia [47]; China [23,27]; France [54,71] Germany [64]; India [52, 72]; Japan [56,70]; Russia [59]; Saudi Arabia [33]; South Africa [10,37,38]; UK [60]; The U.S [62,68].
Land-use (e.g. water bodies, waterways, roads, railways, urban areas, protected areas, parks)	Australia [46,47]; Brazil [48]; Canada [50]; China [20–25]; EU28 [11,12] India [52]; Italy [54]; Japan [55,56]; Mexico [58]; Russia [59]; Saudi Arabia [28,35]; South Africa [10]; Turkey [41–43,45]; UK [61]: The U.S [62,63].	Australia [46,47]; Brazil [48]; Canada [50]; China [23,26,27,67]; EU28 [11]; Germany [64,65]; India [52,72]; Japan [55, 56,70]; Russia [59]; Saudi Arabia [35]; South Africa [10,38]; The U.S [62,66,68].
Protected area (including cultural heritage areas)	Australia [46,47]; Brazil [48]; Canada [50]; China [21,22,24,25]; EU28 [11,12]; India [52]; Indonesia [53]; Italy [54]; Japan [55,56]; Saudi Arabia [31]; South Africa [22,23]; Turkey [44]; UK [60,61]; The U.S [62,63].	Australia [47]; Canada [50]; China [26,27]; EU28 [11]; France [71]; Germany [64,65]; India [52,72]; Japan [55,56, 70]; South Africa [10, 38]; South Korea [73]; UK [60]; The U.S [62,66, 68].
Distance from urban areas/ settlements	Brazil [48]; China [10]; EU28 [12]; India [52]; Indonesia [53]; Russia [59]; Saudi Arabia [28–32]; South Africa [23–25]; Turkey [43,44]	Australia [47]; China [27]; EU28 [11]; Germany [64,65]; India [52,72]; Japan [56], [55, 56,70]; Russia [59]; Saudi Arabia [33]; South Africa [10,37]; UK [60]
Solar irradiation (e.g. GHI, DNI)	Australia [46,47] Brazil [48]; Canada [50,51]; China [20,22,25]; EU28 [11,12]; India [52]; Indonesia [53]; Italy [54]; Japan [55,56]; Mexico [58]; Russia [59]; Saudi Arabia [28–32]; South Africa [22,24]; Turkey [28–31]; UK [60]; The U.S [62].	–
Distance from (main) roads	Australia [46,47]; Brazil [48]; Canada [50]; EU28 [12]; France [71]; India [52]; Indonesia [53]; Mexico [58]; Russia [59]; Saudi Arabia [28–32,35]; South Africa [37]; Turkey [39,43,44]; UK [61]	Australia [46,47]; Canada [50]; China [67]; Germany [64]; India [52]; Japan [70]; Russia [59]; Saudi Arabia [35]; South Africa [37]; The U.S [66].
Wind speed	-	Australia [46,47]; Canada [50]; China [24, 26,67]; EU28 [11]; France [71]; Germany [64]; India [52,72]; Japan [55,56]; Mexico [58]; Russia [59]; Saudi Arabia [33]; South Africa [37,38]; Turkey [42,43, 45]; UK [60]; The U.S [66].
Distance from electricity transmission lines	Italy [54]; Russia [59]; Saudi Arabia [28–32, 35]; South Africa [23–25]; Turkey [26, 29–32]; UK [61]	Germany [64]; India [72]; Indonesia [53]; Japan [70]; Russia [59]; Saudi Arabia [33,35]; South Africa [10,37]
Elevation	Australia [46,47]; China [9]; Italy [54]; Saudi Arabia [32,35]; Turkey [31]	Australia [46,47]; China [23,26]; France [71]; India [52,72]; Japan [56]; Saudi Arabia [35]: South Africa [38]; The U.S [68].
Aspect/orientation	Italy [54]; Mexico [58]; Saudi Arabia [28–30,32, 35]; South Africa [37]; Turkey [39,41–44]; UK [60]; The U.S [63].	-
Temperature	Brazil [48]; India [52]; Indonesia [53]; Italy [54]; Saudi Arabia [29, 30,32,35]; Turkey [29]	India [52]; Saudi Arabia [35]
Distance from water resources	Australia [46,47]; China [21,22,25]; South Africa [36,38]; Turkey [28]	Australia [47]; Japan [56]
Distance from power plant, or substation	Brazil [48]; EU28 [12]; Turkey [26,32]; The U.S [63].	China [14]; France [71]
Proximity to Forest/ protected area	Australia [46,47]; Turkey [45]	Australia [46,47]; Japan [70]; Russia [59]; Saudi Arabia [20]
Soil potential for agriculture/agricultural land classification	Brazil [48]; Italy [54]; Japan [56]; UK [60]; The U.S [63].	Japan [56]; UK [60,61]

Table 5
[R]E Space land-resource constraint factors and criteria.

