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Quantifying a realistic, worldwide wind and solar electricity supply

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ABSTRACT

Nearly all long-term energy projections rely heavily on renewable energy sources on the assumption of abundance. Yet, already today, wind and solar projects can encounter local objections and competition with other uses. This paper presents the ranges of realistic potential supply for solar and wind electricity, using a 1 km^2 grid level analysis covering the whole world at country level. In addition, the potential for building-based solar electricity is assessed. We find that long-term combined potentials range between 730 and 3700 EJ/a worldwide, depending crucially on the acceptable share of land—up to 3.5% of total (non-ice covered) land on earth. Realistic potentials account for limitations such as land-use competition and acceptance, together with resource quality and remoteness as proxies for cost. Today's electricity demand (65 EJ/a) is well covered by the range, but constraints may occur in the long run locally. Amongst large countries, Nigeria and India may need imports to meet electricity demand.

1. Introduction

Faced with the twin challenge of energy security and the largely unmitigated externalities of conventional energy sources, and buoyed by the economic co-benefits and continuing increase in cost-competitiveness of renewables (IEA RETD, 2012), most governments are formulating policy frameworks which encourage a high penetration of renewable power sources in the medium- to long-term. Renewables face many challenges and uncertainties as they grow and become integrated into the energy system. Yet projections often assume that the resource base provides no limitation, notably for wind or solar energy. To test this assumption, we have conducted a detailed, global analysis to provide credible, practical, realistic and consistent potentials for electricity from solar and wind sources, using the highest resolution datasets that are publicly available. We not only take into account technological development but also attempt to address implementation constraints such as grid connection, competition with other uses or possible local opposition. Most significantly we try to quantify real availability of these surfaces, beyond simple technical or geographic limitations, using an availability factor.

We stress that we do not present a full energy system analysis here as is done typical energy analysis studies (IEA, 2012a; GEA, 2012; Lund and Mathiesen, 2009; Deng et al., 2012; Shell, 2013), but rather a detailed quantification of technical resource potentials which are used as an input to such analyses. For example, the results of this study have been used as a key input for the renewable energy projections in Shell's (2013) New Lens Scenarios.

The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation summarised the existing body of work on renewable energy potentials. It highlighted the difficulty of comparing different studies varying in geographic scope, technology scope and approach (Edenhofer et al., 2011). The surveyed studies (Krewitt et al., 2009; REN21, 2008; UNDP et al., 2000; Hofman et al., 2002; Trieb et al., 2009; EEA, 2009; Siegfriedsen et al., 2003; DLR, 2006; Defaix, 2009; Hoogwijk, 2004; de Vries et al., 2007; Zhou et al., 2009; Denholm and Margolis, 2008; Schwartz et al., 2010; Jacobson and Delucci, 2011) are frequently cited, but most of them:

- are primarily meta-analyses themselves (Krewitt et al., 2009; REN21, 2008; UNDP et al., 2000), or
- assess only a single or a handful of related technologies (Hofman et al., 2002; Trieb et al., 2009; EEA, 2009; Siegfriedsen et al., 2003; DLR, 2006; Defaix, 2009) or

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- miss a part of the potential (e.g. assessing roofs, but not façades for solar photovoltaic (PV) energy systems) (Defaix, 2009; Hoogwijk, 2004; de Vries et al., 2007; Zhou et al., 2009; Denholm and Margolis, 2008), or
- pertain to a single country or region, not the whole world with differences in approach or assumptions between regions (EEA, 2009; Siegfriedsen et al., 2003; DLR, 2006; Defaix, 2009; Zhou et al., 2009; Denholm and Margolis, 2008; Schwartz et al., 2010), or
- cover the whole world, but do not provide sub-global detail (Jacobson and Delucci, 2011), or
- focus on theoretical or technical potentials, taking only a limited number of, or no, additional barriers to implementation into account (EEA, 2009; Hoogwijk, 2004; de Vries et al., 2007), or
- use low resolution datasets, potentially over- or under-estimating potential significantly locally (Hoogwijk, 2004; de Vries et al., 2007).

They commonly find (very) large potentials: for land-based solar and wind potentials combined, results on the order of a few thousand to tens of thousands of exajoules of final electric energy per annum are reported.

In contrast to these existing studies this paper presents, for the first time, a comprehensive, bottom-up assessment of renewable electricity potentials across the entire globe for all solar and wind electricity technologies: wind, solar photovoltaic (PV) and concentrated solar power (CSP) including land- and sea-based resources as well as building-based PV potential. The focus in this study is not on *full technical potential*, as is the case for many existing studies, but on an estimate of the *realistic*, or constrained, technical potential, which accounts for technical as well as non-technical limitations, such as acceptance, cost, competition with other uses or remoteness. For land- and sea-based technologies, we achieve this through a detailed analysis of land use and cover in a geographic information system (GIS) with up to ~1 km^2 resolution, the most detailed, global analysis to date. We first find the technically *suitable* area, by successive exclusion of geographic and technical factors. In addition, we include a final step which aims to assess a realistic future maximum *availability* share of all land which is technically suited for use.

For building-based PV potentials we use the same technology and resource assumptions as on land, but calculate the available area on both roofs and façades at country level, starting from a building stock analysis of a representative set of reference countries.

In addition, and for completeness, we present a meta-analysis of existing studies for hydro- and geothermal electricity, with extrapolations to assess realistic long-term potential.

2. Methods

The overall framework to assess any solar or wind energy potential followed a three step approach by determining:

a. the available area (on land, on sea, on building roofs and building façades)
b. the amount of resource incident upon this area (wind speed, solar irradiation)
c. the amount of energy a technology could capture of this total resource (i.e. conversion)

The three steps above are then combined according to Eq. (1) to yield the overall potential estimate for three study periods: 2010, 2030 and 2070.

$$P(p,t) = A(p,t) \cdot I(p,t) \quad (1)$$

where P = potential in EJ per technology, for each study period; A = area in km^2 per technology; I = resource intensity, i.e. potential per area, in EJ/km^2, which is calculated differently for solar and wind technologies and can vary per study year; p = the study period (2010, 2030, 2070); t = the technology per category, i.e. CSP, wind on land or sea, PV on land or building roofs, or façades.

The terms and steps above differ by technology (PV, CSP, wind) and category (sea, land, buildings) and are discussed in detail below.

Of the two factors in Eq. (1), the first factor, the available area, has a much larger uncertainty than the second factor, the effective resource per area. Note that the available area can also vary over time, due to land use changes, e.g. from urbanisation and deforestation. However, these changes are expected to have a much smaller bearing than other elements, most notably the 'availability factor' and have therefore not been taken into account here.

For hydro- and geothermal electricity, the potential is much more discretely distributed across the world, as it is associated with specific localised features. These two resources were not assessed in depth, but via a meta-analysis of existing studies.

2.1. Available area

Land- and sea-based resources were calculated using a geographic information system with datasets with up to 1 km × 1 km resolution. The available area for these resources was calculated by starting with the total world surface area (146×10^6 km^2 on land and 361×10^6 km^2 on sea) and successively excluding areas which would not be suitable for use for a given technology (wind, PV, CSP). In a final step we attempted to estimate the percentage of *suitable* area which would be realistically *available* for renewable electricity production. Note that this availability of a given type of area is the factor with the largest uncertainty. All these steps are described in detail below, first for land-based resources, then for sea-based resources, and formalised in Eq. (2).

$$A(p,t) = \sum_l a_l(t) \cdot \left[\sum_i A_i(p,t) \right] \quad (2)$$

where A = total available area for a given technology and period; a_l = availability factor per land type; A_i = suitable area in km^2 in grid cell i for a given technology; p = the study period (2010, 2030, 2070); t = the technology, i.e. CSP, wind on land or sea, PV on land.

