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Renewable energy potential model – Manual (Solar, Wind) version of 2012/01/16

1 General description of the model

This document explains the features of a model for quantitative assessment of the technical potential of renewable energy using geo-referenced data. The model, developed by Ikegami [1] and applied by Kayo et al. [2], estimates the technical potential at global scale of solar and wind energy for electricity generation using photovoltaic (PV) panels and wind turbines onshore, respectively. Currently, a module for estimating the potential of biomass for energy purposes is being developed.

The definition of technical potential considered for the construction of the model refers to the amount of a given resource that can be harnessed for energy purposes considering technical constraints. In particular, these constraints refer to a maximum slope and altitude where the renewable resource can be harnessed, to restrictions in land use which vary according to the type of land cover, to the occurrence of areas protected for nature conservation reasons or areas difficult to access (referred to a as wilderness areas in the model). In addition, restrictions that are specific to each type of resource are considered; for example, shadowing between solar panels, and resource collection and production rates for the case of biomass. Other restrictions, such as those related to economic, social and political aspects, are out of the scope of the assessment.

2 Model outputs

The model outputs include the resource area, the resource potential, the energy potential, and the costs. The method is based on geo-referenced data describing the availability of each renewable resource and the technical constraints mentioned above. Calculations are performed for grid cells with a 30 seconds resolution. Outcomes are displayed grouping results by country, land cover type and into several grades. Each grade indicates a range where energy potential values fall; grading for solar and wind potentials are indicated in detail in the sections below. 17 land cover types are considered (see annex).

3 Solar energy potential estimation

PV panels of one (1) meter square length and 14% conversion efficiency are considered. Feasibility is limited to altitudes up to 2000 meters above sea level and ground slope up to 60% inclination angle. Primary data on solar resource refer to monthly average solar insolation on horizontal surface, from the Surface meteorology and Solar Energy (SSE) provided by NASA [3], with resolution of one degree.

Table 1 Types and grouping of model outputs

Output	Solar	Wind
Energy potential	Grid cell Country Grading Land cover	Grid cell Country Grading Land cover
Resource potential	Country Grading Land cover	Country Grading Land cover
Number of conversion units (wind turbines)	-	Country Grading Land cover
Area	Country Grading Land cover	Country Grading Land cover
Total annual cost	Country Grading Land cover	Country Grading Land cover
Unit cost	Country Grading Land cover	Country Grading Land cover

3.1 Solar energy potential

The solar energy potential (*SolarPVPot*) for each grid cell is calculated using the following equation:

$$SolarPVPot = A_G \cdot r_{LC} \cdot \frac{\eta}{Interval} \cdot IAInsoY$$

A_G: grid cell area [m^2]

r_{LC}: suitability factor by land cover [-]

η: PV module conversion efficiency [-]

Interval: factor accounting for spacing between PV panels to prevent shadowing [-]

IAInsoY: annual insolation on inclinated surface [$kWh/m^2/yr$]

Annual insolation is estimated based on the monthly insolation data, the optimal inclination angle of PV panels, the landscape elevation angle, and the shadowing between panels. Interval is set equal to the largest length of the shadow projected by panels. Detailed equations are presented in the annexes.

3.2 Solar PV area

$$A_{PV} = \frac{A_G \cdot r_{LC}}{Interval}$$

A_{PV}: area occupied by PV panels [m^2]

3.3 Solar PV total annual cost and unit cost

Capital cost of PV panels is set to 560 USD/m^2. Operation and maintenance costs are assumed as a fraction of investment costs equivalent to 3%. Discounting assumes a lifetime of 25 years and a discount rate of 5%.

$$CostTotal_{PV} = C_{Cap} \cdot A_{PV} \cdot CRF \cdot (1 + \alpha_{OM})$$

$$UnitCost_{PV} = \frac{CostTotal_{PV}}{SolarPVPot}$$

$CostTotal_{PV}$: total annual cost of PV electricity [USD]
$UnitCost_{PV}$: unit cost of PV electricity [USD/kWh]
C_{Cap}: capital cost of PV panels [USD/kW]
CRF: capital recovery factor (or annuity factor) [-]

3.4 Grading of solar potential results

Results have been grouped into 25 different grades according to the amount of solar resource in kWh/m^2/yr; values range from 0 to 2400 kWh/m^2/yr and values over 2400 kWh/m^2/yr, with increments of 100 kWh/m^2/yr.

