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# World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels



Mark Z. Jacobson\*, Vijaysinh Jadhav

Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305-4020, USA

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Keywords: Solar photovoltaics Tracking Optimal tilt Solar radiation ABSTRACT

This study provides estimates of photovoltaic (PV) panel optimal tilt angles for all countries worldwide. It then estimates the incident solar radiation normal to either tracked or optimally tilted panels relative to horizontal panels globally. Optimal tilts are derived from the National Renewable Energy Laboratory's PVWatts program. A simple 3rd-order polynomial fit of optimal tilt versus latitude is derived. The fit matches data better above 40° N latitude than do previous linear fits. Optimal tilts are then used in the global 3-D GATOR-GCMOM model to estimate annual ratios of incident radiation normal to optimally tilted, 1-axis vertically tracked (swiveling vertically around a horizontal axis), 1-axis horizontally tracked (at optimal tilt and swiveling horizontally around a vertical axis), and 2-axis tracked panels relative to horizontal panels in 2050. Globally- and annuallyaveraged, these ratios are ~1.19, ~1.22, ~1.35, and ~1.39, respectively. 1-axis horizontal tracking differs from 2-axis tracking, annually averaged, by only 1-3% at most all latitudes. 1-axis horizontal tracking provides much more output than 1-axis vertical tracking below 65° N and S, whereas output is similar elsewhere. Tracking provides little benefit over optimal tilting above 75° N and 60° S. Tilting and tracking benefits generally increase with increasing latitude. In fact, annually averaged, more sunlight reach tilted or tracked panels from 80 to 90° S than any other latitude. Tilting and tracking benefit cities of the same latitude with lesser aerosol and cloud cover. In sum, for optimal utility PV output, 1-axis horizontal tracking is recommended, except for the highest latitudes, where optimal tilting is sufficient. However, decisions about panel configuration also require knowing tracking equipment and land costs, which are not evaluated here. Installers should also calculate optimal tilt angles for their location for more accuracy. Models that ignore optimal tilting for rooftop PV and utility PV tracking may underestimate significantly country or world PV potential.

#### 1. Introduction

Global solar photovoltaic (PV) installations on rooftops and in power plants are growing rapidly and will grow further as the world transitions from fossil fuels to clean, renewable energy (Jacobson et al., 2017). A critical parameter for installing fixed-tilt panels is the tilt angle, since PV panel output increases with increasing exposure to direct sunlight. Energy modelers also need to know the optimal tilt angle of a panel for calculating regional or global PV output in a given location or worldwide.

Another issue for installers and modelers is whether 1-axis vertical tracked PV panels (panels that face south or north and swivel vertically around a horizontal axis) receive more incident radiation than 1-axis horizontal tracked panels (panels at optimal tilt angle that swivel horizontally around a vertical axis), and the extent to which incident radiation to 1-axis- and 2-axis-tracked panels (which combine 1-axis vertical and horizontal tracking capabilities to follow the sun perfectly

during the day) exceeds that of optimally tilted panels. Finally, because global and regional weather and climate models almost all calculate radiative transfer assuming that radiation impinges on horizontal surfaces, energy modelers also need estimates of the ratio of incident solar radiation to panels that track the sun or are optimally-tilted to that of panels that are placed horizontally on a flat surface.

This study first provides estimates of optimal tilt angles derived from the NREL PVWatts program (NREL, 2017) at 1–4 sites in each country of the world. These optimal tilt angles are representative of assumed historic meteorological conditions near a given site, so are only approximate. Although installers would need to make more precise calculations at each site, the results provided here are still useful rough estimates. The study then provides convenient albeit rough polynomial fits to the PVWatts data of the optimal tilt angle as a function of latitude for both the Northern and Southern Hemispheres. The optimal tilt data by country and by latitude are then input into a global climate model, GATOR-GCMOM for year 2050 meteorological and air quality

E-mail address: jacobson@stanford.edu (M.Z. Jacobson).

<sup>\*</sup> Corresponding author.

conditions, to provide ratios of incident solar radiation normal to an optimally tilted, 1-axis vertically-tracked, 1-axis horizontally-tracked, and 2-axis tracked PV panel relative to a horizontal panel.

