Chapter 7
Renewable Energy Resource Assessment

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Abstract Literature overview of published global and regional renewable energy potential estimates. This section provides definitions for different types of RE potentials and introduces a new category, the economic renewable energy potential in space constrained environments. The potential for utility scale solar and onshore wind in square kilometre and maximum possible installed capacity (in GW) are provided for 75 different regions. The results set the upper limits for the deployment of solar- and wind technologies for the development of the 2.0 °C and 1.5 °C energy pathways.

There is a wide range of estimates of global and regional renewable energy potentials in the literature, and all conclude that the total global technical renewable energy potential is substantially higher than the current global energy demand (IPCC/SRREN 2011). Furthermore, the IPCC has concluded that the *global technical renewable energy potential will not limit continued renewable energy growth* (IPCC/SRREN 2011). However, the technical potential is also much higher than the sustainable potential, which is limited by factors such as land availability and other resource constraints.

This chapter provides an overview of various estimates of global renewable energy (RE) potential. It also provides definitions of different types of RE potential and presents mapping results for the spatial RE resource analysis (see Sect. 1.3 in Chap. 3)—[R]E-SPACE. The [R]E-SPACE results provide the upper limit for the deployment of all solar and wind technologies used in the 2.0 °C and 1.5 °C Scenarios.

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7.1 Global Renewable Energy Potentials

The International Panel on Climate Change—Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC-SRRN 2011) defines renewable energy (RE) as:

> “ (…) any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. Renewable energy is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes low-carbon technologies such as solar energy, hydropower, wind, tide and waves and ocean thermal energy, as well as renewable fuels such as biomass.”

Different types of renewable energy potentials have been identified by the German Advisory Council on Climate Change (WBGU)—World in Transition: Towards Sustainable Energy Systems, Chap. 3, page 44, published in 2003: (WBGU 2003) (Quote):

> “Theoretical potential: The theoretical potential identifies the physical upper limit of the energy available from a certain source. For solar energy, for example, this would be the total solar radiation falling on a particular surface. This potential does therefore not take account of any restrictions on utilization, nor is the efficiency of the conversion technologies considered.
>
> Conversion potential: The conversion potential is defined specifically for each technology and is derived from the theoretical potential and the annual efficiency of the respective conversion technology. The conversion potential is therefore not a strictly defined value, since the efficiency of a particular technology depends on technological progress.
>
> Technological potential: The technological potential is derived from the conversion potential, taking account of additional restrictions regarding the area that is realistically available for energy generation. […] like the conversion potential, the technological potential of the different energy sources is therefore not a strictly defined value but depends on numerous boundary conditions and assumptions.
>
> Economic potential: This potential identifies the proportion of the technological potential that can be utilized economically, based on economic boundary conditions at a certain time […].
>
> Sustainable potential: This potential of an energy source covers all aspects of sustainability, which usually requires careful consideration and evaluation of different ecological and socio-economic aspects […].” (END Quote)

For the development of the 2.0 °C and 1.5 °C Scenarios, an additional renewable energy potential—the economic renewable energy potential in a space-constrained environment (Sect. 3.2 in Chap. 3)—has been analysed and utilized in this study.

The theoretical and technical potentials of renewable energy are significantly larger than the current global primary energy demand. The minimum technical potential of solar energy, shown in Table 7.1 (Turkenburg et al. 2012), could supply the global primary energy of 2015 112 times over.

However, the technical potential is only a first indication of the extent to which the resource is available. There are many other limitations, which must be considered. One of the main constraints on deploying renewable energy tech-

Table 7.1 Theoretical and technical renewable energy potentials versus utilization in 2015

Renewable energy resource	Theoretical potential (Annual energy flux) [EJ/year] IPCC 2011	Technical potential [EJ/year] Global energy assessment 2012, Chap. 11, p. 774	Utilization in 2015 [EJ/year] IEA-WEO 2017
Solar energy	3,900,000	62,000–280,000	1.3
Wind energy	6000	1250–2250	1.9
Bioenergy	1548	160–270	51.5
Geothermal energy	1400	810–1545	2.4
Hydropower	147	50–60	13.2
Ocean energy	7400	3240–10,500	0.0018
Total		76,000–294,500	(Total primary energy demand 2015) 555 EJ/year

nologies is the available space, especially in densely populated areas where there are competing claims on land use, such as agriculture and nature conservation, to name just two.