2.1.1. Land-based solar and wind resource

The area available for land-based wind and solar electricity installations is restricted by the following factors. These factors have been used to estimate *suitable* area onshore based on the data sources in Table 1 in the following steps:

- **Exclusion of Antarctica**: The land area of Antarctica was excluded.
- **Elevation:**
  - **Wind**: Areas above 2000 m were excluded due to the significantly lower power density at such elevation.
- **Land cover–Urban area**: This was excluded for all technologies based on a combination of data on urban land cover and on population density. Note that for PV potential on buildings, a different approach, not based on GIS, was used (see below).
- **Land cover–Forests:**
  - **Solar:** All forest areas were excluded for solar electricity production. Note that we also excluded mixed land covers (cropland or grassland with some forest) in this exclusion step.

Table 1
Data sets used for the GIS modelling of land- and sea-based resources.

Category	Data	Resolution	Source	Reference
Land	Elevation	1 km	USGS (-EROS) GTOPO30	USGS (1996)
	Land cover/use	1 km	USGS GLCC v2	Loveland et al. (2000)
	Population	5 km	NASA–SEDAC v3	CIESIN et al. (2005)
	Country borders	~2 km	VMAP0	NIMA (2000)
	Railways	10 km	NGA/USGS VMAP0/VMAP1	NIMA (2000)
	Solar irradiance	40 km	NASA	LaRC ASDC (2012)
	Wind speed (land)*	19 km	CRU, CL2.0	New et al. (2002)
Land/sea	Wind speed (all)*	120 km	CISL	CISL (2012)
	Protected areas	1 km	WDPA	IUCN and UNEP (2011)
Sea	Coastlines	~2 km	VMAP0	NIMA (2000)
	Ocean depth	2 km	NOAA	Amante and Eakins (2009)
	Maritime use	1 km	NCEAS impacts	Halpern et al. (2008)
	Reefs & marshes	1 km	NCEAS ecosystems	Halpern et al. (2008)
	Offshore borders	~2 km	Exclusive Economic Zones	VLIZ (2012)

* The wind speed on land was determined as an average between these two datasets as the CRU dataset had a better resolution but suffered from sparse data in some world regions (China, Africa, South America).

- **Wind**: Non-protected forests were not excluded for wind power production (but received a lower availability in the final step).

- **Land cover – Ice, Water, Coast, Cliffs, Dune, Rock**: Areas of these land cover types were excluded for all technologies.
- **Protected areas:**
  - From the World Database on Protected Areas (WDPA) data set (see Table 1) all classified protected areas were excluded (Natura 2000 and Cat. I–VI). Non-classified areas were not included in this study due to insufficient information.
  - All land cover classes of 'rain forest' and 'tropical forest' have been fully excluded.
- **Slope:**
  - **Solar – PV and Wind**: Grid cells (1 km × 1 km) with an average slope of more than 15° (~27%) were excluded.
  - **Solar – CSP**: Grid cells (1 km × 1 km) with an average slope of more than 2° (~4%) were excluded.
- **Resource intensity:**
  - **Solar – CSP**: Areas with a direct normal irradiance value of less than 1900 kWh/m^2/a were excluded for CSP. Availability of nearby water was not used as an exclusion criterion as technological developments are currently underway to minimise reliance on water for CSP.
  - **Solar – PV**: No areas were excluded based on resource intensity for PV as current practice shows that latitude is not a strong factor in determining where PV is installed and there is still significant price reduction potential in PV which would likely render all areas within reach of cost-effectiveness. However, we note that the lowest horizontal irradiation levels found at the latitudes included in this study are around 800 kWh/m^2/a.
  - **Wind**: To reflect the fact that areas of low wind speed are unlikely to see significant investment in wind power installations we excluded areas with low average wind speeds in our calculations. The economically feasible minimum average wind speed is heavily dependent on local factors. For this global study, we implemented a critical cut-off of 6 m/s at hub height, with an assumption of average hub-height rising from 80 m now to 90 m for 2030 and 2070 (see also Supplementary Information online). Only areas with average wind speeds below this cut-off in four out of four quarters within a year were excluded.

2.1.2. Sea-based wind resource

The area available for sea-based wind power installations is restricted by the following factors which have been used to estimate *suitable* offshore area based on the data sources listed in Table 1:

- **Economic zone attribution**: Only offshore areas attributed to a country jurisdiction have been included in this study. In case of joint jurisdiction the area has been split evenly between the administrating countries. Disputed areas have been completely excluded from the analysis.
- **Sea ice**: Areas likely to be impacted by sea ice have been excluded by following the winter sea ice line around the Arctic and by implementing a general cut-off at 60° latitude in the Antarctic.
- **Ocean floor depth**: Current technology for offshore wind power primarily relies on pylons driven into the sea-bed. This technology is already in use up to 50 m ocean depth. At (much) higher depths it is expected that floating turbine technology will be deployed. This technology is expected to be deployed within the study time horizon (up to 2070). There is no established upper limit for the depths this technology can reach; we have used a cautious cut-off of 1000 m depths; i.e. offshore areas with deeper ocean floor depths have been excluded.
- The **distance from shore** is not a technical limitation per se, but areas very far from the coast have been assumed to be too costly to connect to land for the foreseeable future. We have used a critical cut-off of 200 km. It is noted, however, that most areas further than 200 km offshore would have been excluded in the previous steps on ocean floor depth and exclusive economic zones anyway.
- **Protected zones**: Where data on ecosystems and protected zones was available, these have been excluded, but freely available data is sparse. Most of the areas excluded in this step were identified through the WDPA data set with some additional exclusions of salty marshes and rocky reefs from NCEAS (see Table 1).
- **Maritime use**: Data on maritime use is not comprehensive. We have excluded the shipping lanes, areas of artisanal fishing and oil rigs (including buffer zones) contained in a dataset provided by NCEAS (see Table 1) to estimate areas unavailable for offshore wind parks due to prior uses. This will lead to underestimates in some areas (only 10% of heavy shipping traffic is logged in the NCEAS data set) and overestimates in other areas (all existing oil rigs are excluded but it is likely that several of them will have been dismantled by 2030/2070).
- **Resource intensity – wind speed**: In analogy with the approach for onshore wind above, we implemented a critical cut-off of 8 m/s at hub height, with an assumption of average hub-height

rising from 90 m now to 110 m for 2030 and 2070 (see online Supplementary Information for more detail). Only areas with average wind speeds below this cut-off in four out of four quarters were excluded.

2.1.3. From suitable to available area

The exclusions above yielded the *suitable* area for solar and wind power. To assess the area which will likely actually be *available* for electricity production we used a geographically non-specific availability factor (see Table 2). This can be interpreted as representing the average share of the suitable area in a given grid cell, region, or country, which is likely to be actually available for a PV, CSP or wind power park in the given period. Because this availability factor is highly uncertain but has a large bearing on the overall potential, we spanned a range of possible values in our assumptions, denoted Low, Medium, High and varied the factor for the High case between industrialised and developing countries, and different land types.

For **solar electricity**, availability factors were based on Trieb et al. (2009) for the Medium case and variations around this number for the Low and High cases.

For **on-shore wind**, we tried to derive availability factors from case studies in Germany, Denmark and the Netherlands. We estimated currently installed wind power capacities to cover around 1–2% of suitable area in these countries (see Supplementary Information for the calculation behind these numbers). Given that these countries are not, on average, at the limit of their wind power density (although individual regions within the countries may be reaching the limits acceptable to the local population), we have assumed that this represents around 20–30% of the possible maximum available area, resulting in an availability factor of 5–6%. This is in line with another European study (EEA, 2009) postulating 4–5% availability. Based on these considerations, we used a range of 3–10% for our three scenarios and a much lower availability for forests.

Since availability for **offshore wind** parks is today primarily impacted by competing use and perceived visual impact, the availability factor was varied by distance from shore (see Table 2).

The factors were based on the following considerations:

- Social acceptance is only expected to play a role <50 km from shore as wind farms at higher distances are not visible, therefore availability has been heavily restricted for distances <50 km from shore.
- The Low case is based on the values used in another study (EEA, 2009), but leads to a more restricted area since that study started with a much larger (less constrained) *suitable* area.
- The Medium and High cases assume full availability (100%) minus an (upper) estimate of areas for protection (Medium Case) or protection and shipping (High Case) which we did not have sufficient data for to exclude above.