Data	Assumptions & Criteria	Source
National boundaries	–	Large Scale International Boundaries - 2017
Land cover/land use	**Land-cover classes**, which are suitable for solar energy and wind energy production were identified from different land-cover maps respectively.	**All countries (except countries below):** Copernicus Global Land Cover - 2019 **Australia:** Catchment scale land use of Australia – 2020 **Europe (EU27, UK, Türkiye):** Copernicus Corine Land Cover – 2018 **The United States:** National Land Cover Database – 2019
Digital Elevation Model (DEM)	For both wind and solar analyses, any land with a **slope** >30 % was eliminated from all scenarios.	Multi-Error-Removed Improved-Terrain DEM (MERIT DEM)
Protected areas	**All protected areas** designated under national parks, wildlife reserves, hunting reserves, conservation area and buffer zones were eliminated from all scenarios.	The World Database on Protected Areas (WDPA)
Solar irradiance (Direct Normal Irradiation: DNI)	The average yearly **DNI** values $\geq$ 1,000 kWh/m^2 per year.	Global Solar Atlas
Wind speed at 100m	**Wind speed** $\geq$5 m/s were considered at a height of 100 m	Global Wind Atlas

important as the previous five factors, especially when selecting economically viable locations for renewable energy projects. However, this study did not include these factors in order to exclude areas that are far from existing populated areas or infrastructures due to inherit uncertainty about the growth of populations and development of infrastructure in all G20 countries by 2050. Furthermore, existing grid-connected electricity distribution systems and infrastructure development may change in the coming decades as a result of the increasing role of renewable energy and stand-alone energy systems (e.g., microgrids) in some countries.

The five criteria used for land evaluation in the current assessment are described below.

3.1.1. Land cover

Some land cover types are not suitable for renewable energy deployments. The criteria are different for solar and onshore wind projects; therefore, two separate spatial layers were prepared to identify areas with potential for solar and onshore wind energy. Copernicus Global Land Cover (100 m) from 2019 [77] was used as land cover data for most G20 areas. For Australia [78], Europe (EU27, UK and Türkiye) [79] and the United States [80], the latest national or continental scale data with detailed land-cover classes were publicly available, and were therefore used for this analysis. In the global land cover data, open/low density forest cover, shrubland, grassland, spare vegetation area, agricultural land and urban/built up areas were considered when determining areas' potential for solar energy. Unlike assessments mainly focusing on large-scale utility solar projects, our analysis incorporated the increasing role of rooftop solar energy on residential, commercial and industrial buildings in urban areas. Therefore, urban/built up areas were considered suitable for solar in our analysis, while certain types of urban land classes (e.g., roads, railways, airports) were excluded from suitable areas in Australia and Europe, where the land cover classes detailed enough to allow this were available. Suitable land-cover classes for onshore wind turbines were more restricted than for solar; for example, urban/built-up areas were completely excluded from this analysis. Additionally, permanent water bodies, closed forests, wetlands and land permanently covered by snow and ice were excluded for both solar and wind energy. For Australia and Europe, land-cover classes indicating high conservation value (e.g., nature reserves, salt marshes, peatbogs) and intensive agricultural and forestry land cover (e.g., plantations, horticulture) were also eliminated from both solar and wind potential areas.

3.1.2. Protected areas

A protected area is a clearly defined geographical space that is recognised, dedicated and managed through legal or other effective measures to achieve the long-term conservation of nature, with its associated ecosystem services and cultural value [81]. Therefore, all protected areas within the G20 must be eliminated from consideration for renewable energy deployment. In this study, spatial data was obtained from the World Database on Protected Areas (WDPA), which is the most comprehensive global database of marine and terrestrial protected areas [82]. The WDPA is a joint project between the UN Environmental Programme (UNEP) and the International Union for Conservation of Nature (IUCN). All renewable energy projects were assumed to be equally banned in the protected areas [82].

3.1.3. Slope

The slope of the land in an area affects its suitability for the installation and maintenance of renewable energy facilities. Slope was calculated using Digital Elevation Model (DEM) data on G20 countries. The upper limit of the slope was set to 30 % (=16.9°): areas with slopes greater than 30 % were regarded as unsuitable for both solar and onshore wind projects. The Multi-Error-Removed Improved-Terrain DEM (MERIT DEM), which covers all areas of the G20 member countries, was used for this project [83].

3.1.4. Solar irradiance

There are multiple indicators for solar irradiance. Global Horizontal Irradiance (GHI), for example, is the total solar irradiation on a horizontal surface, which is the sum of Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI) and ground-reflected radiation. In this study, DNI was used to determine locations for potential solar energy projects. The availability of DNI is one of the most basic and vital factors in applications such as concentrated solar power (CSP) [22] and concentration photovoltaic (CPV) systems [84]. Unlike solar photovoltaic (PV) systems, these technologies can only convert DNI to electricity. In this study, areas with an average yearly DNI of less than 1,000 kWh/m^2 were considered unsuitable for solar energy systems and excluded. Spatial DNI data were obtained from the Global Solar Atlas for all G20 countries and regions [85,86].

