SOLAR ELECTRICITY PRODUCTION FROM FIXED-INCLINED AND SUN-TRACKING C-SI PHOTOVOLTAIC MODULES IN SOUTH AFRICA

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Abstract

We present a method for estimating the energy output from fixed-mounted and sun-axis tracking flat-plate PV systems and compare the yields from different configurations. The method is based on the use of solar radiation and temperature time series representing a historical record of 18 years (1994 to 2011) and PV simulation models for the performance of PV modules assuming different geographic conditions. The data and tools are integrated into SolarGIS online system.

It is found that geographical conditions of South Africa are to be considered when deciding about a particular mounting strategy. One axis tracker with vertical axis inclined 30 degrees North typically gains from 15% up to 35% more electricity, compared to fixed mounting at optimum tilt. Two-axis tracker most typically yields between 20% and 40% more electricity. Yields of two-axis tracking system are only about 3% higher compared to one-axis with tilted axis, making one-axis tracking systems attractive when compared costs and performance.

Keywords: solar radiation photovoltaic potential, sun-tracking, SolarGIS.

1. Introduction

Photovoltaics in South Africa triggers an interest in maximizing the energy yield from the investment. In case of crystalline silicon (c-Si) PV modules an option to consider is mounting the c-Si modules on sun-trackers that adjust their tilt and orientation during in order to increase the amount of received sunlight. The tracker follows the path of the sun exactly (2-axis tracker) or approximately (various types of 1-axis trackers). The choice of mounting type depends on the gain in energy yield and on the investment and running costs of tracking systems relative to the fixed-mounting structures.

This paper shows the energy yield from a PV system, comparing two-axis and one-axis tracking options to the two fixed north-facing mounting options.

2. Data and methods

2.1. Solar radiation

Solar radiation is calculated by numerical models, which are parameterized by a set of inputs characterizing the cloud transmittance, state of the atmosphere and terrain conditions. The methodology is described in several papers [1, 2, 3]. The related uncertainty and requirements for bankability are discussed in [4, 5].

We use the SolarGIS approach, where the clear-sky irradiance (irradiance, which does not consider attenuation effect of clouds) is calculated by the simplified SOLIS model [6]. This model allows fast calculation from the set of input parameters. Sun position is a deterministic parameter - described by the numerical models. Stochastic variability of clear-sky atmospheric conditions is determined by changing concentrations of atmospheric constituents, namely aerosols, water vapor and ozone. The calculation accuracy of the clear-sky irradiance is especially sensitive to the information about aerosols.

In the SolarGIS model, a new generation aerosol data set representing Atmospheric Optical Depth (AOD) is used. This data set is developed and regularly calculated by MACC project (© ECMWF) [7]. An important feature of this AOD data set is that it captures daily variability of aerosols and allows simulating more precisely the events with extreme atmospheric load of aerosol particles [8]. Thus it reduces uncertainty of instantaneous estimates of GHI and especially DNI and allows for improved distribution of irradiance values.

Water vapour is also highly variable in space and time, but it has lower impact on the values of solar radiation, compared to aerosols. The daily GFS (Global Forecast System) and CFSR (Climate Forecast System Reanalysis) values (© NOAA NCEP) are used in SolarGIS, thus representing the daily variability from 1994 to the present. Ozone absorbs solar radiation at wavelengths shorter than 0.3 μm, thus having negligible influence on the broadband solar radiation.

The key factor determining short-term variability of all-sky irradiance is clouds. Attenuation effect of clouds is expressed by the means of a parameter called cloud index (cloud transmittance), which is calculated from the routine observations of meteorological geostationary satellites Meteosat MFG (Meteosat First Generation) and MSG (Meteosat Second Generation) satellite data (© EUMETSAT). To retrieve all-sky irradiance in each time step, the clear-sky irradiance is coupled with cloud index. The cloud index is derived by relating signal recorded by the satellite in four spectral channels and surface albedo to the cloud optical properties. In SolarGIS, the modified calculation scheme Heliosat-2 has been adopted to retrieve cloud optical properties from the satellite data. A number of improvements have been introduced to better cope with specific situations such as snow, ice, or high albedo areas (arid zones and deserts), and also with complex terrain. Spatial resolution of satellite data is about 4 x 4 km and time step is 15 and 30 minutes. SolarGIS data used in this calculation represent a period of 18 years (1994 to 2011).