The reasons for using GATOR-GCMOM rather than PVWatts for the global calculations are (1) GATOR-GCMOM covers the entire world, whereas PVWatts covers locations only near specific meteorological stations, (2) GATOR-GCMOM is used here to examine a future 2050 scenario, where aerosol, cloud, temperature, and wind speed properties differ from today, whereas PVWatts treats only past conditions, and (3) we want to use GATOR-GCMOM to calculate incident solar radiation for the two components of 1-axis horizontal tracking that, when combined, exactly comprise the components of 2-axis tracking, and this cannot be done with current PVWatts output. Specifically, one way for a panel to follow the sun exactly throughout the day (2-axis tracking), is for the panel to swivel horizontally around a vertical axis and, independently, swivel vertically around a horizontal axis. In this study, we calculate incident radiation for both cases - namely vertical tracking (swiveling vertically around a horizontal axis with the panel facing south or north) and horizontal tracking (swiveling horizontally around a vertical axis with the panel at optimal south-north tilt), and separately calculate incident radiation for 2-axis tracking. Whereas PVWatts calculates incident radiation for 2-axis tracking, it does not consider either of the above 1-axis options; instead, it invokes a third option, which is to swivel east-to-west around an axis parallel to a specified tilt, not necessarily the optimal tilt, of the panel. That option is not examined here, but the 1-axis horizontal tracking option treated here results in incident radiation within 1-3% of the 2-axis tilting option at most latitudes, thus may be close to optimal, if not optimal, for 1-axis tracking.

Many studies have provided equations that allow for the theoretical calculation of the optimal tilt angle over time of a solar collector based on Earth-sun geometry (e.g., Kern and Harris, 1975; Koronakis, 1986; Lewis, 1987; Gunerhan and Hepbash, 2009; Chang, 2009; Talebizadeh et al., 2011; Yadav and Chandel, 2013). Some of these studies have derived simple linear expressions of optimal tilt angle versus latitude (Chang, 2009; Talebizadeh et al., 2011). However, optimal tilt depends not only on latitude but also on weather conditions, including cloud cover (Kern and Harris, 1975) and the altitude above sea level (Yadav and Chandel, 2013). Because of the difficulty in determining optimal tilt angle as a function of cloud cover and weather conditions, calculators such as PVWatts (NREL, 2017), are often used to estimate optimal tilt angles at specific locations (Yadav and Chandel, 2013). Here, we first use PVWatts to estimate 1–4 optimal tilt angles for each country of the world.

Breyer and Schmid (2010a) combined satellite data with geometric and radiative equations to map global estimates of optimal tilt angles for solar PV. Similarly, Breyer and Schmid (2010a, 2010b), Breyer (2012), Bogdanov and Breyer (2016), Kilickaplan et al. (2017), Breyer et al. (2017a, 2017b), Sadiqa et al. (2018) have applied tilting, singleaxis, and/or 2-axis tracking equations to regionally- or globally-gridded solar radiation satellite datasets for energy analysis. However, it appears that no 3-D global or regional climate, weather, or air pollution model has included tilting, 1-axis horizontal tracking, 1-axis vertical tracking, or 2-axis tracking interactively within it. Pelland et al. (2011) used horizontal-plate solar radiation output from a downscaled climate model to estimate PV output from fixed-tilt panels. However, the calculation was done offline (after the 3-D model simulation was performed) rather than online (interactive within the 3-D model), thus it could not examine the effects of, for example, instantaneous temperature and wind speed, on panel performance. This study offers the opportunity to estimate global PV output anywhere in the world with tilted or tracked panels relative to horizontal panels using consistent meteorology and accounting for temperature and wind speed on panel

The ideal tracking or tilting option depends not only on the incident solar radiation relative to a horizontal surface but also on the land or roof area needed to avoid shading, and the cost of tracking versus

tilting. For example, 2-axis tracking in a utility PV plant requires more land area to avoid shading panels behind the front row than do 1-axis tracking or optimal tilting, and 2-axis equipment is more expensive than is 1-axis equipment or optimal tilting. Shading depends not only on panel tilting, but also on the height that panels are placed relative to each other. For example, panels that track the sun placed on a southfacing hillside will likely see less shading than will panels on uniformly elevated ground. Shading further depends on the number of panels placed on each single platform that tracks the sun. In sum, the decision about what type of tracking or tilting option is best ultimately depends not only on the incident radiation received normal to each panel, but also on the land or roof area required to avoid shading and on the cost. In this study, we examine only the ratios of incident radiation with different tilting and tracking options relative to horizontal panels. We do not consider areas required or costs. However, these topics are discussed at length in Breyer (2012).

## 2. Methodology for determining optimal tilt angles

We first use PVWatts (NREL, 2017), which combines solar resource data from a specific location with 30 years of historic temperature and wind speed data from a nearby meteorological station, characteristics of a solar panel, and orientation of the panel relative to the sun. PVWatts uses 'typical year' meteorology from each station, which is relevant, since the data have considerable inter-annual variability. For example, in the U.S., solar output during the lowest 10th percentile solar output meteorological year is on average, 4.8% less than that during the 50th percentile year (Ryberg et al., 2015). PVWatts uses solar data from the National Solar Radiation Database 1961-1990 for the U.S., the Canadian Weather for Energy Calculations database for Canada, and both ASHRAE International Weather for Energy Calculations Version 1.1 data and Solar and Wind Energy Resource Assessment Program data for all other countries. "Typical year" solar radiation values from these databases are updated by PVWatts to account for the reduction in sunlight due to clouds and air pollution at each site. Panel altitude, latitude, longitude, and angle relative to the sun are used to estimate exposure of the panel to sunlight. Air temperature and wind speed data are used to estimate panel temperature.