It is neither necessary nor desirable to exploit the entire technical potential. The implementation of renewable energy must respect sustainability criteria to achieve a sound future energy supply. Public acceptance is crucial, especially because the decentralised character of many renewable energy technologies will move systems closer to consumers. Without public acceptance, market expansion will be difficult or even impossible (Teske and Pregger 2015). The energy policy framework in a particular country or region will have a profound impact on the expansion of renewables, in terms of both the economic situation and the social acceptance of renewable energy projects.

7.1.1 Bioenergy

The discrepancy between the technical potential for bioenergy and the likely sustainable potential raises some issues that warrant further discussion. Recent analyses put the technical potential for primary bioenergy supply at 100–300 EJ/year. (GEA 2012; Smith et al. 2014). However, the dedicated use of land for bioenergy—whether through energy crops or the harvest of forest biomass—raises concerns over competition for land and the carbon neutrality of bioenergy (Field and Mach 2017; Searchinger et al. 2017). Research that focused on the trade-offs between bioenergy production, food security, and biodiversity found that less than 100 EJ / year. could be produced sustainably (Boysen et al. 2017; Heck et al. 2018), although such production levels would be dependent on strong global land governance systems (Creutzig 2017).

The carbon neutrality of bioenergy is based on the assumption that the CO_2 released when bioenergy is combusted is then recaptured when the biomass stock regrows (EASAC 2017). Most land is part of the terrestrial carbon sink or is used for food production, so that harvesting for bioenergy will either deplete the existing carbon stock or displace food production (Searchinger et al. 2015, 2017). The use of harvested forest products (e.g., wood pellets) for bioenergy is not carbon neutral in the majority of circumstances because an increased harvesting in forests leads to a permanent increase in the atmospheric CO_2 concentration (Sterman et al. 2018; Smyth et al. 2014; Ter Mikaelian et al. 2015). Leaving carbon stored in intact forests can represent a better climate mitigation strategy (DeCicco and Schlesinger 2018), because increased atmospheric concentrations of CO_2 from the burning of bioenergy may worsen the irreversible impacts of climate change before the forests can grow back to compensate the increase (EASAC 2017; Booth 2018; Schlesinger 2018).

Bioenergy sourced from wastes and residues rather than harvested from dedicated land can be considered carbon neutral, because of the 'carbon opportunity cost' per hectare of land (i.e., bioenergy production reduces the carbon-carrying capacity of land) (Searchinger et al. 2017). The supply of waste and residues as a bioenergy source is always inherently limited (Miyake et al. 2012). Although in some cases, burning residues can still release more emissions into the atmosphere in the mid-term (20–40 years) than allowing them to decay (Booth 2018), there is general agreement that specific and limited waste materials from the forest industry (for example, black liquor or sawdust) can be used with beneficial climate effects (EASAC 2017). The use of secondary residues (cascade utilization) may reduce the logistical costs and trade-offs associated with waste use (Smith et al. 2014).

7.2 Economic Renewable Energy Potential in Space-Constrained Environments

Land is a scarce resource. The use of land for nature conservation, agricultural production, residential areas, and industry, as well as for infrastructure, such as roads and all aspects of human settlements, limits the amount of land available land for utility-scale solar and wind projects. Furthermore, solar and wind generation require favourable climatic conditions, so not all available areas are suitable for renewable power generation. To assess the renewable energy potential of the available area, all ten world regions defined in Table 8 in Sect. 1 of Chap. 5 were analysed with the [R]E-SPACE methodology described in Sect. 3 of Chap. 3.

Given the issues involved in dedicated land-use for bioenergy outlined above, we assume that bioenergy is sourced primarily from cascading residue use and wastes, and do not analyse the availability of land for dedicated bioenergy crops.

This analysis quantifies the available land area (in square kilometres) in all regions and sub-regions with a defined set of constraints.

7.2.1 Constrains for Utility-Scale Solar and Wind Power Plants

The following land-use areas were excluded from the deployment of utility-scale solar photovoltaic (PV) and concentrated solar power plants:

- Residential and urban settlements;
- Infrastructure for transport (e.g., rail, roads);
- Industrial areas;
- Intensive agricultural production land;
- Nature conservation areas and national parks;
- Wetlands and swamps;
- Closed grasslands (a land-use type) (GLC 2000).

7.2.2 Mapping Solar and Wind Potential

After the spatial analysis, the remaining available land areas were analysed for their solar and wind resources. For concentrated solar power, a minimum solar radiation of 2000 kilowatt hours per square meter and year (kWh/m^2 year) is assumed as the minimum deployment criterion, and onshore wind potentials under an average annual wind speed of 5 m/s have been omitted.