Solar data accuracy from SolarGIS has been compared with high-quality ground measurements measured at 75 stations over Europe and Africa, 5 stations being located in high mountains. The overall relative Mean Bias for Global Horizontal Irradiance is +1.1%, and relative Root Mean Square Difference (RMSD) is 18.5%, 9.6% and 4.8% for hourly, daily and monthly data, respectively; 99.4% data coverage. For Direct Normal Irradiance the overall relative Mean Bias is +1.6%, Standard Deviation of Biases is 6.6% and relative Root Mean Square Difference is 34.9%, 21.4% and 8.9% for hourly, daily and monthly data, respectively. In arid regions the hourly RMSD is significantly lower and is below 16% and 20% for GHI and DNI respectively. IEA SHC Task 36 data inter-comparison has identified SolarGIS as the highest quality solar database [9].

2.2. Air Temperature

Air temperature at 2 metres is calculated from GFS and CFSR data (© NOAA NCEP) by post-processing algorithms. Original temporal resolution of the primary parameters is 1 hour. The original spatial resolution of 25 km is recalculated to 1 km. The data represent a period of 1994 to 2011.

2.3. PV modelling

The instantaneous power output from a PV module is a function of the irradiance level in the plane of the module, temperature of PV modules, front surface reflectivity, and variations of spectral composition of sunlight. Power production from the photovoltaic system can be derived from the meteorological variables by numerical models taking into consideration specific system setup and mounting options (fixed mounting, tracking system). The methods differ in complexity and achievable accuracy of results.

In this paper the photovoltaic power production has been calculated using numerical models implemented in SolarGIS. This approach allows for calculation of power production from full time series of solar radiation and air temperature data considering the specific effect of PV system configuration. Thus the diurnal or seasonal changes (e.g. varying irradiation incidence angle, ambient and module temperature, shading from the surrounding terrain) are accurately represented in the resulting power production.

The calculation procedure of PV power plant production used in this paper is based on following methods and assumptions:

- Calculation of global tilted irradiation (GTI) – irradiation impinging on a plane of PV modules. In this step the instantaneous values of tilted irradiation are calculated in respect to the given mounting option. The optimum position of the tracker is calculated using algorithms described by Huld et al [10], the tilted irradiation is calculated using Perez tilted model [11]. The local shading effect of the surrounding terrain is derived by Ruiz-Arias et al method [12]. Terrain shading originally calculated from 80m SRTM3 terrain data was for the purpose of this work downscaled to 1km resolution. To calculate map products, the full 17 years time series (1994-2010) of irradiation and temperature were reduced to the set of aggregated daily profiles allowing fast and detailed calculation of larger territories. For each month a set of seven profiles was generated characterizing different weather conditions occurring in the given location. The method allows for the accurate representation of weather characteristics and calculation of the monthly and annual GTI [13].