Here, PVWatts is used to estimate annually averaged solar output in all countries of the world assuming tilted panels. The optimal tilt angle in each location is found by calculating panel output with different tilt angles until the tilt angle giving the maximum output is found. That tilt angle is the optimal tilt angle. In most countries, an optimal tilt angle is estimated for only one location. For several large countries, estimates are obtained for 2–4 locations (Table 1). The optimal tilt angles calculated here are not necessarily the most cost-effective fixed tilt angles because they do not account for the additional land needed to minimize shading between panels (Section 3.2 of Breyer (2012)).

The main assumptions for the calculations with PVWatts include the following: 10 kW of premium panels with a temperature coefficient of  $-0.0035/\mathrm{K}$  and 10% efficiency losses. Such losses include soiling (2%), wiring (2%), connections (0.5%), mismatch (2%), light-induced degradation (1.5%), nameplate rating (1%), shading (0.5%), and availability (0.5%). All panels are assumed to face due south in the Northern Hemisphere (180° azimuth angle) or due north in the Southern hemisphere (0° azimuth angle), with the exception of Nairobi, Kenya, which is slightly in the Southern Hemisphere ( $-1.32~\mathrm{S}$ ), but has an optimal tilt angle calculated to face  $4^\circ$  southward.

### 3. Optimal tilt angle results

Table 1 provides all optimal tilt angle results from PVWatts. Fig. 1 shows the resulting optical tilt angles versus latitude for each location in each country of the world in Table 1. The results are approximate for each location, so installers would need to make more exact calculations at their location of interest. 3rd-order polynomials are fit through the

Table 1
Optimal tilt angles for fixed tilt solar PV panels for all countries of the world.