In the next step, the existing electricity infrastructure of power lines and power plants was mapped for all regions with WRI (2018) data. Figure 7.1 provides an example of the electricity infrastructure in Africa. These maps provide important insights into the current situation in the power sector, especially the availability of transmission grids. This is of particular interest for developing countries because it allows a comparison of the available land areas that have favourable solar and wind conditions with the infrastructure available to transport electricity to the demand centres. This assessment is less important for OECD regions because the energy infrastructure is usually already fairly evenly distributed across the country—except in some parts of Canada, the United States, and Australia. For some countries, coverage is not 100% complete due to a lack of public data sources. This is particularly true for renewable energy generation assets such as solar, wind, biomass, geothermal energy, and hydropower resources.

Figure 7.2 shows the solar potential for utility-scale solar power plants—both solar PV and concentrated solar power—in Africa. The scale from light yellow to dark red shows the solar radiation intensity: the darker the area, the better the solar resource. The green lines show existing transmission lines. All areas that are not yellow or red are unsuitable for utility-scale solar because there is conflicting land use and/or there are no suitable solar resources. Africa provides a very extreme example of very good solar resources far from existing infrastructure. While roof-top

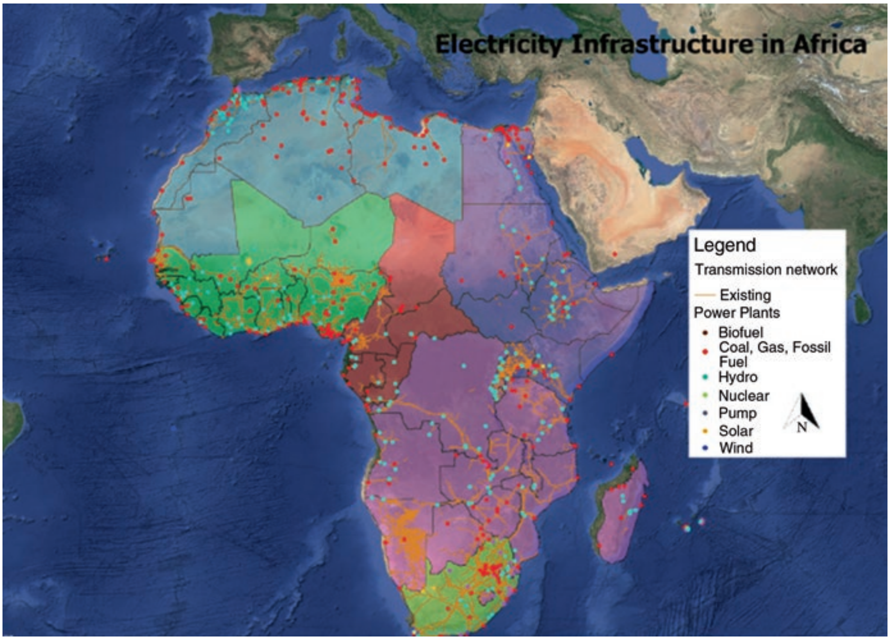

Fig. 7.1 Electricity infrastructure in Africa—power plants (over 1 MW) and high-voltage transmission lines