- Losses due to angular reflectivity: solar irradiation is further subjected to losses from angular reflectivity (angle of incidence effects) on the surface of PV modules, and the magnitude of effects depends on relative position of the sun and plane of the module, module clearness and specific properties of the module (antireflection coating, texture, etc.). The model developed by Martin and Ruiz is used [14] and typical low iron float glass and "average" effect of dust are assumed.
- Losses due to performance of PV modules outside of STC (Standard Test Conditions). The conversion efficiency of a module is non-linear and depends on the distribution of pair of values of irradiance and temperature. Relative change of produced energy from this stage of conversion depends on modules technology and mounting type. Typically, loss is higher for crystalline silicone (cSi) modules than thin films due to higher negative thermal power coefficient of crystalline silicon and better behaviour of thin film at low light levels. For the simulation of the performance of PV module the approach by King et al [15] further developed by Huld T. [16, 17] is used in SolarGIS. In this paper a generic cSi module with average temperature coefficient is assumed. The relative change of production (compared to STC) calculated in South Africa is usually within the range of -9% to -14%.
- Inverter losses from conversion of DC to AC depend on the type of inverter and may vary significantly between the models. For the purpose of this study a generic inverter with fixed losses 2.4% (97.6% efficiency) is assumed.
- Other DC losses may be result of several effects: (1) mismatch due to different MPP operating point of modules connected into an inverter; (2) ohmic losses in the interconnections and cables; (3) dirt and dust, soiling, bird droppings on PV modules; (4) electricity losses caused by inter-row shading in the field of PV modules. The cumulative effect of these losses assumed in this study is 5%.
- AC cables and transformer losses of 1% are considered.
- Availability of 99% is considered – e.g. 1% of annual production is lost due to maintenance and power shutdowns.

The cumulative effect of estimated losses (Inverter, Other DC, AC cables and transformer losses and Availability) is 9.1%. Time degradation of PV modules is not considered, however for a complete project planning this element has to be also taken into account [18].

3. Results

The grid resolution of 1 km has been used for the country solar and temperature data, taking into account also shading from terrain with a reasonable accuracy for a country study.

3.1 Fixed mounting at an optimum tilt

The reference case used for a comparison of suntracking options is the yearly energy output of a PV system mounted in a fixed position in a rack facing North and inclined at an optimum tilt, i.e. the angle at which the annual sum of global tilted irradiation received by PV modules is maximum. This type of mounting is very common and provides a robust solution with minimum maintenance effort. However, it may not be effective in terms of harvesting maximum possible solar energy. Fig. 1 shows a map of the annual PV output from a grid-connected open-space PV system with a nominal peak power of 1 kW.