| Country               | Representative City | Nearest Meteorological Station | Station Lat. (deg.) | StationLon. (deg.) | Opt tilt        |
|-----------------------|---------------------|--------------------------------|---------------------|--------------------|-----------------|
| Iceland               | Reykjavík           | Reykjavík                      | 64.13               | -21.9              | 43              |
| Afghanistan           | Kandahar            | Karachi, Pakistan              | 24.9                | 67.13              | 25              |
| Albania               | Sarande             | S Maria Di Leuca               | 39.65               | 18.35              | 30              |
| Algeria               | Algiers             | Algiers                        | 36.72               | 3.25               | 31              |
| Andorra               | Andorra La Vella    | =                              | 41.9                | 2.77               | 37              |
|                       |                     | Gerona, Spain                  |                     |                    | -22             |
| Angola                | Luanda              | Harare, Zimbabwe               | -17.92              | 31.13              |                 |
| Antigua and Barbuda   | St. Johns           | Fort-De-France                 | 14.6                | -61                | 14              |
| Argentina             | Buenos Aires        | Buenos Aires                   | -34.82              | -58.53             | -30             |
| Armenia               | Yerevan             | Tabriz, Iran                   | 38.05               | 46.17              | 30              |
| Australia             | Darwin              | Darwin                         | -12.42              | 130.88             | -18             |
| Australia             | Perth               | Perth                          | -31.93              | 115.95             | -27             |
| Australia             | Sydney              | Sydney                         | -33.95              | 151.18             | -31             |
| Austria               | Graz                | Graz                           | 47                  | 15.43              | 33              |
| Azerbaijan            | Lankaran            | Tabriz, Iran                   | 38.05               | 46.17              | 30              |
| Bahamas               | Nassau              |                                | 22.82               | -80.08             | 21              |
|                       |                     | Saua La Grande                 |                     |                    |                 |
| Bahrain               | Riffa               | Riyadh                         | 24.7                | 46.8               | 26              |
| Bangladesh            | Chittagong          | Chittagong                     | 22.27               | 91.82              | 25              |
| Barbados              | Bridgetown          | Fort-De-France                 | 14.6                | -61                | 14              |
| Belarus               | Minsk               | Minsk                          | 53.87               | 27.53              | 32              |
| Belgium               | Saint Hubert        | Saint Hubert                   | 50.03               | 5.4                | 35              |
| Belize                | Belize City         | Belize                         | 17.53               | -88.3              | 16              |
|                       | •                   |                                |                     | -0.17              | 6 <sup>a</sup>  |
| Benin                 | Port Novo           | Accra, Ghana                   | 5.6                 |                    |                 |
| Bhutan                | Thimphu             | Pagri, China                   | 27.73               | 89.08              | 32              |
| Bolivia               | La Paz              | La Paz                         | -16.52              | -68.18             | -22             |
| Bosnia Herzegovina    | Banja Luka          | Banja Luka                     | 44.78               | 17.22              | 33              |
| Botswana              | Gaborone            | Johannesburg                   | -26.13              | 28.23              | -29             |
| Brazil                | Manaus              | Manaus                         | -3.13               | -60.02             | -7 <sup>a</sup> |
| Brazil                | Rio De Janeiro      | Rio De Janeiro                 | -22.9               | -43.17             | -22             |
|                       |                     |                                |                     |                    | 5 <sup>a</sup>  |
| Brunei Darussalam     | Bandar Seri Begaw   | Bandar Seri Begawan            | 4.93                | 114.93             |                 |
| Bulgaria              | Plovdiv             | Plovdiv                        | 42.13               | 24.75              | 30              |
| Burkina Faso          | Banfora             | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup>  |
| Burundi               | Bujumbura           | Kisii, Kenya                   | -0.67               | 34.78              | $-3^{a}$        |
| Cabo Verde            | Praia               | Dakar, Senegal                 | 14.73               | -17.5              | 14              |
| Cambodia              | Phnom Penh          | Bangkok, Thailand              | 13.92               | 100.6              | 15              |
| Cameroon              | Douala              | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup>  |
|                       |                     |                                |                     |                    |                 |
| Canada                | Calgary             | Calgary                        | 51.12               | -114.02            | 45              |
| Canada                | Vancouver           | Vancouver                      | 49.18               | -123.17            | 34              |
| Canada                | Montreal            | Montreal                       | 45.5                | -73.62             | 37              |
| Central Afr. Republic | Carnot              | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup>  |
| Chad                  | N'Djamena           | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup>  |
| Chile                 | Antofagasta         | Antofagasta                    | -23.43              | -70.43             | -22             |
| China                 | Beijing             | Beijing                        | 39.93               | 116.28             | 37              |
| China                 |                     | Shanghai                       | 31.17               | 121.43             | 23              |
|                       | Shanghai            |                                |                     |                    |                 |
| China                 | Lhasa               | Lhasa                          | 29.67               | 91.13              | 31              |
| China                 | Kunming             | Kunming                        | 25.02               | 102.68             | 25              |
| Colombia              | Bogota              | Bogota                         | 4.7                 | -74.13             | 5 <sup>a</sup>  |
| Comoros               | Moroni              | Antananarivo                   | -18.8               | 47.48              | -18             |
| Congo                 | Owando              | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup>  |
| Congo Dem Rep of      | Lubumbashi          | Harare, Zimbabwe               | -17.92              | 31.13              | -22             |
| Costa-Rica            | San Jose            | Rivas, Nicaragua               | 11.42               | 85.83              | 14              |
|                       |                     |                                |                     |                    |                 |
| Croatia               | Zadar               | Ancona, Italy                  | 43.62               | 13.37              | 30              |
| Cuba                  | Sancti Spiritus     | Sancti Spiritus                | 21.93               | - 79.45            | 21              |
| Cyprus                | Larnaca             | Larnaca                        | 34.88               | 33.63              | 30              |
| Czech Republic        | Ostrava             | Ostrava                        | 49.72               | 18.18              | 33              |
| Denmark               | Copenhagen          | Copenhagen                     | 55.63               | 12.67              | 36              |
| Djibouti              | Djibouti            | Combolcha/Dessie               | 11.08               | 39.72              | 15              |
| Dominica              | Roseau              | Fort-De-France                 | 14.6                | -61                | 14              |
|                       |                     | Aquadilla Boringuen            |                     |                    | 20              |
| Dominican Republic    | Santo Domingo       | 1 1                            | 18.5                | -67.13             |                 |
| Dutch-Antilles        | Willemstad          | Caracas, Venezuela             | 10.6                | -66.98             | 10              |
| Ecuador               | Quito               | Quito                          | -0.15               | -78.48             | -3 <sup>a</sup> |
| Egypt                 | Aswan               | Aswan                          | 23.97               | 32.78              | 24              |
| El Salvador           | Ilopango            | Ilopango                       | 13.7                | -89.12             | 18              |
| Equatorial Guinea     | Bata                | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup>  |
| Eritrea               | Keren               | Gondar, Ethiopia               | 12.53               | 37.43              | 18              |
| Estonia               | Tartu               | Helsinki, Finland              | 60.32               |                    | 39              |
|                       |                     |                                |                     | 24.97              |                 |
| Ethiopia              | Gondar              | Gondar                         | 12.53               | 37.43              | 18              |
| Fiji                  | Nadi                | Nadi                           | -17.75              | 177.45             | -18             |
| Finland               | Helsinki            | Helsinki                       | 60.32               | 24.97              | 39              |
| France                | Lyon                | Lyon                           | 45.73               | 5.08               | 30              |
| France                | Bordeaux            | Bordeaux                       | 44.83               | -0.7               | 33              |
| Gabon                 | Libreville          |                                |                     |                    | 6 <sup>a</sup>  |
|                       |                     | Accra, Ghana                   | 5.6                 | -0.17              |                 |
| Gambia                | Banjul              | Dakar, Senegal                 | 14.73               | -17.5              | 14              |
|                       |                     |                                |                     |                    |                 |
| Georgia               | Tbilisi             | Tabriz, Iran                   | 38.05               | 46.17              | 30              |