Table 2
Availability factor for technologies on land (Ind. = industrialised, Dev. = developing country).

Technology	Land class or distance from shore class	Availability (by case and country type)			
		Low	Med.	High	
		Ind./Dev.	Ind./Dev.	Ind.	Dev.
Wind on-shore	Forest	0.5%	1%	2%	2%
	Agriculture	3%	6%	10%	20%
	Desert				
	Grassland				
	Barren land				
PV/CSP	Agriculture	0.1%	0.5%	2%	5%
	Grassland	0.5%	1%	3%	5%
	Barren land				
	Desert	2%	5%	8%	15%
Wind off-shore	0–10 km	4%	5%	5%	
	10–50 km	10%	30%	40%	
	50–200 km	25%	60%	80%	

For more information about how these factors were established, see the Supplementary Information online.

2.1.4. Resource cut-offs

Although this study is not attempting to calculate economic potentials, it is instructive to translate the resource intensity cut-offs into approximate production cost values at least for our base year and 2030. These are shown in Table 3 with inputs derived from literature (Teske et al., 2011; Schlömer et al., 2014) and assuming a lifetime of 20 years and a weighted cost of capital of 10%. Note that these approximate costs are higher than typical current costs, as they represent costs for low resource intensity areas and that actual production costs would be minimised on a project-by-project basis.

2.1.5. Building-based solar resource

A GIS approach for assessing roof and façade area would carry a large uncertainty as the global GIS dataset only identifies artificial surfaces at a 1 km × 1 km scale, not differentiating between roofs on buildings and other structures. Instead we have used floor space to derive the roof and façade area suitable for solar resources as shown in Eq. (3).

$$A_{\text{roof, façade}}(p,c) = \text{Pop}(p,c,u) \cdot \frac{A_{\text{floor}}}{\text{Pop}}(p,c,u) \cdot \left[F_{\text{roof}}(b,u) \cdot S_{\text{roof}} + F_{\text{façade}}(b,u,o) \cdot S_{\text{façade}}\right] \quad (3)$$

where A_{roof} = area of building roofs suitable for energy harvesting using PV; $A_{\text{façade}}$ = area of building façades suitable for energy harvesting using PV; Pop = population for each country per period and urbanisation level (United Nations, 2009); p = the study period (2010, 2030, 2070); c = country; u = urbanisation level; A_{floor}/Pop = floor area per capita for each country per period and urbanisation level; F_{roof} = roof to floor ratio, dependent on building type and urbanisation level; $F_{\text{façade}}$ = façade to floor ratio, dependent on building type, urbanisation level and orientiation; b = building type; o = orientation; $S_{\text{roof/façade}}$ = suitability factor on roofs/façades, i.e. share of full roof/façade deemed suitable and available for energy harvesting.

2.1.5.1. Floor area. We calculated floor area for each country based on the floor area per capita and the population per country. The floor area per capita was first estimated for ten reference countries and all other countries were mapped to these ten reference countries based on several characteristics (region, climate zone, GDP per population). The mapping is shown in the Supplementary Information online.

Table 3
Estimated production costs for the medium term at the resource cut-offs used here.

Technology	Resource cut-off	Approximate levelised costs in EUR_{2012}/kWh	
		2010	2030
Wind on-shore	6 m/s at hub height	0.08–0.12	0.05–0.08
Wind off-shore	8 m/s at hub height	0.10–0.18	0.07–0.14
CSP	1900 kWh/m²/a DNI	0.24–0.68	0.12–0.33
PV	[~800 kWh/m²/a GHI]	0.53–0.80	0.11–0.21

For the ten reference countries, we differentiated between building types (multi-family home, single-family home, non-residential buildings), urbanisation level (rural and urban), period (2010, 2030, 2070) and new or existing buildings and also tried to account for the increasing share of the population living in multi-family homes and urban areas in the future. We first estimated base year (2010) values for floor area per capita in all of these categories based on existing statistics, where available (de la Rue du Can, 2009; DoE, 2009; Diefenbach and Loga, 2011; EIA, 2006; IFO Institute, 1999; IBGE, 2005; Milford, 2009; Ministerio de Fomento, 2010; Ministerio de industria tourismo y comercio, 2007; Schlomann et al., 2009; Statistisches Bundesamt, 2009; Zhou et al., 2007). For future years, we trended historic growth, but moderated this growth where necessary to achieve consistency across countries.

This iterative approach yielded values for the floor area per capita from 10 to 76 m^2 in 2010 and 23 to 71 m^2 in 2070 for residential buildings and 1–29 m^2 in 2010 and 5–37 m^2 in 2070 for non-residential buildings based on modelling of building stock development in each of the reference countries. For more detail, see the Supplementary Information online.

2.1.5.2. Roof to floor ratio/façade to floor ratio. We determined roof-to-floor and façade-to-floor (North, South, East and West) ratios, differentiating between single-family and multi-family homes in rural and urban areas and non-residential buildings. We established these ratios for three reference countries and mapped all other countries to these reference countries, based on the same characteristics as above. The roof-to-floor ratios ranged from 0.17 to 1.00. The façade-to-floor ratios varied between 0.10 and 0.33 or 0.00 and 0.47 depending on orientation. A zero value represents a wall connected to the wall of an adjacent building. For more detail, see the Supplementary Information online.

2.1.5.3. Suitability. From the total roof and façade area, the suitable area (synonymous with available area here) was estimated. For this we used a suitability factor of 33% for roofs and 10% for façades, rising to 30% in 2070. These factors were derived from literature (Bergamasco and Asinari, 2011; Ghosh and Vale, 2006; IEA-PVPS, 2002; Izquierdo et al., 2008; Montavon et al., 2004; NREL, 2008; Pillai and Banerjee, 2007; Scartezzini et al., 2002).

2.2. Potential per area

In the final step, the conversion of raw resource incident on the available area was converted to usable electricity through an effective conversion efficiency. Note that we do not differentiate further between different types of sub-technologies, e.g. mono- vs. polycrystalline solar cells, etc., but characterise each technology by one efficiency which is representative of the whole sub-technology spectrum.

2.2.1. Solar electricity production

The potential per area for solar electricity production can be calculated from the solar energy incident upon the surface per year and the conversion efficiency of the harvesting technology, as shown in Eq. (4).

$$\frac{P}{A}(p,t) = I(t) \cdot E(p,t) \tag{4}$$

where P/A = potential per area in EJ/km^2 per study period and technology (PV vs CSP); p = the study period (2010, 2030, 2070); t = the technology (PV or CSP); I = resource intensity in J/m^2 for solar irradiation; E = conversion efficiency in % by technology.

2.2.1.1. Resource intensity. For solar photovoltaics (PV) on land or building roofs, the global horizontal irradiation (GHI) per grid cell or country was derived from the solar irradiance data source in kWh/km^2/a listed in Table 1. The GHI includes the total gross solar energy from both direct and diffuse radiation incident on a horizontal plane. For buildings, we calculated an average irradiation value per country across all grid cells, weighted by population density.

For solar photovoltaics (PV) on building façades we also calculated the gross vertical irradiation (GVI) in kWh/km^2/a by orientation (North, South, East, West).

For concentrated solar power (CSP), the direct normal irradiance (DNI) per grid cell in kWh/km^2/a was derived from the solar irradiance data source listed in Table 1. The DNI is the total direct gross solar energy incident on an area perpendicular to the incoming radiation.

2.2.1.2. Conversion efficiency for PV. The overall conversion efficiency for PV is the product of these factors:

- The module efficiency of the individual solar modules[1] (E_m)
- The performance ratio, capturing the system's conversion efficiency from the module's output to usable electricity (PR)
- (For land-based PV only): A ground coverage value representing the share of land capturing energy, i.e. the share of the total area of a PV plant actually covered with PV cells (GC)[2]

Table 4 shows the values used for each of these three factors as well as the overall resulting conversion efficiency for buildings (E_m·PR) and for land (E_m·PR·GC).