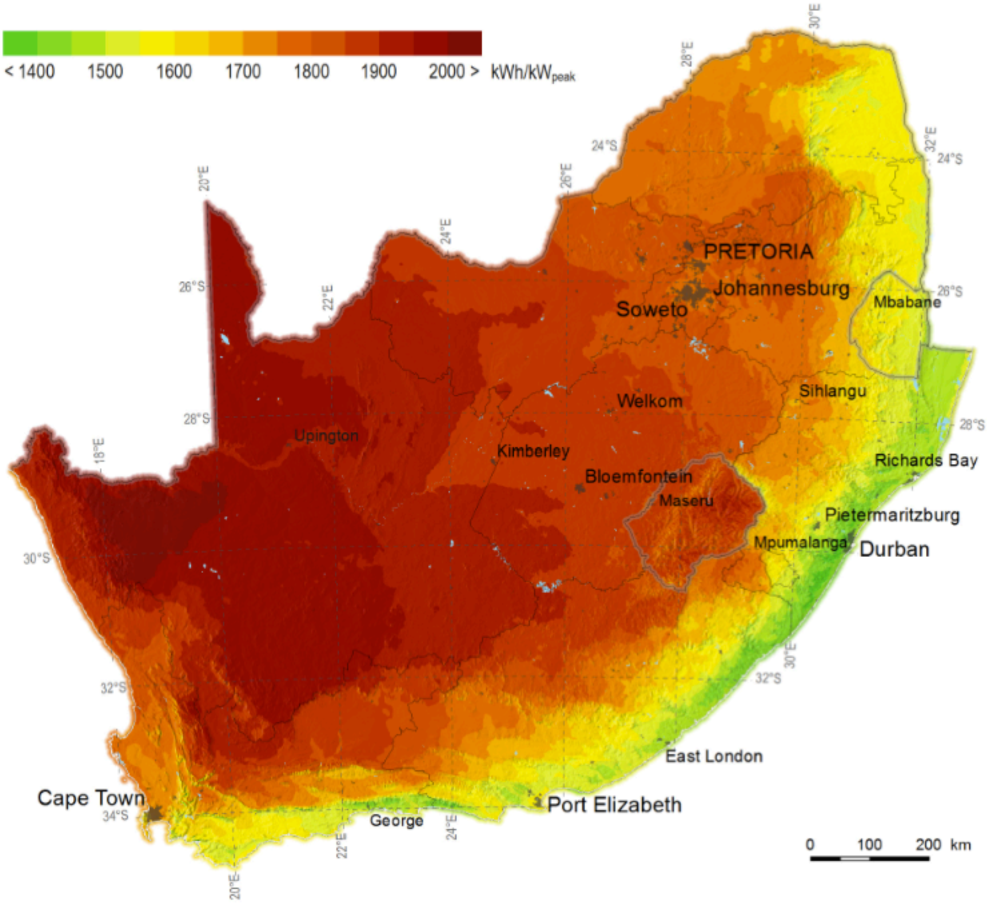

Fig. 1. Map of annual electricity potential output from a grid-connected system at a fixed-mounted open-rack PV system with modules tilted at an annual optimum (kWh/kWp).

Considering fixed mounting and optimum tilt of c-Si photovoltaic modules, the pattern of higher energy output (up to 2000 kWh/kWp) in the arid areas is not surprising. The lowest PV electricity production is seen in the coastal zone (less than 1500 kWh/kWp), which is determined by the regional climate influenced by the Ocean and by higher cloud creation.

Fig. 2 shows a map of the optimum tilt of PV modules to maximize energy yield. The optimum tilt does not follow latitudinal gradient. It increases from about 24° in the Northern part of the country towards Southeast, where it reaches values up to 35°.

Tab. 1 and Fig. 3 show the electricity production values for six selected sites in South Africa, representing typical climate regions.

3.2. One-axis tracking with North-tilted axis at 30 degrees

For this configuration, a tilt of the North-facing axis was considered close to the optimum value, which does not change geographically very much and stays close to 30 degrees. Fig. 4A shows the percentage gain of crystalline silicon PV modules mounted on a one-axis tracker as compared to fixed mounting with one tilt. The geographical pattern follows the climate zones and the typical energy gain is between 20% and 35%.

Tab. 1 shows that the gain from one-axis tracking is lowest in the climate with high ratio of diffuse irradiation. For example, in Durban the diffuse component controls 44% of annual global horizontal irradiation, while in Aggeneys it is only 22%.

In the morning and evening, the suntracking for this type of systems is often limited to a certain axis-rotation angle, when so-called backtracking is applied to prevent local shading and to harvest more diffuse light.