Table 2 Grading of solar potential

Grade	Solar insolation (kWh/m^2/yr)	Grade	Solar insolation (kWh/m^2/yr)
1	0 - 100	14	1,300 – 1,400
2	100 – 200	15	1,400 – 1,500
3	200 – 300	16	1,500 – 1,600
4	300 – 400	17	1,600 – 1,700
5	400 – 500	18	1,700 – 1,800
6	500 – 600	19	1,800 – 1,900
7	600 – 700	20	1,900 – 2,000
8	700 – 800	21	2,000 – 2,100
9	800 – 900	22	2,100 – 2,200
10	900 – 1,000	23	2,200 - -2,300
11	1,000 – 1,100	24	2,300 – 2,400
12	1,100 – 1,200	25	> 2,400
13	1,200 – 1,300		

4 Wind energy potential estimation

Wind turbines considered have a rated power output of 2,000 kW, hub height of 80 meters, rotor diameter of 90 meters. Feasibility is limited to altitudes up to 2000 meters above sea level and ground slope up to 30% inclination angle. The potential of wind energy for electricity generation with wind turbines is estimated using data on average monthly wind speed at 50 meters above ground, with a resolution of one degree, from the Surface meteorology and Solar Energy (SSE) [4]. Data are corrected for hub height of 80 meters using the wind shear exponential formula. Offshore wind power is not included in the estimation.

4.1 Wind energy potential

Wind energy potential for each grid cell is calculated using the following formula.

$$WindPot = A_G \cdot r_{LC} \cdot \frac{P_{Turbine}}{A_{Turbine}} \cdot FullLoadH$$

A_G: grid cell area [m^2]
r_{LC}: suitability factor by land cover [-]
$P_{Turbine}$: rated power output of wind turbine [kW]
$A_{Turbine}$: required area for one wind turbine [m^2]
FullLoadH: operation hours at full load capacity [h]

The full load time is estimated considering a Rayleigh distribution function dependent on the turbine electricity output. This output is calculated using the power curve. In addition, losses in harnessing wind energy due to land roughness and land cover type are accounted for. A correction factor of 20% for other losses is also included.

4.2 Onshore wind area

$$A_{Wind} = A_G \cdot r_{LC}$$

A_{Wind} : area occupied by wind turbines

4.3 Number of wind turbines

$$N_{Turbine} = \frac{A_G \cdot r_{LC}}{A_{Turbine}}$$

4.4 Wind power total annual cost and unit cost

Capital cost of wind turbines per electricity output is set to 2,000 USD/kW. Operation and maintenance costs are assumed as a fraction of investment costs equivalent to 3%. Discounting is performed using a lifetime of 25 years and a discount rate of 5%.

$$CostTotal_{Wind} = C_{Cap} \cdot P_{Turbine} \cdot N_{Turbine} \cdot CRF \cdot (1+\alpha_{OM})$$

$$UnitCost_{Wind} = \frac{CostTotal_{Wind}}{WindPot}$$

$CostTotal_{WInd}$: total annual cost of wind electricity [USD]

$UnitCost_{Wind}$: unit cost of wind electricity [USD/kWh]

C_{Cap}: capital cost of wind turbines [USD/kW]

CRF: capital recovery factor (or annuity factor) [-]

4.5 Grading of wind potential results

Results have been grouped into 10 different grades according to the amount of wind resource measured as the percentage of the full load hours (*FullLoalH*), ranging from 0% to 100% with intervals of 10% increments.

Table 3 Grading of wind energy potential

Grade	Full load fraction (%)
1	0 – 10
2	10 – 20
3	20 – 30
4	30 – 40
5	40 – 50
6	50 – 60
7	60 – 70
8	70 – 80
9	80 – 90
10	90 – 100

5 Future tasks

- Introduce biomass potential calculations using land cover data.
- Collect data for estimation of biomass potential.
- Formulate methodology for estimation of biomass potential from resources derived of agricultural activities.

6 Annexes

6.1 Land cover data

Land cover includes 17 types following the classification of MODIS/Terra released by the U.S. Geological Service [5].