3.1.5. Wind speed

For wind energy projects, mean wind speed is the most basic and vital factor in the selection of appropriate location. In consideration of the average hub height of wind turbines, data on wind speed at a height of 100m was input in this analysis. Areas with a mean wind speed of less than 5 m/s were considered unsuitable for onshore wind projects. Spatial data on wind speed were obtained from the Global Wind Atlas for all G20 countries and regions [86].

3.2. Mapping procedure

All spatial data were converted into Boolean data (where a value of 0 indicates 'not suitable' and a value of 1 indicates 'suitable' for solar or wind energy projects) and overlain to exclude the land-resource constraint areas for both the solar and onshore wind potential maps (Fig. 1). The following raster calculation formula was applied in GIS to derive solar energy potential areas:

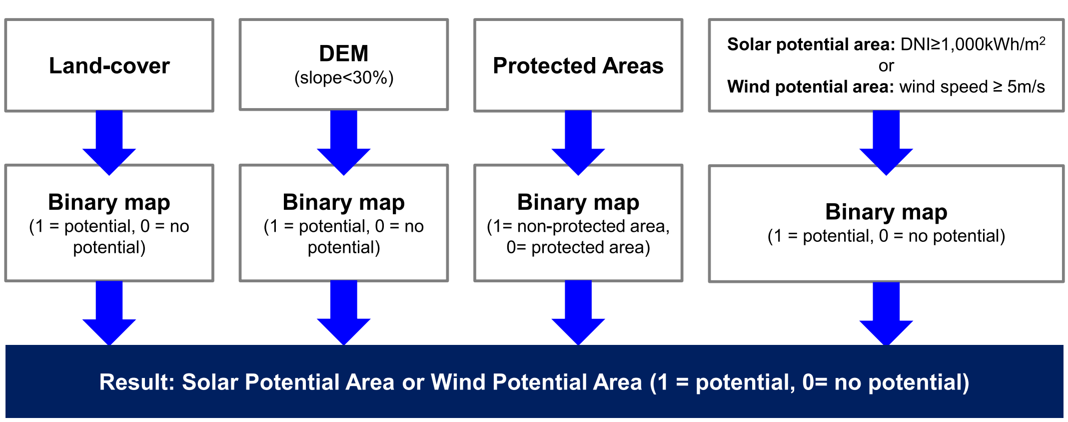

Fig. 1. GIS-based mapping procedure.

Solar Energy Potential Area (0,1) = Protected areas (0,1) × Slope (0,1) × Land-cover (Solar) (0,1) × DNI (0,1).

To derive onshore wind energy potential areas, the following raster calculation formula was applied in GIS:

Wind Energy Potential Area (0,1) = Protected areas (0,1) × Slope (0,1) × Land-cover (Wind) (0,1) × Wind speed (0,1).

This resulted in the development of two maps at the national scale for each G20 member country and the EU (which includes France, Germany and Italy, also listed a individual member countries).

4. Results

4.1. Solar energy potential area and onshore wind energy potential area in the G20

The result of spatial analysis identified that a total of 33.6 million square kilometres (km^2) of the analysed land within the G20 has potential for solar energy production. This land area could potentially provide 839 TW in installed capacity and generate 923,322 TWh/year of solar electricity. Additionally, 31.1 million km^2 of land was identified as having potential for onshore wind development, which could accommodate 156 TW in installed capacity and generate 466,925 TWh/year of wind electricity.

When comparing the results with both global and G20's final electricity demands, which was 22,112 TWh/year in 2020 while the projected electricity demand in 2050 according to the OECM's 1.5 °C pathway would increase to 64,988 TWh/year [15]. The electricity generation from solar energy potential areas in the G20 were calculated to be able to supply 42 times the global electricity demand in 2020 and 14 times the projected global electricity demand for 2050. Similarly, these areas have the potential to supply 49 times the G20's electricity demand in 2020 and 19 times the G20's projected electricity demand in 2050.

Conducting the same comparisons for onshore wind potential, it was found that onshore wind energy potential areas in the G20 could supply 21 times the global electricity demand in 2020, and seven times the projected global demand for 2050. The results indicate that these areas could potentially supply 25 times the G20's electricity demand in 2020 and ten times the G20's projected electricity demand for 2050.

Finally, it was concluded that using 5.3 % of the G20's total solar energy potential area (Table 6) or 10.5 % of G20's total onshore wind energy potential area (Table 7) could supply the projected final energy demand of the G20 in 2050.