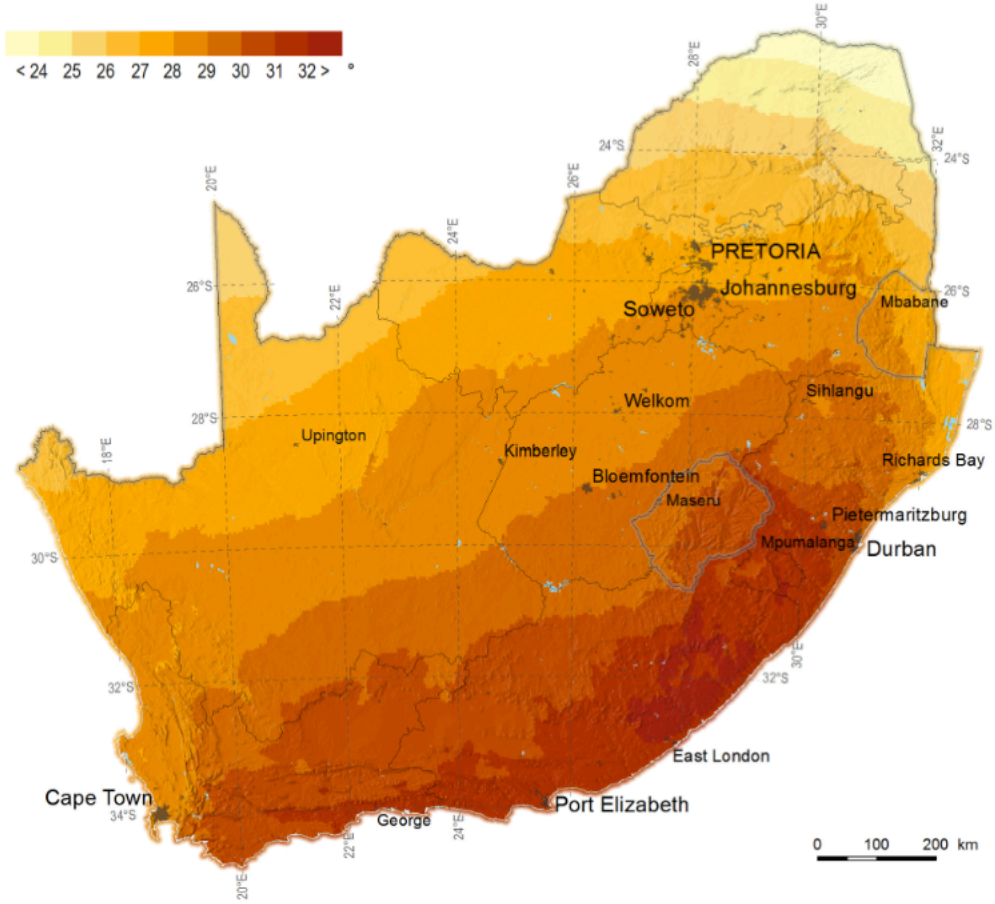

Fig. 2. Optimum tilt for maximising annual energy yield (Degrees).

	Durban	Cape Town	Sasolburg	Kimberley	Upington	Aggeneys
Fixed mounting, optimum tilt	1442 kWh/kWp	1687 kWh/kWp	1815 kWh/kWp	1878 kWh/kWp	1944 kWh/kWp	1999 kWh/kWp
Annual diffuse/global horizontal irradiation	44%	32%	33%	27%	26%	22%
1-axis tracker inclined at 30°	+20%	+30%	+28%	+31%	+32%	+34%
2 axis tracker	+24%	+34%	+32%	+36%	+36%	+39%

Table 1. Gain in PV electricity production for 1 axis and 2 axis tracker, when compared to the optimum tilt

3.3. Two axis tracking

The highest yield can obtained by using a two-axis tracking system, where the normal to the plane of the PV modules always follows the sun, and the typical energy gain over the year is between 25% and 40%.

In case of strong local shading other mounting types may have a higher overall energy production. While producing higher energy yield, two-axis trackers are also more complex and hence demanding higher capital and maintenance costs. When compared to one-axis trackers discussed above, the gain of two axis trackers is relatively small, about 3%. One reason is that flat plate photovoltaics is not sensitive to precise tracking and one axis tracker can better harvest diffuse sunlight in low sun-angle positions.

Important is that trackers need to be deployed in the terrain in a way to reduce self-shading from the nearby trackers and PV modules. The tracking software may also assume the local configuration of trackers either by backtracking or by application of sub-optimal tracking.