2.2.1.3. Conversion efficiency for CSP. The overall conversion efficiency for CSP is the product of two factors:

- the net efficiency which represents the internal conversion efficiency[1] of the CSP system and is understood to include the (small) efficiency losses in plants with storage capacity.
- a space factor which represents the additional factors to take into account when converting from gross resource over the entire plant area to final electricity produced from the full plant.

The values used for these two factors and the overall resulting conversion efficiency are shown in Table 5.Note that assumptions on the development of technologies (in the form of conversion efficiencies for PV and CSP and hub heights for wind) were not explicitly linked across technologies in a prior scenario, e.g. on installed capacities, but were deemed consistent as they were derived from similar considerations of continued growth.

2.2.2. Electricity from wind on land and sea

The wind power potential per area per year for each grid cell was calculated for each period according to Eq. (5) (based on Held, 2010, p.60) which includes the approximate relationship between the full load hours per year and average annual wind speed, based on a range of turbines, as well as an average power density:

$$\begin{aligned}\frac{P}{A}(p,t) &= H(p,t) \cdot D \cdot E(p,t) \\ &= (a \cdot \upsilon_2 - b) \cdot D \cdot E(p,t)\end{aligned} \tag{5}$$

where P/A = potential per area in EJ/km^2 per period and technology; p = the study period (2010, 2030, 2070); t = the technology (on-shore vs off-shore wind); H = full load hours in a given

[1] Note that an average efficiency across a range of technologies was used here as the range of module efficiencies has a much smaller effect on the overall result than other factors, e.g. availability.

[2] The ground coverage factor was derived from typical power densities of solar farms (25–50 MW/km^2) in comparison with the raw module power density of a typical solar cell of 125–150 MW/km^2.

Table 4
Conversion efficiency values used for building- and land-based PV.

Year	Module efficiency (E_m)	Performance ratio (PR)	Gross conversion efficiency (buildings) (E_m·PR)	Ground coverage (land) (GC)	Net conversion efficiency (land) (E_m·PR·GC)
2010	16%	75%	12%	20%	2.4%
2030	24%	80%	19%	23%	4.5%
2070	35%	80%	28%	30%	8.4%

timeframe; D = power density, here 7 MW/km^2; E = conversion efficiency in % by technology; v_2 = the average wind speed at hub height in that timeframe; a = 728; b = 2368.

2.2.2.1. Conversion efficiency. There are also small efficiency losses in wind power production which lower the overall resource intensity. The intensity is therefore moderated (multiplied) by the following additional efficiency factors, which range from 90% to 100%.

- **Operational efficiency**: The share of total *possible* operation time that the wind turbine is actually producing electricity, i.e. not stopped for maintenance. We have varied this by country (industrialised vs. developing) and by distance from shore for offshore wind.
- **Array efficiency**: Multiple turbines can cause interference. The amount of interference depends on land use for onshore wind (not applicable to solitary turbines, as assumed here for agriculture and forest).

The values used for efficiencies for wind power are shown in Table 6.

2.3. Distance from infrastructure

With the exception of offshore wind, renewable electricity installations today do not usually require additional electricity transmission capacity to be connected to existing transmission and distribution grids. When assessing long-term potentials across larger areas, however, the distance from existing electricity lines may be important, depending on the share of the cost of connection in the overall cost for the installation.

To get a first impression of the distribution of our calculated potentials across differing distances from existing electricity grids we have tried to assess the distance of each grid cell from an electricity grid that connects to a significant demand for electricity. Since a global data set for electricity lines was not readily available, we have estimated a 'distance from infrastructure' as a marker for electricity grids based on the approach described in the following. Each grid cell was either classed as 'with infrastructure' or 'without infrastructure', based on land cover, population density and railways as detailed below. For each grid cell without infrastructure we then calculated the distance to the nearest grid cell with infrastructure and then grouped grid cells into distance classes based on the results.

Table 5
Conversion efficiency values used for CSP.

Year	Net efficiency	Space factor	Overall conversion efficiency
2010	15%	20%	3.0%
2030	18%	20%	3.6%
2070	20%	20%	4.0%

Table 6
Efficiency values used for wind power (Ind. = industrialised, Dev. = developing country).

Category	Land class or distance from shore class	Operational efficiency		Array efficiency	
		Ind.	Dev.	Ind.	Dev.
Land	Forest	0.98	0.90	[1.0]	[1.0]
	Agriculture			[1.0]	[1.0]
	Grassland/Barren land			0.925	0.90
Sea	0–10 km	0.925	0.95	0.9	0.8
	10–50 km	0.925	0.95		
	50–200 km	0.9	0.925		

2.4. Classification of grid cells with infrastructure as a marker of grids

To assess whether the potential would be able to supply power into an electricity grid, we used a combination of data sets to estimate the distance from "infrastructure" which we use as a marker for the distance from electricity grids. The presence of infrastructure was based on a combination of:

- land cover being of 'built-up' type or being within 100 km of a cell of such land cover
- population density being above 500/km^2 or within 100 km of a cell of such density
- presence of rail network lines in the cell

Note that road networks were deemed too pervasive to be a good indicator of electricity connections. The exact approach to the infrastructure classification is depicted in Fig. 1. We have attempted to depict the expansion of settlements through time by combining these datasets differently for 2070 vs 2010/2030.

2.5. Distance classification

Based on the previous step we then decided to group the calculated potentials into the following groups:

- For offshore resources: Above or below 70 km from infrastructure
- For land-based resources: Above 500 km, below 500 km or below 100 km from infrastructure

2.6. Hydro- and geothermal electricity

2.6.1. Hydroelectricity

We differentiate between 'small' and 'large' hydroelectricity potentials. 'Small' hydroelectricity tends to denote run-of-the-river type installations, using newer technologies and resulting in smaller projects of around <10 MW in size although no official definition exists. 'Large' hydroelectricity is commonly used to denote traditional reservoir projects of larger capacity, up to several tens of gigawatts. We used a range of existing data sources on hydroelectricity potentials to get an estimate of the potentials split into these two categories (DLR, 2006; IJHD, 2008; IEA, 2012b, 2013).

- The International Hydropower & Dams World Atlas (IHDWA) contains estimates for total hydroelectricity potential (IJHD, 2008)
- The IEA's Small-Hydro Atlas which was designed to report potential for small hydroelectricity projects, but still lacks data for most countries (IEA, 2013)
- The IEA's official statistics on current (2007/2009) production of hydroelectricity were used to fill gaps in the reported historic data (IEA, 2012b)

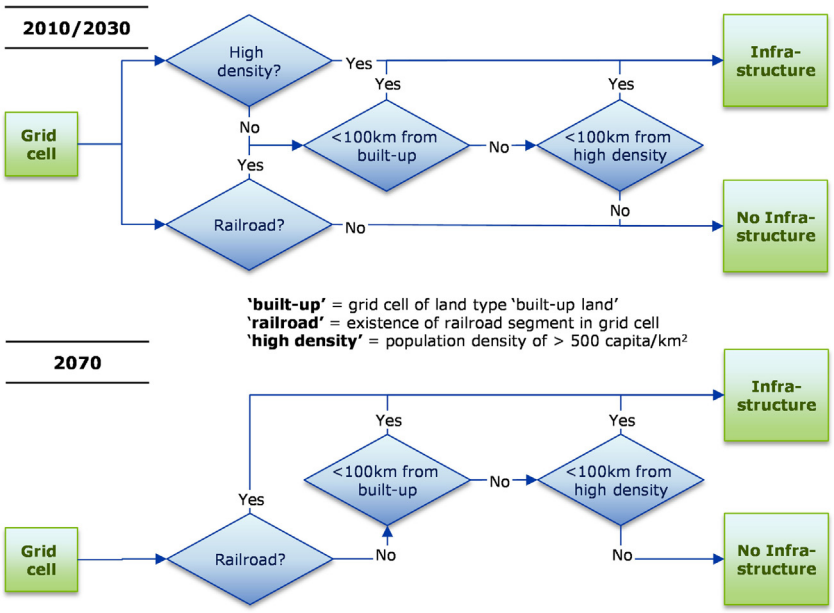

Fig. 1. Logic used to classify grid cells as with or without infrastructure for the distance class grouping.