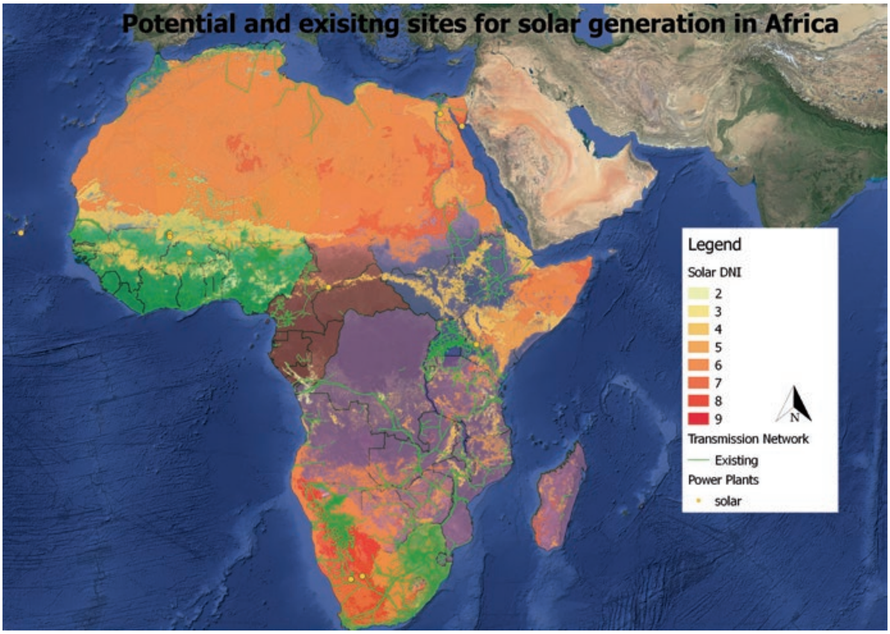

Fig. 7.2 Solar potential in Africa

solar PV can be deployed virtually anywhere and only needs roof space on any sort of building, bulk power supply via solar—to produce synthetic and hydrogen fuels—requires a certain minimum of utility-scale solar applications. The vast solar potential in the north of Africa—as well as in the Middle East—has been earmarked for the production of synthetic and hydrogen fuels and for the export of renewable electricity (via sub-sea cable) to Europe in the long-term energy scenarios in the 2.0 °C and 1.5 °C Scenarios.

Europe, in contrast, is densely populated and has fewer favourable utility-scale solar sites because of both its lower solar radiation and conflicting land-use patterns. Figure 7.3 shows Europe's potential for utility-scale solar power plants. Only the yellow and red dots across Europe, most visible in the south of Spain, south of the Alps, south-west Italy, and the Asian part of Turkey, mark regions suitable for utility-scale solar, whereas roof-top solar can be deployed economically across Europe, including Scandinavia.

However, Africa and Europe are in a good position, from a technical point of view, to form an economic partnership for solar energy exchange.

The situation for onshore wind power differs from that for solar energy. The best potential is in areas that are more than 30° north and south of the equator, whereas the actual equatorial zone is less suitable for wind installation. North America has significant wind resources and the resource is still largely untapped, even though there is already a mature wind industry in Canada and the USA. Figure 7.4 shows the existing and potential wind power sites. While significant wind power