Table 4 Land cover types [5]

Land cover	Class
Evergreen Needleleaf Forest	1
Evergreen Broadleaf Forest	2
Deciduous Needleleaf Forest	3
Deciduous Broadleaf Forest	4
Mixed Forest	5
Closed Shrublands	6
Open Shrublands	7
Woody Savannas	8
Savannas	9
Grasslands	10
Permanent Wetlands	11
Croplands	12
Urban and Built-Up	13
Cropland/Natural Vegetation Mosaic	14
Snow and Ice	15
Barren or Sparsely Vegetated	16
Water Bodies	17

Table 5 Land suitability factor and land roughness factor

Land cover type	Class	Land suitability factor [%]		Roughness factor [%]
		Solar	Wind	
Closed shrublands, Woody savannas	6, 8	1	0	90
Open shrublands, Savannas, Grasslands	7,9,10	1	50	95
Croplands, Cropland/Natural vegetation mosaic	12,14	1	30	90
Barren or sparsely vegetated	16	1	50	90
Urban and built-up	13	1	0	90
All forests, Permanent wetlands, Snow and ice, Water bodies	1-5,11,15,17	0	0	90

6.2 Other equations solar energy potential

a. Annual insolation on inclinated surface (*IAInsoY*), [kWh/m^2/yr]

$$IAInsoY = \sum_{M,T} IAInsoH_{M,T} \cdot Days_M$$

Days: days per month (28, 30 or 31)

IAInsoH: insolation on inclinated surface

b. Insolation on inclinated surface (*IAInsoH*), [kWh/m^2]

$$IAInsoH_{M,T} = \begin{cases} InsoH_{M,T} \cdot ShadowL_{M,T} & \left(ShadowL_{M,T} \geq 0\right) \\ 0 & \left(ShadowL_{M,T} < 0\right) \end{cases}$$

ShadowL: length of shadow projected by solar PV panel in North-South direction

InsoH: insolation on horizontal surface

c. Length of shadow projected by solar PV panel in North-South direction (*ShadowL*), [m]

$$ShadowL_{M,T} = \cos\theta - \frac{\cos Az_{M,T}}{\tan El_{M,T}} \cdot \sin\theta$$

θ: inclination angle of PV panel with respect to North-South direction (optimal inclination angle).

Az: solar azimuth angle [rad]

El: solar elevation angle [rad]

d. Insolation on horizontal surface (*InsoH*) , [kW/m^2]

$$InsoH_{M,T} = \frac{\sin El_{M,T}}{TotSin_M} \cdot InsoD_M$$

$$TotSin_M = \sum_{T}^{(El>0)} \sin El_{M,T}$$

El: solar elevation angle [rad]

InsoD: insolation on horizontal surface [kWh/m^2/day]

e. Solar azimuth angle (*Az*), [rad]

$$AZ = \arctan 2\left(\frac{-\cos\delta \cdot \sin h}{\cos El}, \frac{\sin\delta \cdot \cos\psi - \cos\delta \cdot \sin\psi \cdot \cos h}{\cos El} \right)$$

El: solar elevation angle [rad]

ψ: latitude [rad]

δ: declination [rad]

h: hour angle [rad]

f. Solar elevation angle (*El*), [rad]

$$El = \arcsin(\sin\psi \cdot \sin\delta + \cos\psi \cdot \cos\delta \cdot \cos h)$$

ψ: latitude [rad]

δ: declination [rad]

h: hour angle [rad]

g. Hour angle (*h*), [rad]

$$h = \frac{\pi}{12} \cdot (T - 12)$$

T: hour of the day

h. Delta

$$\begin{aligned}\delta = 0.0064979 + 0.4059059 \cdot \sin\omega + 0.0020054 \cdot \sin 2\omega - 0.0029880 \cdot \sin 3\omega \\ - 0.0132296 \cdot \cos\omega + 0.0063809 \cdot \cos 2\omega + 0.0003508 \cdot \cos 3\omega\end{aligned}$$

i. Omega

$$\omega = \frac{2\pi}{365.2422}\left(N - 0.5 - \frac{\lambda}{2\pi} - N_0 \right)$$

λ: longitude [rad]

N: number of days between January 1st and day of calculation (Table 3 on pg. 15 of documentation).