4.2. Solar energy potential by country

Results of spatial analysis of solar energy potential areas are summarised here by country (Table 6). To closely assess the data, the calculated solar electricity generation potential was compared with the projected final electricity demand in 2050 for G20 countries. Of all G20 members, Australia has by far the greatest solar potential: it could be able to supply over 256 times its projected national final electricity demand in 2050. This is largely due to its abundant solar and land resources, combined with relatively low domestic population and energy demand. Australia is followed by Argentina (144 times the projected national final electricity demand in 2050), Brazil (75 times), Saudi Arabia (59 times), South Africa (59 times), Canada (51 times), Russia (48 times), Mexico (46 times), the United States (16 times), Türkiye (12 times), China (nine times) and India (nine times). The ratio between electricity generation potential from solar energy potential areas and the final electricity demand exceeds a value of 1 in all countries except South Korea and the United Kingdom. The spatial analysis identified that the largest solar energy potential area (5.1 million km^2) is found in China, where the greatest electricity demand (15,000 TWh/year) of the G20 members is projected for 2050—more than double the projected demand of India. This indicates that China will have to utilise additional renewable energy sources to satisfy its high energy demand. The analysis also identified large areas with solar energy potential in the United States (4.8 million km^2) and India (2.4 million km^2). However, extensive growth in electricity demand is also projected for both these countries: the United States' projected electricity demand in 2050 is the second highest (8,530 TWh/year) among the G20 countries, and India's is the third highest (7,451 TWh/year).

The percentage of each country's solar potential area required to supply its final electricity demand in 2050 was also calculated. In Australia, the use of only 0.4 % of the solar potential area would be sufficient to supply the country's projected electricity demand in 2050. Similarly, this analysis showed that the use of only a small percentage of several countries' total solar potential area could satisfy their entire

Table 6
Summary of solar energy potential by country.

	Solar Potential Area (km^2)	% of country area	Installed potential (GW)	Solar electricity generation potential (TWh/year)	Final electricity demand 2050 (TWh/year)	Compared to projected final electricity demand 2050	% of Solar Potential Area required to supply final electricity demand 2050
G20 (total)	33,575,355	42	839,384	923,322	48,859	19	5.3
China	5,151,340	55	128,784	141,662	15,000	9	10.6
Australia	5,140,920	67	128,523	141,375	552	256	0.4
United States	4,810,580	51	120,265	132,291	8,530	16	6.4
Brazil	3,494,390	41	87,360	96,096	1,279	75	1.3
Russia	2,667,510	16	66,688	73,357	1,544	48	2.1
India	2,389,050	76	59,726	65,699	7,451	9	11.3
Canada	2,095,810	21	52,395	57,635	1,137	51	2.0
Argentina	1,797,550	65	44,939	49,433	344	144	0.7
Saudi Arabia	1,682,780	87	42,070	46,276	781	59	1.7
EU27	1,376,011	33	34,400	37,840	5,247	7	13.9
Mexico	1,160,220	59	29,006	31,906	697	46	2.2
South Africa	959,713	79	23,993	26,392	446	59	1.7
Türkiye	527,680	68	13,192	14,511	1,223	12	8.4
France[a]	265,645	48	6,641	7,305	848	9	11.6
Indonesia	227,007	12	5,675	6,243	1,425	4	22.8
Italy[a]	158,780	53	3,970	4,366	597	7	13.7
Japan	60,837	16	1,521	1,673	1,647	1	98.5
Germany[a]	57,852	16	1,446	1,591	1,136	1	71.4
South Korea	32,823	33	821	903	975	0.9	–
UK	1,134	0.5	28	31	581	0.1	–

(Note) It is assumed that the installed capacity per square kilometre (km^2) is 25 MW on average, and solar electricity generation potential (TWh/year) is calculated with an assumption of 1,100 h per year (h/year).

[a] Countries in EU27.

Table 7
Summary of onshore wind energy potential by country.

	Onshore wind Potential Area (km^2)	% of country area	Installed potential (GW)	Wind electricity generation potential (TWh/a)	Final electricity demand 2050 (TWh/a)	Compared to projected final electricity demand 2050	% of Wind Potential Area required to supply final electricity demand 2050
G20 (total)	31,128,332	39	155,642	466,925	48,859	10	10.5
Australia	4,850,800	63	24,254	72,762	552	132	0.8
China	4,793,340	51	23,967	71,900	15,000	5	20.9
Russia	4,643,550	27	23,218	69,653	1,544	45	2.2
United States	4,351,580	46	21,758	65,274	8,530	8	13.1
Canada	3,350,930	34	16,755	50,264	1,137	44	2.3
Argentina	1,932,520	70	9,663	28,988	344	84	1.2
Brazil	1,682,680	20	8,413	25,240	1,279	20	5.1
Saudi Arabia	1,619,240	84	8,096	24,289	781	31	3.2
EU27	1,326,087	32	6,630	19,891	5,247	4	26.4
India	886,384	28	4,432	13,296	7,451	2	56.0
South Africa	793,516	65	3,968	11,903	446	27	3.7
Mexico	491,606	25	2,458	7,374	697	11	9.4
France[a]	249,782	46	1,249	3,747	848	4	22.6
Türkiye	229,396	29	1,147	3,441	1,223	3	35.5
Germany[a]	139,767	39	699	2,097	1,136	2	54.2
UK	119,854	49	599	1,798	581	3	32.3
Italy[a]	49,812	17	249	747	597	1	79.9
Indonesia	24,890	1	124	373	1,425	0.3	–
Japan	21,340	6	107	320	1,647	0.2	–
South Korea	10,620	11	53	159	975	0.2	–