- An existing meta-analysis from 2008 published by REN21 was used to fill gaps in the projected data for large hydropower (REN21, 2008)
- The total size of water bodies in a country was used as a proxy to infer potential for small hydropower for countries without reported potentials (FAO, 2007).

The numbers reported in the sources above at country level were combined with additional sources for individual countries (REN21, 2008; DLR, 2006; Fulton et al., 2011; SETIS, 2011) to arrive at estimates for the potential for hydroelectricity split into 'large' and 'small' hydroelectricity as follows:

For **large hydroelectricity potential**:

1. We set the 2030 potential to the lower bound of the 'mid-term projected output' reported in the IHDW atlas.
2. We set the 2070 potential as the half-way point between this and the IHDWA 'economic potential'.
   a. Where values from IHDWA 2007 and IEA 2007/9 differed for current production we have used the larger number.
   b. Where current (2007/9) production from IEA was larger than the IHDWA mid-term or economic potentials we have used the larger IEA number.

For **small hydroelectricity potential:**

1. We have assumed that the reported potential was economically feasible (not technical) potential and have used this as our 2070 potential. This is a reasonable assumption given that this is estimated here at ~1.6 EJ, whereas the global technical potential is estimated at 1.9–2.0 EJ in REN21.
2. We have set the 2030 potential as the point between the current (2009) capacity (zero for most countries due to underreporting) and the 2070 potential along a linear development path.

2.6.2. Geothermal electricity

We analysed ~30 different country-level studies, presentations and briefing papers containing potential estimates for ~100 different countries in a meta-study (GEA, 2010; IEA, 2010; Bertani, 2009a, 2009b, 2010; Brooks and Bala, 2010; Chandrasekharam, 2000; DECC, 2006; DLR, 2005, 2006; EBRD, 2009; Eliasson, 2008; Energy and Mineral Resources Ministry, 2010; IEA, 2006, 2011; Green and Nix, 2006; Goldstein et al., 2011; Jelić et al., 2000; Joseph, 2008; Krewitt et al., 2009; RECIPES, 2006; Richter, 2011; Sarmiento and Steingrimsson, 2007; Simsek et al., 2005; Teklemariam, 2006; Tester et al., 2006; USGS, 2008).

We mapped the reported potentials at the most detailed geographic level reported to a common nomenclature as shown in Table 7, where we differentiate currently used conventional technology and enhanced geothermal systems which allow electricity production from a wider range of geographies.

In case of inconsistencies between sources, the larger number was reported. In addition, if potential was reported in periods, but not in others, we extrapolated values, where possible, for the missing periods based on the available data. For EGS, which is less location-dependent, potentials were estimated for countries without data based on other countries.

It must be noted that the range of values reported in the literature was very large and the extrapolations above were primarily designed to yield a gap-free regional data set. We acknowledge that a meta-study such as this is necessarily simplistic and yields results with very large uncertainties. The full range of resulting estimates is shown in Section 3.

3. Results

3.1. Large global potential even under strict constraints

We assessed the renewable electricity potential for the most common solar and wind technologies (on- and offshore wind,

Table 7
Category mapping for geothermal literature survey.

Categories in this study	Categories from other studies grouped in this definition
2010	Actual production reported from GEA (2010) and IEA ETSAP (2010)
2030	'Short-term (economic)' potential if reported
2070	'Long-term (economic)' potential if reported
Conventional vs. EGS	If explicitly stated
All technologies	If no technology stated explicitly

concentrated solar power (CSP) and solar photovoltaics (PV) on land and on buildings).

We find that of the total 146×10^6 km^2 of (non-ice covered) land, less than 5×10^6 km^2, or 3.5%, are deemed available for energy harvesting after exclusions due to elevation, land cover/use, slope, ecosystem protection, resource intensity and the additional availability factor. This stands in contrast to current (2008) total urban land area of ~0.18%, and total cropland of 11% (FAO, 2013).

Offshore, less than 10×10^6 km^2, or ~2.2% of the 361×10^6 km^2, remain due to limitations based on sea ice, distance to shore, depth, competitive uses, jurisdiction, protection, resource intensity and the additional availability factor. The area exclusions are visualised in Fig. 2.

For buildings we find a total of 62×10^3 km^2 of total current (2010) suitable area for PV, including roofs and façades, rising to 169×10^3 km^2 by 2070. This represents around 20% (2010) to 30% (2070) of our estimated total roof and façade space.

All results for suitable and available area on land and sea are shown in Table 8.

As expected, on land the assumptions on *availability* have a larger impact on the final available area than the assumptions on *suitability*, i.e. the availability factor carries the greatest uncertainty affecting the results. It depends crucially on future societies' attitudes towards devoting land and sea use to renewable energy, and economic competition with other uses. We have tried to estimate realistic availability factors which capture restrictions on