(continued on next page)

Table 1 (continued)

| Country                | Representative City | Nearest Meteorological Station | Station Lat. (deg.) | StationLon. (deg.) | Opt til        |
|------------------------|---------------------|--------------------------------|---------------------|--------------------|----------------|
| Germany                | Munich              | Munich                         | 48.13               | 11.7               | 33             |
| Ghana                  | Accra               | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup> |
| Gibraltar              | Catalan Bay         | Ceuta, Spain                   | 35.89               | -5.29              | 31             |
| Greece                 | Athens              | Athens                         | 37.9                | 23.73              | 29             |
| Guatemala              | Guatemala City      | Guatemala City                 | 14.58               | -90.52             | 18             |
| Guinea                 | Conakry             | Dakar, Senegal                 | 14.73               | -17.5              | 14             |
| Guinea-Bissau          | Bissau              | Dakar, Senegal                 | 14.73               | -17.5              | 14             |
| Guyana                 | Dadanawa            | Boa Vista (Civ/Mil)            | 2.83                | -60.7              | 6 <sup>a</sup> |
| Haiti                  | Port-Au-Prince      | Punta Maisi, Cuba              | 20.25               | -74.15             | 19             |
| Honduras               |                     |                                |                     |                    |                |
|                        | Catacamas           | Catacamas                      | 14.9                | -85.93             | 15             |
| Hong Kong              | Hong Kong           | Hong Kong                      | 22.32               | 114.17             | 20             |
| Hungary                | Debrecen            | Debrecen                       | 47.48               | 21.63              | 30             |
| ndia                   | Rajkot              | Rajkot                         | 22.31               | 70.8               | 24             |
| India                  | Chennai             | Chennai                        | 13.07               | 80.24              | 13             |
| ndonesia               | Balikpapan          | Bandar Seri Begawan            | 4.93                | 114.93             | 5 <sup>a</sup> |
| ran                    | Tehran              | Tehran                         | 35.41               | 51.19              | 31             |
| ran                    | Yazd                | Yazd                           | 31.88               | 54.28              | 26             |
| raq                    | Baghdad             | Tabriz, Iran                   | 38.05               | 46.17              | 30             |
| reland                 | Kilkenny            | Kilkenny                       | 52.67               | -7.27              | 36             |
| srael                  | Be'Er Sheva         | Be'Er Sheva                    | 31.25               | 34.8               | 29             |
|                        |                     |                                |                     |                    |                |
| taly                   | Catania             | Catania                        | 37.47               | 15.05              | 27             |
| vory Coast             | Yamoussoukro        | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup> |
| Jamaica                | Kingston            | Santiago De Cuba               | 19.97               | −75.85             | 20             |
| fapan                  | Osaka               | Osaka                          | 34.78               | 135.45             | 30             |
| Iordan                 | Amman               | Jerusalem, Israel              | 31.87               | 35.22              | 28             |
| Kazakhstan             | Zhezqazghan         | Tashkent                       | 41.27               | 69.27              | 32             |
| Kenya                  | Nairobi             | Nairobi                        | -1.32               | 36.82              | 4 <sup>a</sup> |
| Kiribati               | South Tarawa        | Kwajalein Atoll                | 8.73                | 167.73             | 12             |
| Korea                  | Kwangju             | Kwangju                        | 35.13               | 126.92             | 29             |
| Korea DPR              |                     |                                | 39.03               | 125.78             | 36             |
|                        | Pyongyang           | Pyongyang                      |                     |                    |                |
| Kosovo                 | Prishtina           | Podgorica                      | 42.37               | 19.25              | 36             |
| Kuwait                 | Kuwait City         | Shiraz, Iran                   | 29.32               | 52.36              | 26             |
| Yyrgyz Republic        | Jalal-Abad          | Kashi, China                   | 39.47               | 75.98              | 35             |
| aos                    | Vientiane           | Hanoi, Vietnam                 | 21.2                | 105.8              | 16             |
| Latvia                 | Daugavpils          | Kaunas, Lithuania              | 54.88               | 23.88              | 33             |
| Lebanon                | Beirut              | Damascus, Syria                | 33.42               | 36.52              | 29             |
| Lesotho                | Maseru              | Johannesburg                   | -26.13              | 28.23              | -29            |