(Note) It is assumed that the installed capacity per square kilometre (km^2) is 5 MW on average, and solar electricity generation potential (TWh/year) is calculated with an assumption of 3,000 h a year (h/year).
[a] Countries in EU27.

projected national 2050 energy demand: Argentina (0.7 %), Brazil (1.3 %), Saudi Arabia (1.7 %), South Africa (1.7 %), Canada (2.0 %), Russia (2.1 %), and Mexico (2.2 %). Therefore, the results confirm the rationale for accelerating solar energy development, specifically by making use of the solar energy potential areas of these countries. In reality there is competition for land, and supplying the entire projected national 2050 energy demand would thus be more challenging in the United States (6.4 %), Türkiye (8.4 %), China (10.6 %) and India (11.3 %). However, the findings identify large areas with potential for solar energy generation in these countries, thus solar energy can still play a significant role in their respective renewable energy scenarios.

4.3. Onshore wind energy potential by country

Results of onshore wind energy potential are summarised here by country (Table 7). As with potential for solar electricity generation, onshore wind electricity generation potential was compared with G20 countries' projected final electricity demands in 2050. Australia has more than 4.8 million km^2 of land identified as onshore wind energy potential area, and is in by far the most advantageous position with regard to onshore wind potential, with the potential to produce over 132 times its projected national energy demand in 2050. Argentina has the next highest-ranking onshore wind potential (84 times the projected national final electricity demand in 2050), followed by Russia (45 times), Canada (44 times), Saudi Arabia (31 times), South Africa (27 times), Brazil (20 times), Mexico (11 times), and the United States (eight times). The analysis also indicates that using only 0.8 % of the onshore wind potential area in Australia could supply the country's entire projected electricity demand in 2050. Similarly, using a relatively small percentage of the wind potential areas could satisfy the projected 2050 national electricity demand in Argentina (1.2 %), Canada (2.3 %), Russia (2.2 %), Saudi Arabia (3.2 %), South Africa (3.7 %), Brazil (5.1 %), and Mexico (9.4 %).

China ranks second in onshore wind energy potential area, behind Australia (4.8 million km^2). However, the country ranks tenth when comparing energy potential with projected final electricity demand in 2050 (five times), still representing significant potential. Apart from Indonesia, Japan and South Korea, the ratio between wind electricity generation potential and final demand exceeds a value of 1 in 17 countries and the EU, suggesting that onshore wind also has high potential to grow under energy scenarios which aim at decarbonising energy supply.

5. Discussion

In the 2023 G20 Summit declaration, global leaders endorsed and encouraged the effort to triple global renewable energy capacity [87], and this target was confirmed at the 2023 UN Climate Change Conference in December 2023. This commitment is expected to drive further cooperation initiatives to develop and demonstrate renewable energy technologies and solutions across G20 member countries. This study provides a timely insight into the extent of solar and onshore wind potential across G20 nations, both in terms of location and potential electricity generation. Our results confirm that there are areas of land with potential for renewable energy generation within the boundaries of the G20 countries that are large enough to supply global electricity demand—in total, 33.6 million km^2 with a solar electricity generation potential of 923,322 TWh/year, as well as 31.1 million km^2 with a wind electricity generation potential of 466,925 TWh/year. The following opportunities and challenges were derived from the findings of this study.

5.1. Opportunities and barriers in G20 countries identified as having high renewable energy potential

Our country level analysis identified that the electricity that could be generated from solar energy potential areas would exceed over ten times the projected national electricity demand in 2050 in Australia, Argentina, Brazil, Saudi Arabia, South Africa, Canada, Russia, and Mexico. The same analysis for onshore wind additionally highlighted high potentials in Australia, Canada, Argentina, Russia, Saudi Arabia, South Africa, Brazil and Mexico, with the onshore wind electricity generation potential of each of these countries exceeding their projected national electricity demands in 2050 by ten times. Unsurprisingly, these countries have a strong advantage due to their larger land availability and favourable climate and geographic conditions as compared to land-constrained countries such as many EU countries, the United Kingdom, South Korea and Japan.

The last G20 Summit's outcome formed the foundation for 2023 UN Climate Change Conference (COP29) [88] and further international climate action, but criticism was made of the lack of agreement on fossil fuel reduction actions. It is important to note that countries that are currently significant exporters of non-renewable resources have some of the highest renewable energy potential. Russia (coal, natural gas, and timber), the United States (coal, timber, natural gas), Saudi Arabia (oil), Canada (oil, uranium, timber, natural gas), China (coal, timber), and Australia (coal, timber, uranium) are all ranked among the top ten countries with the most 'valuable' natural resource reserves, according to total estimated values in 2021 [89]. Mexico (oil, natural gas, timber), India (coal, natural gas) and South Africa (uranium) are also rich in a variety of natural resources. For example, the GeGaLo index indicates geopolitical gains and losses after energy transition, and G20 countries with high renewable energy potential were identified as potential "losers" due to high fossil fuel dependency [8]. Australia and Canada rank highly in terms of the renewable energy potential and fossil fuel reserve indicators considered for the index, but neither country is ranked among the top 100 winners from the renewable energy transition [8]. China, India, Russia, Saudi Arabia and the United States were also identified as "losers" from the energy transition (i.e. were ranked outside the top 100) in the analysis [8]. However, the findings from this spatial analysis indicate that many of G20 countries have the potential to catalyse a global trend towards energy transition and decarbonisation. Therefore, further commitments by G20 leaders are expected to encourage international scaling down of fossil fuel use, a process in which developing economies, and specifically those countries with high renewable energy potential, should also be emboldened not to miss opportunities and to take necessary actions.