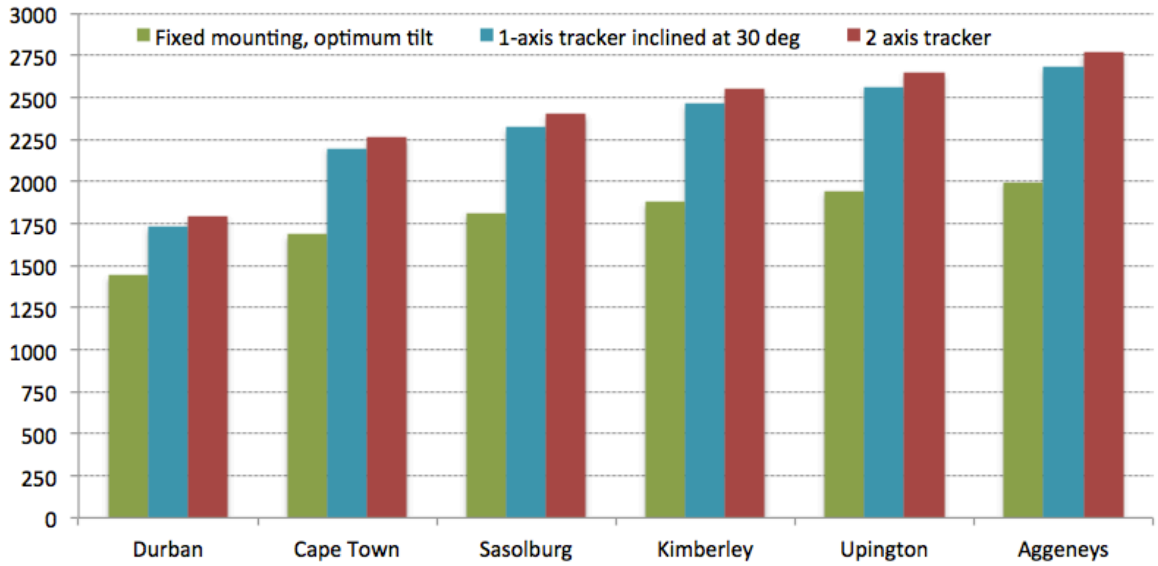

Fig. 3. PV electricity yield for three mounting configurations.

3.4. Other mounting options

In case of fixed mounting, there is a possibility to change tilt of PV modules seasonally. For example, having two different seasonal tilts and changing them every half-year may result in a gain of yearly electricity production from 3% to 4%.

The tracking options in this paper are also not exhaustive. In case of one-axis tracking, there are options of fixing the axis horizontally and have it rotating in the North-South or East-West direction. The other option is to rotate the axis vertically.

The simulation presented here provides a simplified picture as some of technical elements are not fully considered. When designing a tracker field, optimization of tracker position and of their moving behaviour is needed in order to minimize the effects of self-shading and maximise the yield. For example, reducing the inclination angles of the PV modules may help to reduce the length of the shadow cast by the tracking system, but at a cost in its performance.

There are a number of software options, which are not considered here, where a tracker can react on changing local light conditions by adaptive or suboptimal tracking.

4. Conclusions

Fixed mounted crystalline silicon PV modules can provide annual electrical energy in the range of 1500 and 2000 kWh/kWp. Compared to this very typical configuration, the energy gain of one-axis tracking system with axis inclined at 30 degrees amounts to about 15% to 35%. When compared to one-axis trackers with inclined axis, the gain of two axis trackers is relatively small, about 3%.

In systems with several trackers placed close to each other, partial shading is an issue. In this case, the optimal inclination angle may be lower than that calculated using the methods described here. The method presented here does not calculate the local shading effects. Use of multiyear time series of hourly or sub-hourly solar radiation and temperature data is important for designing the optimum position and moving behaviour of the trackers.

Different mounting and suntracking strategies can be tested in the online system SolarGIS pvPlanner at http://solargis.info/pvplanner/.