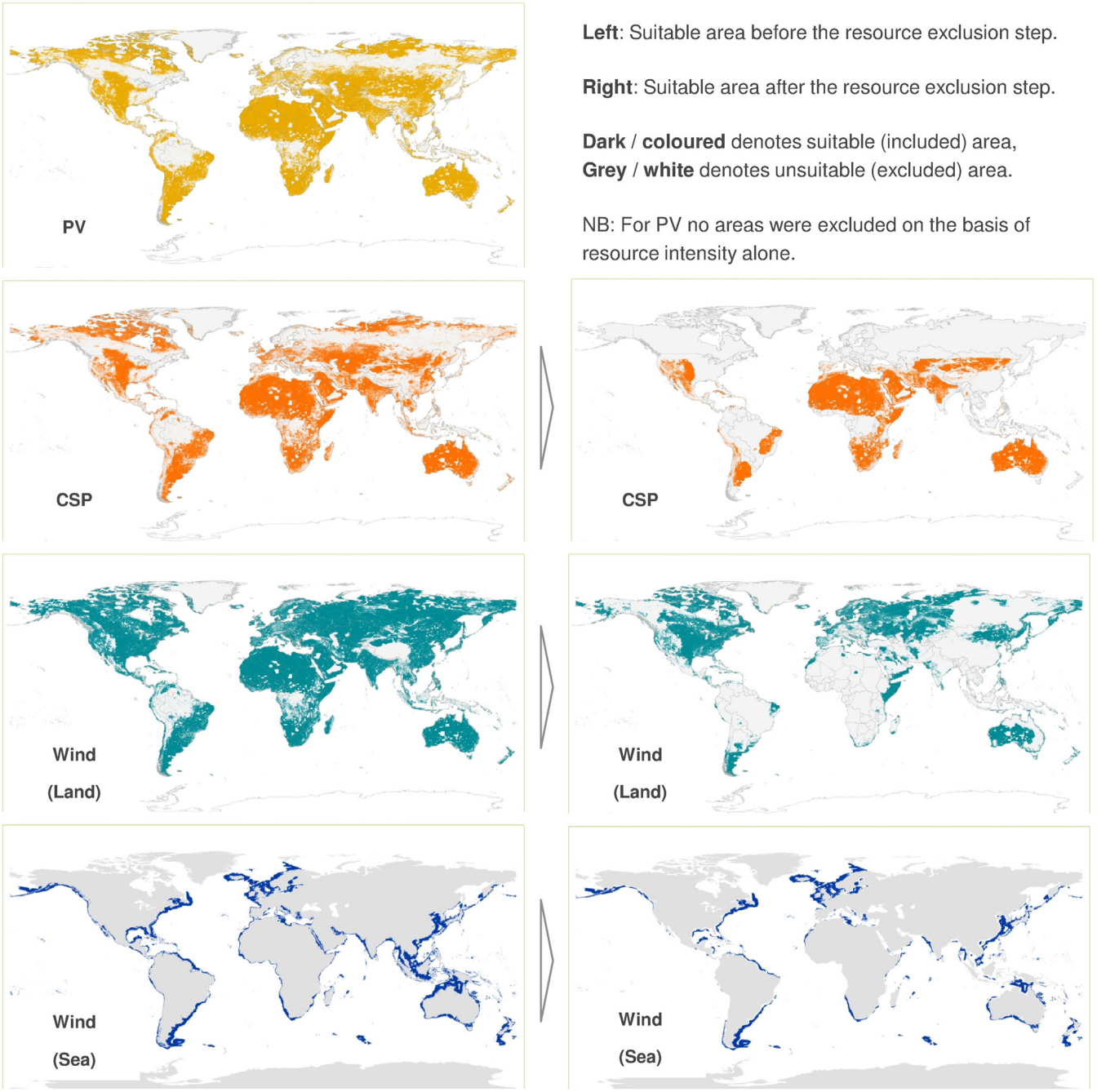

Fig. 2. Suitable area by technology. The suitable area on land and sea is found by successive exclusions for technical and economic reasons, using the resource intensity as a marker for economic viability. The figure shows available area before (left) and after (right) the resource exclusion step. From top to bottom: PV on land, CSP on land, Wind on land, Wind on sea. Dark/coloured denotes suitable area, grey/white denotes excluded area.

Table 8
Suitable/available area for electricity generation by technology.

Area (million km^2)	Period	Building-integrated		Land-based			Off-shore
		PV on roofs	PV on facades	PV on land	CSP on land	Wind on land	Wind on sea
Methodology		Country level		GIS level			
Total (excl. Antarctica)	2010	0.13	0.19	146 (134)			361; EEZ:148 (140)
	2030	0.17	0.25				
	2070	0.21	0.33				
Suitable area (before resource cut-off)	All	n/a	n/a	81	65	97	21
Suitable area	2010	0.04	0.02	n/a	41	35	13
	2030	0.06	0.02			37	13
	2070	0.07	0.10			37	13
Available area	All	n/a	n/a	0.6–5.0	0.4–3.1	0.5–3.9	2.4–8.1
… % of suitable area	All	n/a	n/a	0.7%–6.2%	0.9%–7.5%	1.4%–10.4%	18.8%–62.2%
… % of total area	All	33%	10%–30%	0.4%–3.4%	0.3%–2.1%	0.3%–2.6%	0.7%–2.2%

PV: photovoltaic; CSP: concentrated solar power; EEZ: Economic Exclusion Zones, i.e. zone denoting areas of the ocean attributable to a country.

land use beyond technical limitations or economic attractiveness. Based, where possible, on an assessment of the difference between existing and maximum penetration levels, we developed cases covering a range of values (denoted Low, Medium, High), from 0.1% for PV on available agricultural land to 80% for offshore wind far from the coast (see Table 2). For comparison, if the ~33 GW of PV installed in Germany today was entirely from solar farms it would cover around 0.64% of the suitable country area (or 0.31% of total land area).

After establishing the area available for energy harvesting, the resource intensity incident upon this area was calculated and converted into final useful electric energy. We used conversion factors which account for expected technological progress. The largest improvements are expected in solar PV technologies, and we have assumed a module efficiency which increases from around 16% today to 35% by 2070 with additional increases in the net conversion efficiency from increasing packing densities on the ground. Note that even this doubling of efficiency for PV has only a moderate impact on the final results: the largest uncertainty stems from the availability factor which spans a range of up to a factor 20 for some land types. In wind and CSP the gains are expected to be smaller (see also the approach to availability factors in Section 2 and the Supplementary Information).

The total long-term potential for renewable electricity onshore, offshore and on buildings is calculated to be between 730–3700 EJ/a depending on the availability case. An estimated additional potential of 50–110 EJ/a could be contributed from geothermal and hydroelectricity. The latter two technologies were assessed through a meta-study with additional extrapolations. Table 9 summarises the results for potentials and shows a comparison with previous studies.

Ranges indicate: range found in literature for literature studies (Edenhofer et al., 2011; de Vries et al., 2007); and cases for all other results.

We find global *single technology* potentials are largest for the land-based solar resources (ground-based PV and CSP), ranging between 130 EJ/a and 2800 EJ/a in 2070. The *total* land-based potential is estimated at 320–2800 EJ/a. Note that the potentials are not additive across technologies as they can originate from the same area. Our GIS-based approach allows an assessment of this overlap when reporting *total potential*. We have chosen the potential in a given grid cell to be that of the single technology with the largest potential in that grid cell.[3] In practice some of this potential could be additive locally, i.e. solitary wind turbines could co-exist with PV installations meaning our approach may lead to a slight underestimate of the total cross-technology potential.

Note also that we have used fixed land-use through time. Expansion of cropland, whether for food or biomass energy use, could overlap with long-term PV and CSP potentials. However, at an aggregate level, the overlap is likely to be small, and, in our view, the availability factors should easily accommodate it. The land type which is most likely to be affected is 'grassland'; the potential on this land type represents around 4–8% of the total PV and CSP potential.

Fig. 3 shows the results in graphical form, for the single technologies as well as the total potential, accounting for overlaps. The main driver behind the increase in the PV potentials for both, buildings and on land, is the increase in net conversion efficiency. A further important factor in both cases is the increase in area used for PV. The available roof and façade area is expected to grow substantially with population and housing growth, while on land, we assume a rising ground coverage level.

Global electricity demand (65 EJ/a in 2010) may increase by a factor 2–5 by 2050, as a result of increased per capita energy use in developing regions and an increased shift from fuel to electricity (IEA, 2012a; GEA, 2012; Lund and Mathiesen, 2009; Deng et al., 2012; Shell, 2013). To illustrate this, Fig. 3 also shows a range of future electricity demand estimates for comparison with our 2070 potential estimates. These demand estimates are based on a long-term global population of 10 billion (reached in the 2080s in the UN mid-case projections (United Nations, 2011) and a range of per-capita electricity demand projections of 24–40 GJ/cap/a (IEA, 2012a; GEA, 2012; Deng et al., 2012; Shell, 2013). These per-capita demand projections include transmission and distribution losses and are driven by an increasing demand for energy services (primarily in developing regions) and continuing electrification of demand, and are only partially offset by energy efficiency even in high efficiency projections. For comparison, current levels in developed regions are around 30 GJ/cap/a. At a world level, this increased demand would not exceed the global resource base, even in the Low case. However, country or regional constraints may occur within this.

4. Discussion

4.1. Comparison with other studies

As shown in Fig. 4, our results fall within the ranges of (constrained) technical potential reported in the meta-analysis for individual technologies of the IPCC's Special Report on Renewables

[3] The total potential on land was calculated by summing the potential of the best technology on those available areas where more than one technology was suitable. If the lowest yielding technology is used instead, then the total land potential figure in the Low case changes from 320 EJ/a to 199 EJ/a, and the total solar and wind potential from 728 EJ/a to 606 EJ/a.

Table 9
Potential for electricity generation by technology and period.

Potential (EJ/a)	Period	Buildings		On-shore			Off-shore	Country meta-study	
		PV on roofs	PV on facades	PV	CSP	Wind on land	Wind on sea	Geoth. elec.	Hydro
Single technology	2010	31	7	90–804	98–808	25–170	189–624	1	12
	2030	64	15	166–1,480	118–970	27–185	197–652	3–8	16
	2070	121	90	316–2,815	131–1,078	27–185	197–652	27–84	26
Total potential on land (all technologies), accounting for overlaps	2010	n/a	n/a		132–1,112		n/a	n/a	n/a
	2030				172–1,497				
	2070				320–2,832				
Potential ranges from literature	Technical (constrained) potential	n/a	n/a	1340–14,780	250–10,790	350–1800 (70–220) All wind: 1000–3050 (140–450)	n/a	118–1109	53

(Edenhofer et al., 2011). Where our results are smaller than the SRREN maximum potentials ranges (i.e. for PV and CSP), this is primarily due to our stricter constraints on land availability. The only exception is off-shore wind where we find a much *larger* potential than SRREN. 85% of our potential is found at depths over 200 m. This goes beyond the typical depths used today (~40 m) and the majority of the studies surveyed in the IPCC's report.