5.2. Wider benefits to broader society

The advantages of solar and onshore wind energy are often discussed only in terms of the benefits of decarbonisation. In reality, these energy sources can offer many more advantages to broader society through community projects [90]. These could include the strengthening of energy security, equity and resilience, and local socio-economic benefits for remote and rural communities [91]. This analysis highlights Australia as having the largest comparative potential for solar energy and onshore wind energy in terms of its projected 2050 national electricity demand. Australia has the lowest national population density (three people per km^2) among the G20 countries. The great majority of the population is concentrated on the eastern seaboard, and the national electricity grid, the National Electricity Market (NEM) which provides 80 % of national electricity consumption, connects these populated areas uses 40,000 km of transmission lines and cables to connect these populated areas [92]. However, around 500,000 people (2 % of the population) live in inland remote areas with no connection to the electricity grid. Energy infrastructure development, extension and maintenance has been always a challenge in remote areas of Australia; however, stand-alone energy systems powered by solar and wind are expected to play a crucial role in such 'off-grid' communities [93,94]. In remote communities, electricity supply often depends on expensive and unreliable diesel generators, which are also highly vulnerable to supply and logistic disturbances caused by extreme natural events. Provision of energy security and reliability for all communities is imperative, and emerging energy systems powered by solar and wind are believed to have the potential not only to bring decarbonisation but also energy independence and equity, as well as socio-economic opportunities for communities. These economic opportunities range from job creation to the development of new businesses and income streams. The benefits of these forms of emerging energy systems integrating renewable energy sources are internationally recognised, and have been discussed in the context of remote, rural and/or Indigenous communities. Feasibility studies and case studies have also been conducted in both developed and developing countries, such as Argentina [95], Brazil [96], Canada [97–99], Russia [100,101], Saudi Arabia [102], India [103], and China [104,105]. In the G20 New Delhi declaration, G20 leaders also addressed the importance of fighting poverty and inequality. From this perspective, renewable energy should be further promoted by removing current political, financial and social barriers to the deployment of renewable energy in regional and remote communities, and by ensuring stable and effective national and regional policy environments.

5.3. Limitations and future work

This study generated solar potential and onshore wind potential maps by overlaying publicly available spatial data with five key land-resource constraint factors (Figs. 2 and 3). This enabled the identification of indicative locations with potential for solar and onshore wind energy generation within G20 member regions, and allowed us comparison of this potential among member countries, as well as against future global and national electricity demand. The spatial maps were generated primarily using a global-scale dataset and a consistent methodology across the G20 countries to enable comparisons between countries presenting diverse climate, political, economic and environmental characteristics. Land-resource constraint factors for the mapping process were derived from a review of previous studies; many of the reviewed studies were conducted with the aim of finding specific project sites within their study areas, and used local-specific constraint factors and specific criteria such as climate conditions, elevations, ecological restrictions, and agricultural productivity. However, they faced limitations in this regard, as they were not generated for the purpose of locally-specific site analysis. The spatial maps generated in this study serve as foundational work for such further analysis. To meet specific local needs, it is important to note that a finer scale analysis considering additional economic, social and environmental constraint factors that carefully align with local policy regime for each location or site. This finer scale spatial analysis can be combined with Analytic Hierarchy Process (AHP), a multi-criterion decision-making tool that is more suitable for identification of the sites with the most potential for renewable energy generation. The literature review indicated that AHP is the most frequently applied method in this context, combined with GIS for land suitability studies at national, regional and local scales (Tables 2 and 3).

In addition, this study only identified theoretical and geographical potential for renewable energy generation. It is not realistic to assume that the entirety of the areas with potential for renewable energy generation will be covered with solar panels and onshore wind projects. However, this study's findings have confirmed that, in some G20 countries, the use of a small portion of the identified areas with potential for renewable energy projects would be sufficient to supply energy demand in 2050 globally, and these opportunities should be better utilised. More importantly, the authors fully acknowledge that there is growing competition for land in many parts of the world, and that this may have possible impacts on land use change. In the maps, solar energy potential areas include existing built-up areas, to allow for increased rooftop solar PV installations, while some land already in incompatible use (i.e., without available roof-tops) will need to be excluded in further analyses. Similarly, the areas identified as renewable energy potential in this study include agricultural land and parts of forested areas. In future analyses using fine resolution data, the quality of agricultural land in terms of productivity might be considered to reflect better integration of renewable energy systems into effective food production (e.g. agri-voltaics). Areas proximate to high conservation priority areas will also need to be excluded from future analyses, with consideration given to the habitats of local flora and fauna and areas with significant ecological and cultural values to support optimal land use decisions. These additional spatial layers may be developed by integrating local information and knowledge into future work.