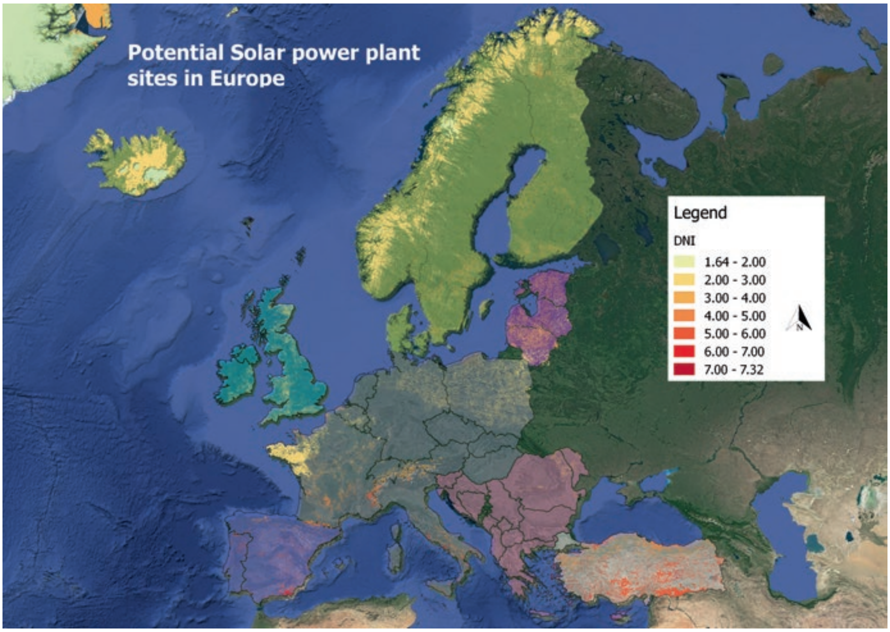

Fig. 7.3 Europe's potential for utility-scale solar power plants

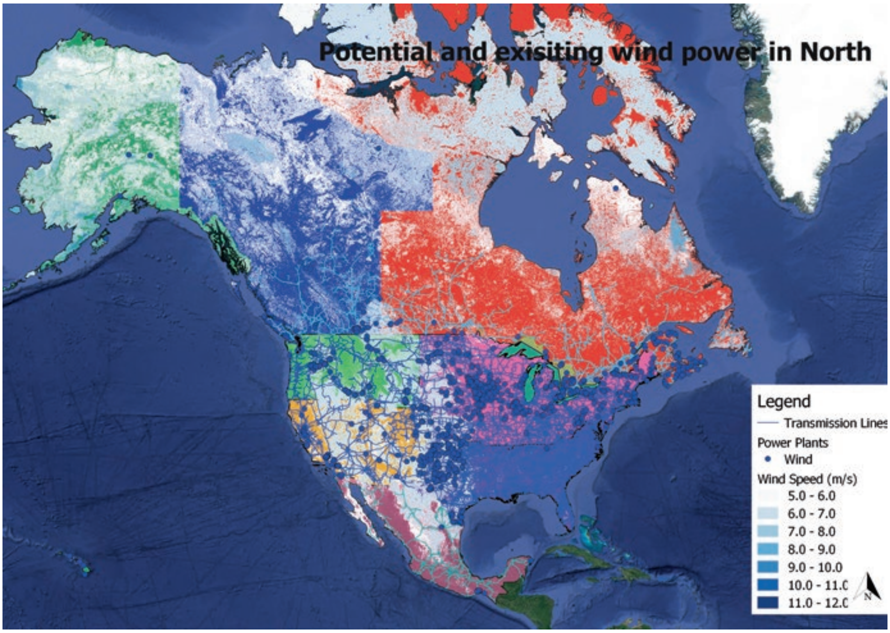

Fig. 7.4 OECD North America: existing and potential wind power sites

installations are already in operation, mainly in the USA, there are still very large untapped resources across the entire north American continent, in Canada and the mid-west of the USA.

Unlike the situation in the USA, wind power in Latin America is still in its initial stages and the industry, which has great potential, is still in its infancy. Figure 7.5 shows the existing wind farm locations—marked with blue dots—and the potential wind farm sites, especially in coastal regions and the entire southern parts of Argentina and Chile.

The available solar and wind potentials are distributed differently across all world regions. Whereas some regions have significantly more resources than others, all regions have enough potential to supply their demand with local solar and wind resources—together with other renewable energy resources, such as hydro-, bio-, and geothermal energies.

Table 7.2 provides an overview of the key results of the [R]E-SPACE analysis. The available areas (in square kilometres) are based on the space-constrained assumptions (see Sect. 2.1 in Chap. 7). The installed capacities are calculated based on the following space requirements (Table 7.2):

- Solar photovoltaic: 1 MW = 0.04 km^2
- Concentrated solar power: 1 MW = 0.04 km^2
- Onshore wind: 1 MW = 0.2 km^2

Note: Mapping Eurasia was not possible because the data files were incomplete.