| Liberia                | Monrovia            | Dakar, Senegal                 | 14.73               | -17.5              | 14             |
| Libyan Arab Jamahiriya | Tripoli             | Tripoli                        | 32.67               | 13.5               | 27             |
| iechtenstein           | Vaduz               | •                              | 42.27               | 11.35              | 37             |
|                        |                     | Innsbruck, Austria             |                     |                    |                |
| Lithuania              | Kaunas              | Kaunas                         | 54.88               | 23.88              | 33             |
| Luxembourg             | Luxembourg          | St Hubert                      | 50.03               | 5.4                | 35             |
| Macedonia              | Bitola              | Thessaloniki                   | 40.52               | 22.97              | 33             |
| Malaysia               | Kuala Lumpur        | Kuala Lumpur                   | 3.12                | 101.55             | 1 <sup>a</sup> |
| Maldives               | Gan Island          | Gan Island                     | -0.68               | 73.15              | $-2^{a}$       |
| Mali                   | Bamako              | Dakar, Senegal                 | 14.73               | -17.5              | 14             |
| Malta                  | Rabat               | Cozzo Spadaro                  | 36.68               | 15.13              | 28             |
| Marshall Islands       | Kwajalein Atoll     | Kwajalein Atoll                | 8.73                | 167.73             | 12             |
| Mauritania             | Nouakchott          | Dakar, Senegal                 | 14.73               | -17.5              | 14             |
|                        | Port Louis          | Antananarivo                   | -18.8               | 47.48              | -18            |
| Mauritius<br>Mexico    |                     |                                |                     |                    |                |
|                        | Mexico City         | Mexico City                    | 19.43               | -99.08             | 17             |
| Mexico                 | Merida              | Belize                         | 17.53               | -88.3              | 16             |
| Micronesia             | Palikir             | Guam, Hi                       | 13.55               | 144.83             | 14             |
| Ioldova Republic       | Chisinau            | Odessa, Ukraine                | 46.45               | 30.7               | 31             |
| Ionaco                 | Monaco-Ville        | Nice, France                   | 43.65               | 7.2                | 35             |
| Mongolia               | Ulaanbaatar         | Ulaanbaatar                    | 47.93               | 106.98             | 43             |
| Iontenegro             | Podgorica           | Podgorica                      | 42.37               | 19.25              | 36             |
| Morocco                | Casablanca          | Casablanca                     | 33.37               | -7.58              | 28             |
|                        |                     |                                | - 26.13             |                    | - 29           |
| Mozambique<br>Tourne   | Maputo              | Johannesburg                   |                     | 28.23              |                |
| Myanmar                | Yangon              | Bangkok, Thailand              | 13.92               | 100.6              | 15             |
| Iamibia                | Windhoek            | Cape Town                      | -33.98              | 18.6               | -30            |
| lauru                  | Yaren               | Kwajalein Atoll                | 8.73                | 167.73             | 12             |
| Iepal                  | Kathmandu           | Kathmandu                      | 27.7                | 85.37              | 29             |
| letherlands            | Beek                | Beek                           | 50.92               | 5.78               | 34             |
| lew Zealand            | Auckland            | Auckland                       | -37.02              | 174.8              | -30            |
| licaragua              | Rivas               | Rivas                          | 11.42               | 85.83              | 14             |
| · ·                    | Niamey              | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup> |
| liger                  | •                   |                                |                     |                    |                |
| ligeria                | Lagos               | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup> |
| Iorway                 | Oslo                | Oslo                           | 59.9                | 10.62              | 40             |
| man                    | Salalah             | Abu Dhabi, UAE                 | 24.43               | 54.65              | 25             |
| akistan                | Karachi             | Karachi                        | 24.9                | 67.13              | 25             |
| alau                   | Koror               | Koror Island                   | 7.33                | 134.48             | 8 <sup>a</sup> |
| alestine               | Jerusalem           | Jerusalem                      | 31.87               | 35.22              | 28             |
| anama                  | Panama City         | Rivas, Nicaragua               | 11.42               | 85.83              | 14             |
|                        |                     |                                | 11.74               | 00.00              | 14             |
| Papua New Guinea       | Port Moresby        | Weipa, Australia               | -12.68              | 141.92             | -17            |

(continued on next page)