Lastly, this study only focuses on land-based renewable energy technologies, as offshore wind energy was beyond its scope. Therefore,

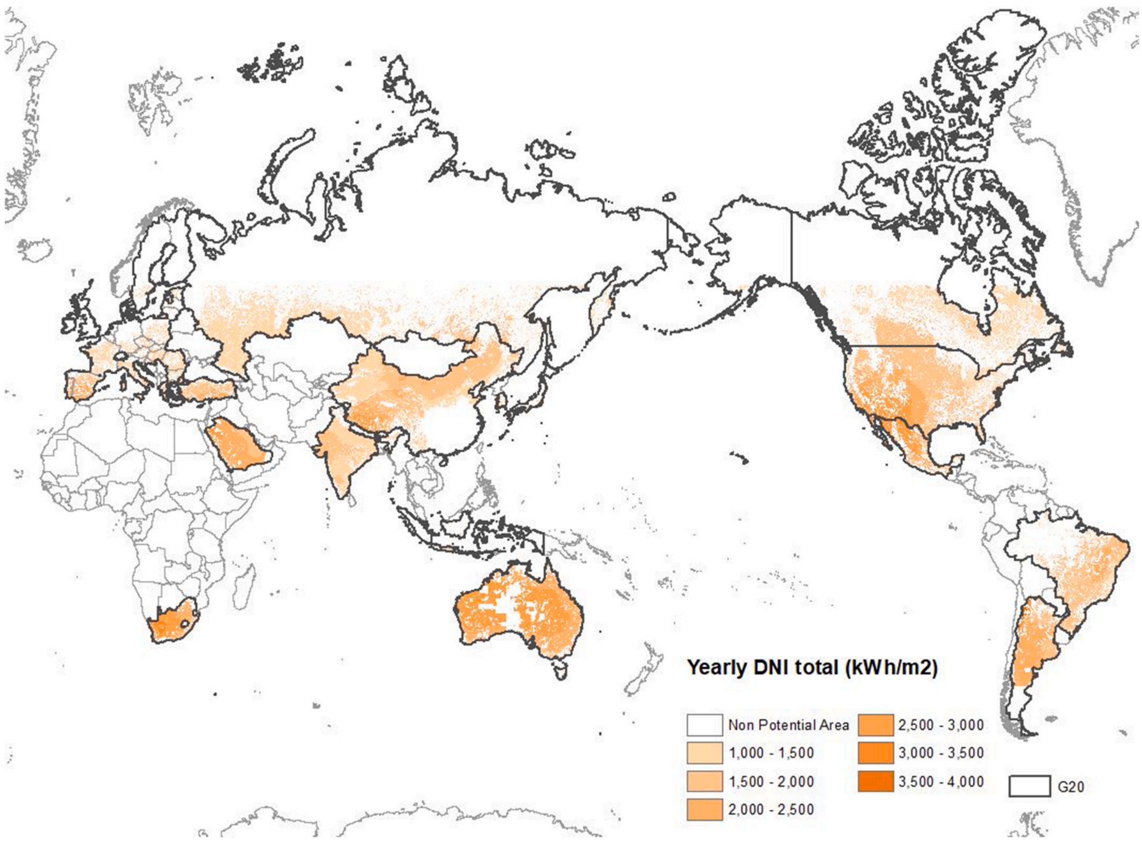

Fig. 2. Solar energy potential areas in the G20 – yearly DNI total (khW/m^2).