4.2. Additional on-shore wind potential locally

There is uncertainty over where to place the threshold for excluding areas based on available wind resource. This is due to the wide range of local wind speeds local orography can result in but also the uncertainty in some geographies of our wind speed data set (which nevertheless has a higher resolution than that used in several previous global studies). Because our motivation was to find reliable potential estimates, we have used a value for the threshold which is at the lower end of current practice (~6 m/s at hub height), meaning we may have excluded areas which may have local potential. In addition, in the time horizon used in this study, more areas with even lower average annual speeds are likely to become attractive for developers, as various constraints force projects into less resource rich locations.

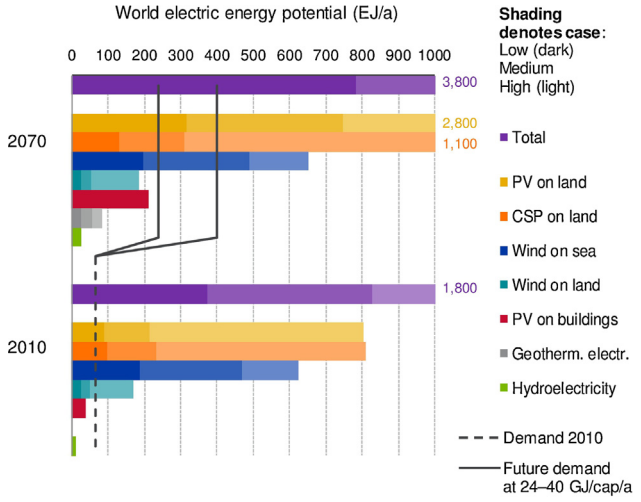

Fig. 3. Global potential results. Annual achievable electricity potential is shown by technology for 2010 and 2070. Shading within each technology shows the Low, Medium and High availability cases. The lines show indicative estimates of future demand for a global population of 10 billion (IEA, 2012a; GEA, 2012; Lund and Mathiesen, 2009; Deng et al., 2012; Shell, 2013).

It should also be noted here that our assumption on the power density for wind of 7 MW/km^2, while in line with current practice and previous studies, has been called into question recently, for wind farm installations spanning hundreds of square kilometres (Adams and Keith, 2013) due to turbine interference beyond the level we have assumed here. In such very large single farms, achievable power densities as low as 1 MW/km^2 have been suggested. Our availability assumptions on land imply a small likelihood of a necessity for very large single wind farms.

For offshore wind, our results are slightly larger than comparable studies (EEA, 2009; Schwartz et al., 2010). This is primarily due to the limits other studies place on ocean floor depth, usually around 50–200 m maximum: the current predominant off-shore wind technology requires anchoring on the ocean floor. However, innovative technologies, such as floating turbines or similar, have the potential to extend our reach and we have included areas as deep as 1000 m to reflect this potential. This highest depth class represents around 160–550 EJ/a, equivalent to ~85% of the total offshore wind potential in all cases.

4.3. Buildings could host over a third of PV potential

For building-based PV, the approach in this study is broadly consistent with other studies. Based on floor area, an estimate of sun-facing roof and façade area is obtained, followed by a suitability factor. For the resulting available area the annual irradiation is multiplied by the system efficiency of the solar panel which results in the net potential. We find a potential of 210 EJ/a in 2070, compared with 38 EJ/a in the base year (2010).

There are few global studies with similarly detailed approaches to compare to. Compared to other national studies the 2010 potentials we find are generally larger. For example, a study for PV on roofs in the United States reported 2.9 EJ/a (Denholm and Margolis, 2008) while this study reports 4.6 EJ/a and a study for China found 1.9 EJ/a (Zhou et al., 2009) while we report 5.2 EJ/a. Assumptions are often not clearly stated, but the differences are likely due to the exclusion of rural roof areas or different available area and suitability factor estimates.

When comparing our potential estimates for PV on buildings with the low end of the range of our estimates for PV potential on land, we find that buildings could contribute as much as a third of PV potential and could thus make a meaningful contribution to solar renewable electricity provision. This could warrant focussing support policies in this area, especially considering that building-based PV does not require additional land, is already cost-competitive with conventional sources in some regions and has the potential to alleviate system costs by reducing peak electricity demand.

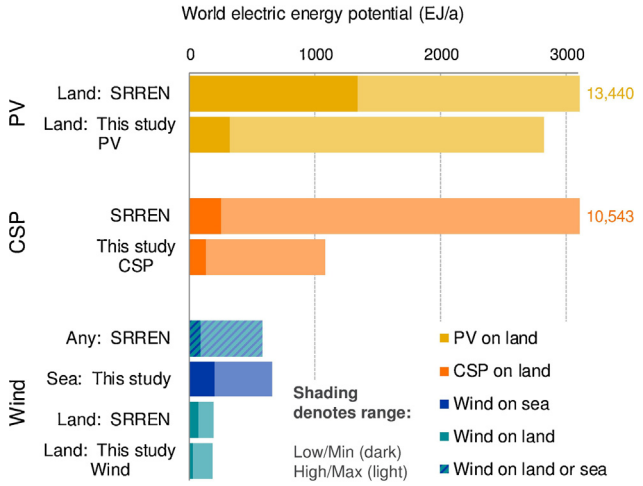

Fig. 4. Comparison of the results in this study with ranges for renewable potentials published in literature, based on the IPCC SRREN report (Edenhofer et al., 2011).

4.4. Local shortages within a vast global potential

The global resource potential is very large, but the regional picture is more varied with some regions of high abundance (e.g. North Africa and the Americas) and others *potentially* constrained (e.g. Europe and parts of Asia). Fig. 5 shows results for all technologies for 12 world regions in 2070.

As expected, the balance between wind and solar resources depends heavily on the region, with African regions clearly dominating in the 'solar-rich' group.

Comparing the potentials to the population per region confirms the large variability: the PV potential per capita is highest in Oceania at ~2500 GJ/cap/a (large solar resource, sparse population) and lowest in the EU at ~40 GJ/cap/a (dense population with comparatively little solar resource).

Fig. 5 also shows a range of prospective long-term electricity *demand* for each region, again based on a long-term global population of 10 billion, expected for the 2080s (United Nations, 2011), and a range of per-capita electricity demand projections of 24–40 GJ/cap/a (see above for explanation on these projections).