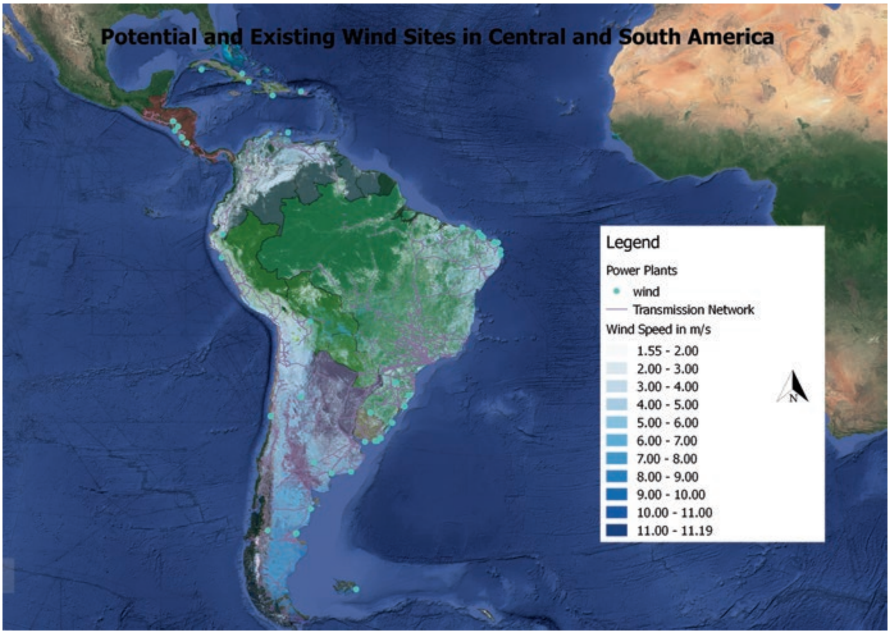

Fig. 7.5 Latin America: potential and existing wind power sites

Table 7.2 [R]E-SPACE: key results part 1

		Solar		Onshore wind	
Region	Subregion	Potential availability for utility-scale installations [km^2]	Space potential [GW]	Potential availability for utility-scale installations [km^2]	Space potential [GW]
OECD North America	Canada East	2,742,668	68,567	2,530,232	12,651
	Canada West	2,242,715	56,068	2,180,271	10,901
	Mexico	3,365,974	84,149	3,341,940	16,710
	USA – South East	269,650	6741	254,976	1275
	USA – North East	1,043,033	26,076	1,043,026	5215
	USA – South West	1,847,162	46,179	1,840,980	9205
	USA – North West	431,277	10,782	427,709	2139
	USA – Alaska	1,152,288	28,807	1,091,698	5458

(continued)

Table 7.2 (continued)

Region	Subregion	Solar		Onshore wind	
		Potential availability for utility-scale installations	Space potential	Potential availability for utility-scale installations	Space potential
		[km^2]	[GW]	[km^2]	[GW]
Latin America	Caribbean	34,238	856	34,238	171
	Central America	17,529	438	17,603	88
	North Latin America	869,811	21,745	869,811	4349
	Brazil	1,623,625	40,591	1,623,625	8118
	Central South America	1,023,848	25,596	1,024,340	5122
	Chile	693,990	17,350	693,990	3470
	Argentina	1,651,168	41,279	1,651,168	8256
	CSA – Uruguay	32,360	809	32,360	162
Europe	EU – Central	146,797	3670	146,797	734
	EU – UK and Islands	22,406	560	22,406	112
	EU – Iberian Peninsula	15,608	390	15,608	78
	EU – Balkans + Greece	4825	121	4825	24
	EU – Baltic	32,090	802	32,090	160
	EU – Nordic	218,496	5462	218,496	1092
	Turkey	134,354	3359	134,354	672
Middle East	East – Middle East	165,302	4133	5738	29
	North – Middle East	91,970	2299	7123	36
	Iraq	119,967	2999	9104	46
	Iran	586,595	14,665	57,965	290
	United Arab Emirates	530	13	530	3
	Israel	386	10	217	1
	Saudi Arabia	13,284	332	13,284	66
Africa	North – Africa	9,726,388	243,160	9,784,694	48,923
	East – Africa	6,378,561	159,464	6,980,497	34,902
	West – Africa	8,336,960	208,424	8,669,628	43,348
	Central – Africa	7,229,129	180,728	7,509,351	37,547
	Southern – Africa	3,269,644	81,741	3,547,591	17,738
	Rep. South Africa	1,626,528	40,663	1,650,471	8252

Table 7.3 [R]E-SPACE: key results part 2

		Solar		Onshore wind	
		Potential availability for utility-scale installations	Space potential	Potential availability for utility-scale installations	Space potential
Region	Subregion	[km^2]	[GW]	[km^2]	[GW]
Non-OECD Asia	Asia-West (Himalaya)	1,315,395	32,885	801,044	4005
	South and South East Asia	9062	227	8184	41
	Asia North West	184,503	4613	43,710	219
	Asia Central North	138,861	3472	81,228	406
	Philippines	2634	66	941	5
	Indonesia	106,581	2665	12,162	61
	Pacific Island States	5510	138	673	3
India	North – India	229,314	5733	163,118	816
	East – India	32,511	813	5195	26
	West – West	224,355	5609	121,441	607
	South – Incl. Islands	129,346	3234	103,177	516
	Northeast – India	77,379	1934	1821	9
China	East – China	47,621	1191	39,648	198
	North – China	425,350	10,634	825,272	4126
	Northeast – China	193,006	4825	192,110	961
	Northwest – China	5,642,854	141,071	1,603,909	8020
	Central – China	256,272	6407	211,229	1056
	South – China	500,211	12,505	317,046	1585
	Taiwan	5862	147	2791	14
	Tibet	5460	137	377,610	1888
OECD Pacific	North Japan	8697	217	8213	41
	South Japan	3567	89	3036	15
	North Korea	10,724	268	9854	49
	South Korea	2411	60	1892	9
	North New Zealand	22,699	567	22,163	111
	South New Zealand	25,106	628	46,266	231
	Australia – South and East (NEM)	2,080,117	52,003	2,035,523	10,178
	Australia – West and North (NT)	2,813,791	70,345	2,762,499	13,812

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