No: number of days between January 1st and spring equinox

j. Number of days between January 1st and spring equinox (*No*)

$$N_0 = 78.8946 + 0.2422 \cdot (yr - 1957) - INT[0.25 \cdot (yr - 1957)]$$

yr: year of calculation in A.D. system (set as 2005)

k. Landscape elevation angle (*LSA*)

$$\tan LSA = \frac{Elv(\mathrm{A}) - Elv(\mathrm{T})}{Distance\,(\mathrm{A},\mathrm{T})}$$

T: target grid cell

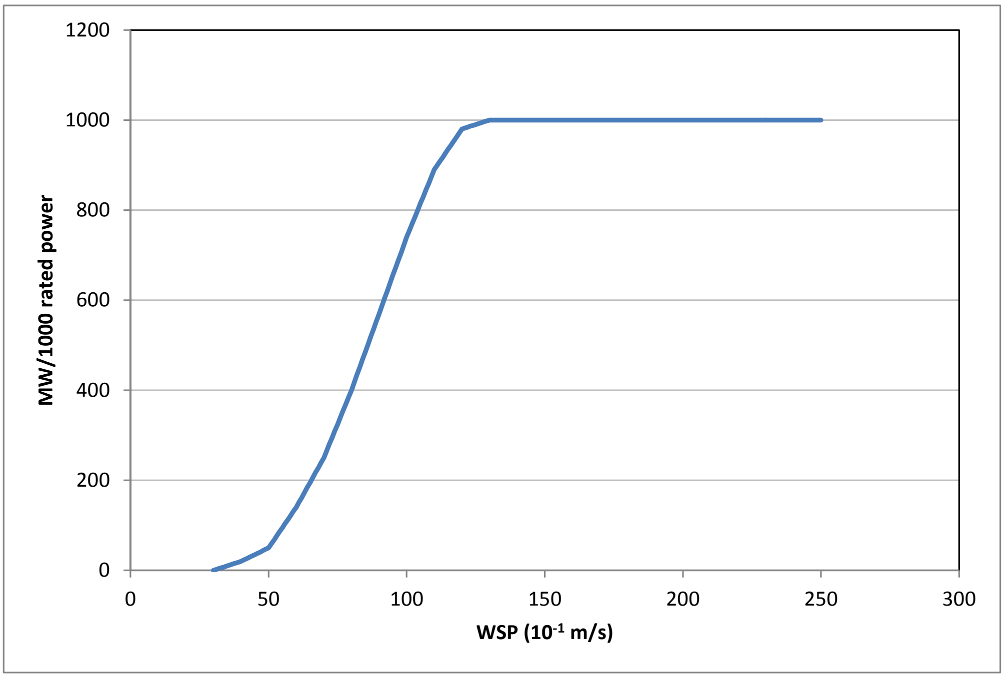
A: any grid cell within 30 km distance to target cell (T)

Elv: elevation at a certain grid cell

Distance: center-to-center distance between a pair of grid cells [km]

6.3 Other equations wind energy potential

Operation of wind turbine is set to wind speeds in the range of 3 and 25 m/s, considering a fixed wind maximum output above 12 m/s. The figure below represents the power curve for transforming wind speeds to equivalent power output units.



a. Area required by wind turbines ($A_{Turbine}$) [m^2]

The area required for each wind turbine ($A_{Turbine}$) assumes a distance between turbines equivalent to 10 times the rotor diameter. The formula is as follows.

$$A_{Turbine} = \frac{121\sqrt{3}}{2} D^2$$

D: rotor diameter [m]

b. wind shear exponential formula.

$$v_1 = v_2 \left(\frac{h_1}{h_2} \right)^{\alpha}$$

v_x: wind speed at x meters height from ground [m/s]

h: hub height of wind turbine [m]

α: wind shear factor [-]

6.4 Capital recovery factor (CRF)

$$\mathrm{CRF} = \frac{r(1+r)^t}{(1+r)^t - 1}$$

t: Lifetime of wind turbines [years]

r: Discount rate [-]

6.5 Information on other input data

a. Elevation: land altitude and oceans depth; resolution of 30 seconds [6, 7, 8].
b. Slope: meters of change in vertical direction per 100 meters; resolution of 30 seconds [9].
c. Wilderness areas: areas away from human activities (6km away from roads and settlements, larger than 400,000 ha); data with 30 seconds resolution, based on Sierra Group and World Bank information published by UNEP [10].
d. Country data: codes and list of countries (244).

7 References

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[7] Hastings, D. A. and Dunbar, P. K., 1999: Global Land One-km Base Elevation (GLOBE) Digital Elevation Model Documentation, Boulder, Colorado, NOAA National Geophysical Data Center, Publication KGRD 34.

[8] GEBCO One Minute Grid - Version 1.02, 2006: General Bathymetric Chart of Oceans (GEBCO). (http://www.gebco.net/data_and_products/gridded_bathymetry_data/)

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