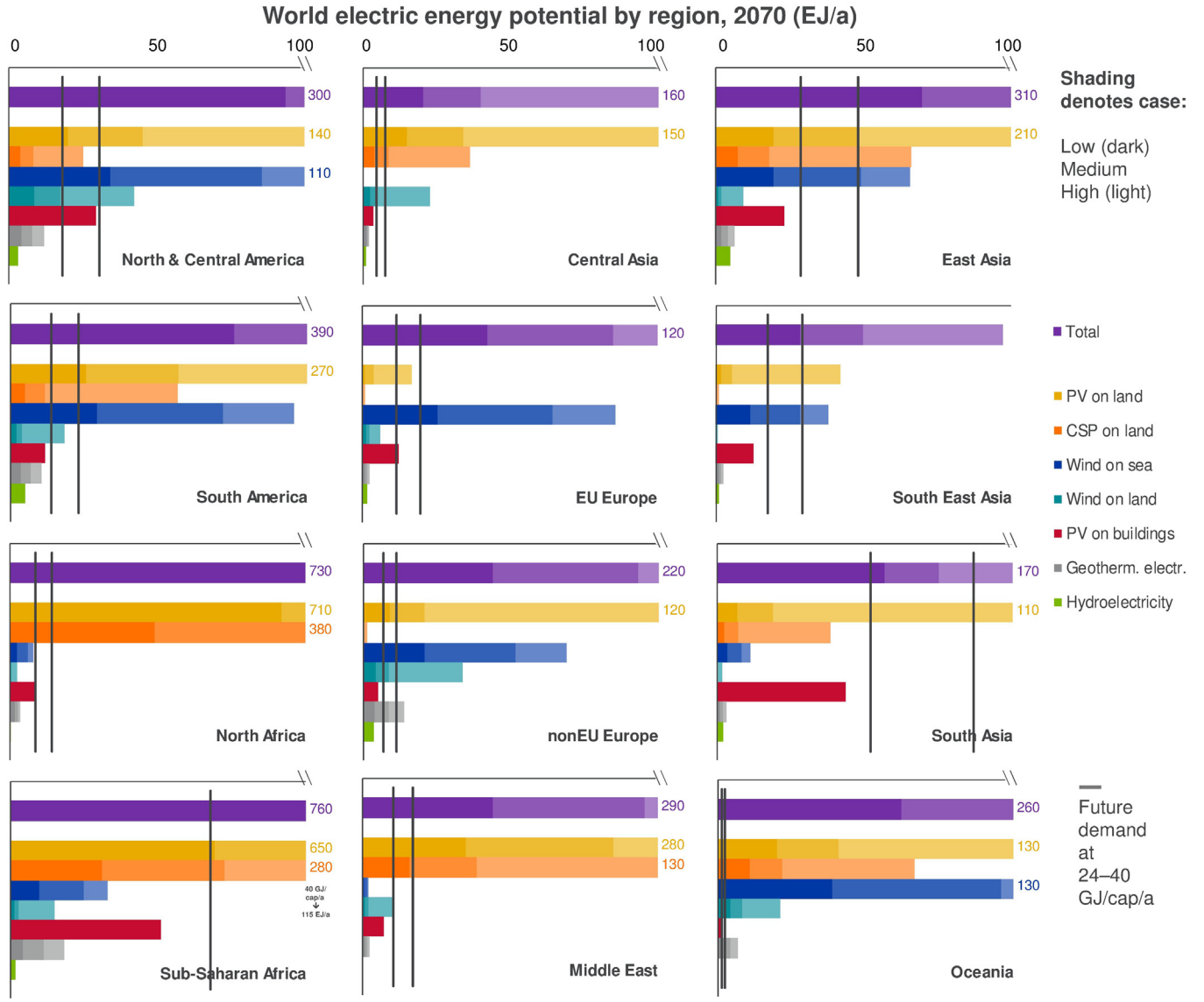

Fig. 5. Regional potential results. Annual achievable electricity potential is shown by technology for 2070 for 12 world regions. The lines show indicative estimates of future demand for a global population of 10 billion. Shading within each technology shows the Low, Medium and High availability cases.

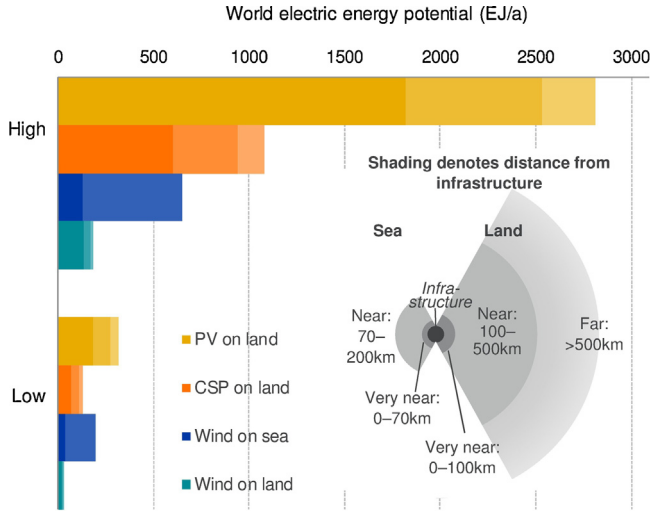

Fig. 6. Potential results by distance. Annual achievable electricity potential on land is shown for 2070, differentiated by distance from infrastructure and per resource type. Top: High availability case, bottom: Low availability case.

Combining resources on land, sea and buildings yields renewable electricity potentials which outstrip the prospective long-term regional demand for almost all regions. The exception is South Asia, where the Medium availability case may not provide sufficient electricity if the higher demand projections transpire.

The picture looks even less uniform at individual country level: Brazil and Egypt have the prospect of being self-sufficient even with high demand, based on solar and wind electricity alone. In contrast, India and Nigeria would not necessarily be able to satisfy demand from national sources alone at 24–40 GJ/cap/a, except in the High availability case: Nigeria's long-term resource base is 16–52 GJ/cap/a, although intra-regional trade within West Africa could satisfy regional demand in the Medium case. India's long-term potential is 23–66 GJ/cap/a but it lies within a similarly constrained region. As such, India and its region will need to unlock the potentials in the High availability case or supplement supply with other energy options or long-distance transport of renewable electricity. These constraints are not imminent however: electricity demand today is only 2.1 GJ/cap/a in India and 0.5 GJ/cap/a in Nigeria.

Based on these demand assumptions, between 60% and 90% of the world's population in the 2080s will live in countries which could be self-sufficient in the Medium case, depending on the demand per capita. The remaining 10–40% would need to mobilise potentials found in the High availability case, import electricity from neighbouring countries or use different sources of electricity.

4.5. How far do we have to transport this electricity?

We addressed the question of usability of renewable potential in remote locations by differentiating potentials based on their distance from "infrastructure", which we use as a marker for the distance from an electricity grid. We defined the existence of this marker infrastructure based on datasets of population density, railways, and urban land cover. The results are shown in Fig. 6 for the Low and High cases for 2070.

On land, between one to two thirds of the potential are situated in the most accessible distance ranges. The much larger potential offshore is primarily concentrated in higher distance categories, consistent with the very restrictive availability factors we have used near-shore.

5. Conclusion

We have presented a bottom-up assessment of renewable electricity potentials for five technologies: PV on buildings and on land, CSP, wind on land and on sea. The study builds on high resolution publicly available geographic datasets and presents aggregated results at regional level. Global totals fall within the ranges found in the existing literature.

The debate about electricity potentials is often dominated by the expected development of the conversion technology. Our study confirms, however, that it is more important to carefully assess the overall availability of *surface area*, as this carries the largest uncertainty. Within the assessment of the land area we have taken care to try and estimate a feasible availability factor and show the influence that variations in this availability factor have on the final results. In establishing the availability factor, we have tried to use countries with high technology penetration as a guide. For wind power, for example, current (end of 2011) installed capacities imply land penetration across all land types of around 1% of suitable area. Given that deployment still continues in these countries, but current societal debate suggests that it is reaching local thresholds in some regions, we have estimated the long-term availability factors for wind to be around 5–6% for our Medium case.

To enable interpretation of our findings, we have also shown comparison of our long-term (2070) estimates with prospective future demand. We show that even our lowest estimates would provide (just) enough renewable electricity for a population of 10 billion, expected for the early 2080s, if the total achievable potential could be mobilised at global level. When focusing on individual regions and countries, differences emerge: some regions could easily satisfy current and future demand whereas others may run into supply shortages in the Low availability cases, especially where the distance to infrastructure may be problematic.

Whether all of this potential could be deployed requires an energy system scenario calculation which also addresses issues around system integration of various sources and their interaction with demand patterns which have not been addressed explicitly in this study. However, focusing simply on the resource potential does define the range of possibilities for the future. While there is scope for substantial renewables growth from today's levels, in the long run the large global potentials may contain within them constraints in specific countries or regions. These findings may guide society in formulating long-term visions for energy systems as a basis for energy policy in the decades to come.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2015.01.005.

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