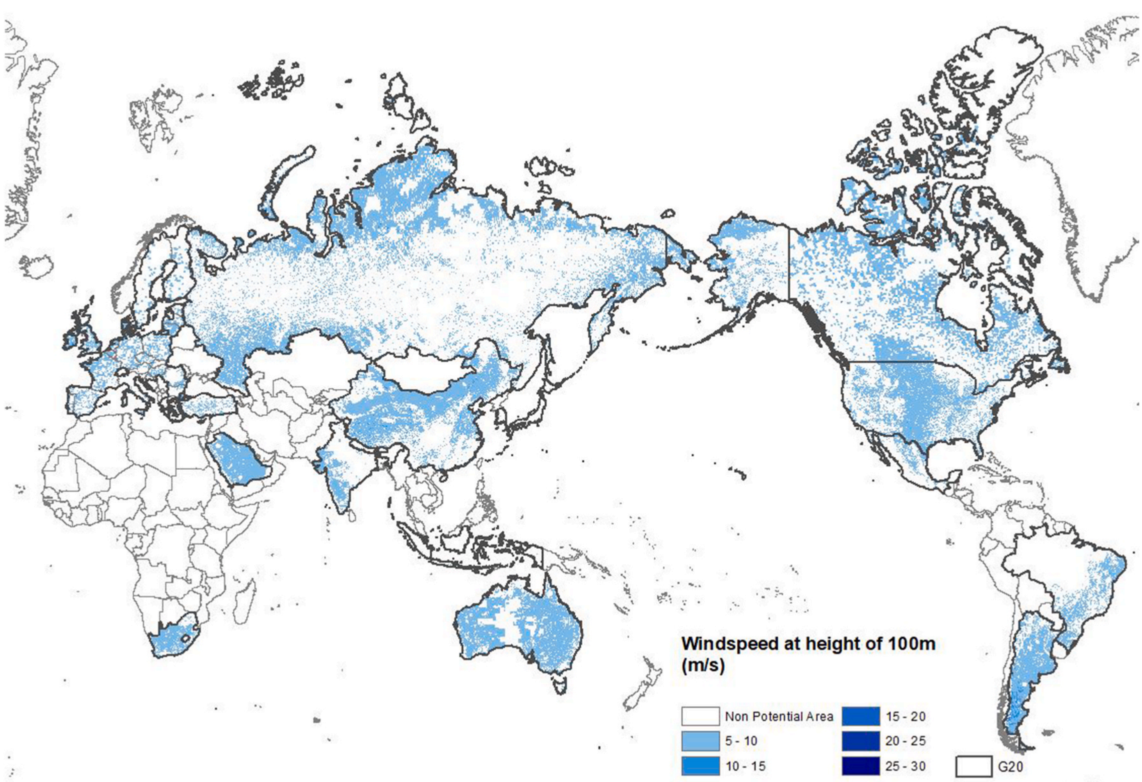

Fig. 3. Onshore wind energy potential area in the G20 – windspeed at a height of 100 m (m/s).

the results depict strong advantages for countries with large land availability. In reality, countries with long coastal lines could have greater potential for ocean-based renewable energy, such as offshore wind and tidal power, even though such countries may be affected by land-resource constraints (e.g., Japan). Taking this additional potential into account, it is likely that less land space will be needed to satisfy future electricity demand, thus minimising the impact of land use change. From this perspective, it is important for future work to consider ocean-based renewable energy technologies, particularly offshore wind energy.

6. Conclusion

The Group of Twenty (G20) represents the world's largest economies, accounting for 86 % of global final electricity demand and 87 % of global energy-related CO_2 emissions in 2020. Limiting global warming to 1.5 °C will be heavily dependent on the successful transition to renewable energy sources in the G20 countries. As there will be additional pressure on land resources as the energy transition continues to scale, an increasing number of studies have been conducted to investigate and/or assess areas with potential for large-scale renewable energy projects and the energy generation potential of different geographical locations. However, to date no spatial assessments specifically for the G20 that consider future opportunities for renewable energy development across these countries and the regions have been published. This is the first comparative analysis of solar and onshore wind energy potential across the G20 countries. This study also presented an initial assessment of the renewable energy potential of individual G20 member states against the projected electricity demands for 2050 as modelled using the OECM. The findings of this study will help to further develop current understanding of the energy transition and geopolitical dynamics, and the strategies for addressing current issues. A GIS-based spatial analysis was conducted to calculate geographical potential areas for solar and onshore wind energy generation across the G20 countries.

The results of this analysis have confirmed that the potential for renewable energy generation within the G20 countries is high enough to supply projected global electricity demand in 2050. In the analysis, a total of 33.6 million km^2 of land was identified as solar energy potential areas within the G20, which could provide 923,322 TWh/year of electricity generation. The results also indicated that 31.1 million km^2 of land within the G20 countries is suitable for onshore wind energy generation, which has the potential to generate 466,925 TWh/year of electricity. These areas in the G20 are sufficient to generate over 42 times (solar) or 21 times (onshore wind) the global electricity demand in 2020, or 14 times (solar) or seven times (onshore wind) the projected global electricity demand in 2050. The findings also highlighted significant variance in renewable energy potential by country, and confirmed that the countries with strong advantages in solar or onshore wind energy potential (e.g. Australia, Canada) are often current exporters of non-renewable resource or/and fossil fuels. This could hinder the rapid energy transition of the G20, for example by contributing to the ongoing lack of agreement on actions to reduce fossil fuel use. The advantages of solar and onshore wind energy generation are not limited to decarbonisation. They can also offer many more advantages, such as strengthening of energy security, equity and resilience, and the socio-economic development of remote and rural communities in many countries. G20 leaders are therefore expected not to miss this opportunity, and to make further commitments to taking the actions necessary to transition to renewable energy.

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CRediT authorship contribution statement

Saori Miyake: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft. **Sven Teske:** Supervision, Funding acquisition, Conceptualization, Methodology, Writing – review & editing. **Jonathan Rispler:** Investigation, Writing – review & editing. **Maartje Feenstra:** Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Spatial data can be viewed from the online mapping platform here:

Solar potential map (online platform): http://mgo.ms/s/vqlj1

Onshore wind potential map (online platform): http://mgo.ms/s/ef57o

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