Table 1 (continued)

| Country  | Representative City     | Nearest Meteorological Station | Station Lat. (deg.) | StationLon. (deg.) | Opt tilt        |
|--|-------------------------|--------------------------------|---------------------|--------------------|-----------------|
| Paraguay   | Asuncion                | Asuncion                       | -25.25              | -57.57             | -23             |
| Peru   | Lima                    | Lima                           | -12                 | -77.12             | -7 <sup>a</sup> |
| Philippines  | Manila                  | Manila                         | 14.52               | 121                | 9 <sup>a</sup>  |
| Poland   | Bielsko-Biala           | Bielsko-Biala                  | 49.67               | 19.25              | 31              |
| Portugal   | Lisbon                  | Lisbon                         | 38.73               | -9.15              | 35              |
| Qatar  | Doha                    | Abu Dhabi, UAE                 | 24.43               | 54.65              | 25              |
| Romania  | Bucharest               | Bucharest                      | 44.5                | 26.13              | 32              |
| Russia   | St Petersburg           | St Petersburg                  | 59.97               | 30.3               | 40              |
| Russia   | · ·                     | e e                            | 55.75               | 37.63              | 37              |
|  | Moscow                  | Moscow                         |                     |                    |                 |
| Russia   | Omsk                    | Omsk                           | 54.93               | 73.4               | 42              |
| Rwanda   | Nyagatare               | Kisii, Kenya                   | -0.67               | 34.78              | -3ª             |
| Saint Kitts And Nevis                              | Basseterre              | Charlotte Amalie               | 18.35               | -64.97             | 18              |
| Saint Lucia  | Castries                | Fort-De-France                 | 14.6                | -61                | 14              |
| Samoa  | Apia                    | Nadi, Fiji                     | - 17.75             | 177.45             | -18             |
| San Marino   | Fiorentino              | Rimini, Italy                  | 44.03               | 12.62              | 31              |
| Sao Tome & Principe                                | Sao Tome                | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup>  |
| Saudi Arabia                                       | Riyadh                  | Riyadh                         | 24.7                | 46.8               | 24              |
| Senegal  | Dakar                   | Dakar                          | 14.73               | -17.5              | 14              |
| Serbia   | Belgrade                | Belgrade                       | 44.82               | 20.28              | 34              |
|  | •                       | <u> </u>                       |                     |                    | -2 <sup>a</sup> |
| Seychelles   | Victoria                | Lamu/Manda Island              | -2.27               | 40.83              |                 |
| Sierra Leone                                       | Freetown                | Dakar, Senegal                 | 14.73               | -17.5              | 14              |
| Singapore  | Singapore               | Singapore                      | 1.37                | 103.98             | $0^{a}$         |
| Slovakia   | Kosice                  | Kosice                         | 48.7                | 21.27              | 33              |
| Slovenia   | Ljubljana               | Ljubljana                      | 46.22               | 14.48              | 29              |
| Solomon Islands                                    | Honiara                 | Weipa, Australia               | -12.68              | 141.92             | -17             |
| Somalia  | Mogadishu               | Marsabit, Kenya                | 2.3                 | 37.9               | 4 <sup>a</sup>  |
| South Sudan  | Juba                    | Lowdar, Kenya                  | 3.12                | 35.62              | 5 <sup>a</sup>  |
| South Africa                                       | Johannesburg            | · •                            | -26.13              | 28.23              | -29             |
|  | · ·                     | Johannesburg                   |                     |                    |                 |
| South Africa                                       | Cape Town               | Cape Town                      | -33.98              | 18.6               | -30             |
| Spain  | Castellón               | Castellón                      | 39.95               | -0.07              | 36              |
| Spain  | Ceuta                   | Ceuta                          | 35.89               | -5.29              | 31              |
| Sri-Lanka  | Colombo                 | Colombo                        | 6.82                | 79.88              | 9 <sup>a</sup>  |
| St. Vincent/Grenadines                             | Kingstown               | Fort-De-France                 | 14.6                | -61                | 14              |
| Sudan  | Khartoum                | Gondar, Ethiopia               | 12.53               | 37.43              | 18              |
| Suriname   | Kabalebo                | Boa Vista, Brazil              | 2.83                | -60.7              | 6ª              |
| Swaziland  | Mbabane                 | Johannesburg                   | -26.13              | 28.23              | -29             |
| Sweden   | Stockholm               | Stockholm                      | 59.65               | 17.95              | 41              |
|  |                         |                                |                     |                    |                 |
| Switzerland  | Geneva                  | Geneva                         | 46.25               | 6.13               | 32              |