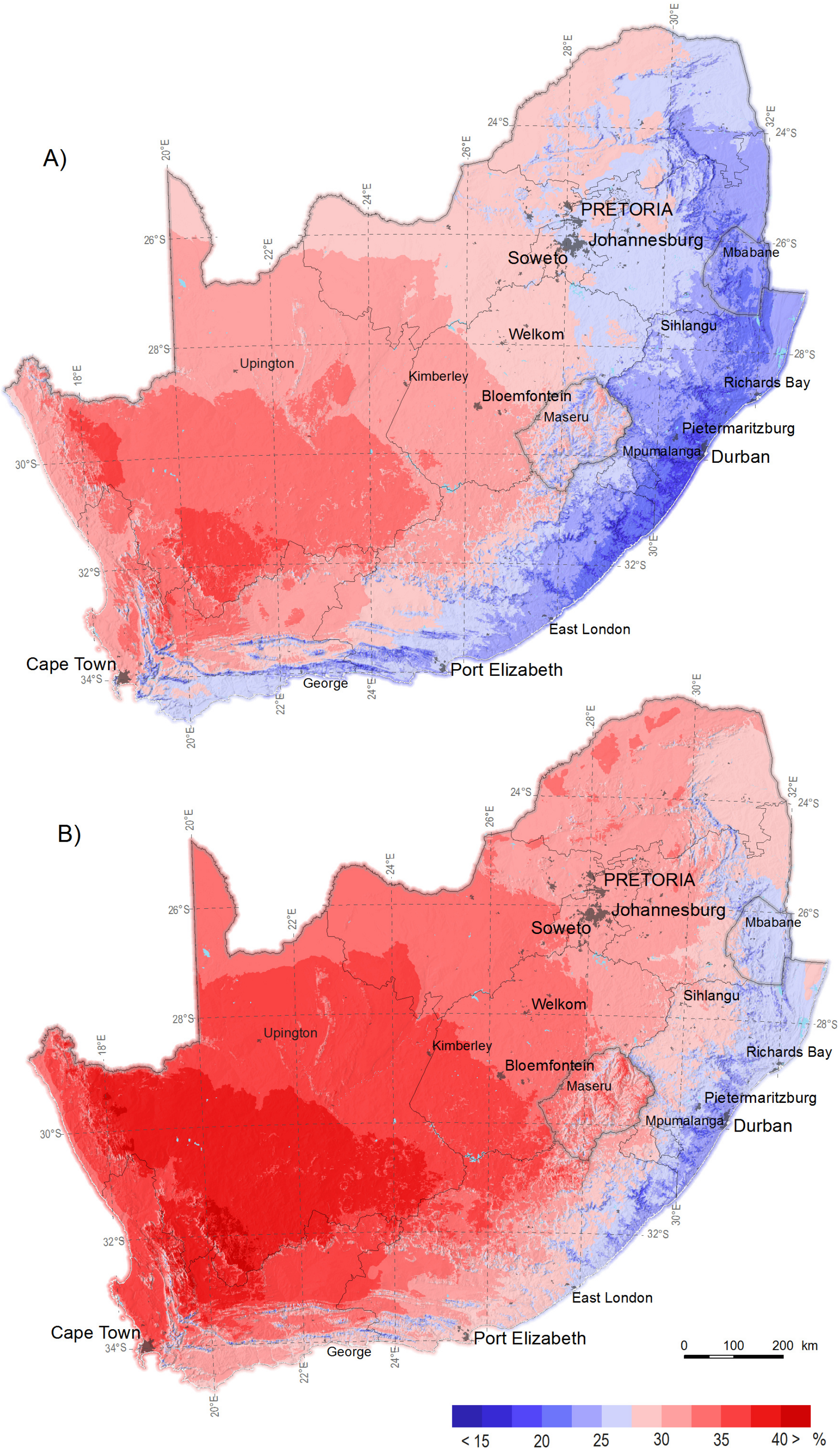

Fig. 4. Relative gain (in %) in PV annual energy output as compared to fixed mounted PV system. A) modules mounted on 1 axis tracker with axis inclined at 30 degrees North. B) modules installed on a two-axis tracker.

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