| Syrian Arab Republic                               | Damascus                | Damascus                       | 33.42               | 36.52              | 29              |
| Taiwan   | Taipei                  | Taipei                         | 25.07               | 121.55             | 17              |
| Гаjikistan   | Dushanbe                | Tashkent                       | 41.27               | 69.27              | 32              |
| Гаnzania   | Arusha                  | Makindu, Kenya                 | -2.28               | 37.83              | -4 <sup>a</sup> |
| Thailand   | Bangkok                 | Bangkok                        | 13.92               | 100.6              | 15              |
| Timor-Leste  | Dili                    | Darwin, Australia              | -12.42              | 130.88             | -18             |
| Годо   | Lome                    | Accra, Ghana                   | 5.6                 | -0.17              | 6 <sup>a</sup>  |
| ·  | Nukunuku                |                                | - 17.75             |                    | -18             |
| Tonga  |                         | Nadi, Fiji                     |                     | 177.45             |                 |
| Trinidad and Tobago                                | San Fernando            | Fort-De-France                 | 14.6                | -61                | 14              |
| Tunisia  | Tunis                   | Tunis                          | 36.83               | 10.23              | 28              |
| Гurkey   | Ankara                  | Ankara                         | 40.12               | 32.98              | 29              |
| Гurkey   | Diyarbakır              | Tabriz, Iran                   | 38.05               | 46.17              | 30              |
| Turkmenistan                                       | Ashgabat                | Tehran Mehrabad,               | 35.41               | 51.19              | 31              |
| Гuvalu   | Vaitupu                 | Nadi, Fiji                     | -17.75              | 177.45             | -18             |
| Uganda   | Kampala                 | Kisii, Kenya                   | -0.67               | 34.78              | $-3^a$          |
| Ukraine  | Kiev                    | Kiev                           | 50.4                | 30.45              | 35              |
|  |                         |                                |                     |                    |                 |
| Ukraine  | Odessa                  | Odessa                         | 46.45               | 30.7               | 31              |
| United States                                      | Raleigh, NC             | Raleigh, NC                    | 35.86               | -78.78             | 32              |
| United States                                      | Bakersfield, CA         | Bakersfield, CA                | 35.43               | -119.05            | 29              |
| United States                                      | Austin, TX              | Austin, TX                     | 30.29               | -97.74             | 28              |
| United Arab Emirates                               | Abu Dhabi               | Abu Dhabi                      | 24.43               | 54.65              | 25              |
| United Kingdom                                     | Hemsby                  | Hemsby                         | 52.68               | 1.68               | 34              |
| United Kingdom                                     | London                  | London                         | 51.15               | -0.18              | 34              |
| Uruguay  |                         |                                |                     |                    | -32             |
|  | Montevideo              | Montevideo                     | -34.83              | -56                |                 |
|  | Tashkent                | Tashkent                       | 41.27               | 69.27              | 32              |
| Uzbekistan   |                         | NT - 31 TOUR                   | - 17.75             | 177.45             | -18             |
|  | Elia                    | Nadi, Fiji                     | 17170               |                    |                 |
| Uzbekistan   | Elia<br>Vatican City    | Roma-Ciampino                  | 41.8                | 12.58              | 30              |
| Uzbekistan<br>Vanuatu                              |                         |                                |                     |                    | 30<br>10        |
| Uzbekistan<br>Vanuatu<br>Vatican City<br>Venezuela | Vatican City<br>Caracas | Roma-Ciampino<br>Caracas       | 41.8<br>10.6        | 12.58<br>-66.98    | 10              |
| Uzbekistan<br>Vanuatu<br>Vatican City              | Vatican City            | Roma-Ciampino                  | 41.8                | 12.58              |                 |

(continued on next page)

Table 1 (continued)

| Country  | Representative City | Nearest Meteorological Station | Station Lat. (deg.) | StationLon. (deg.) | Opt tilt |
|----------|---------------------|--------------------------------|---------------------|--------------------|----------|
| Zimbabwe | Harare              | Harare                         | -17.92              | 31.13              | -22      |

<sup>&</sup>lt;sup>a</sup> Indicates the optimal tilt angle is between  $+/-10^{\circ}$ , thus panels will likely be tilted in practice either  $+10^{\circ}$  for positive values or  $-10^{\circ}$  for negative values to allow for rain to naturally wash them.

Data are derived from PVWatts (NREL, 2017). The meteorological station used for radiation and meteorological data and its latitude and longitude are also shown. The optimal tilt angles are calculated assuming all panels are roof mount, premium panels with rated power of 10 kW, system losses of 10%, and facing due south in the Northern Hemisphere (180° azimuth angle, positive optimal tilt angle) or north in the Southern Hemisphere (0° azimuth angle, negative optimal tilt angle). In one case (Kenya), which is slightly in the Southern Hemisphere, the optimal tilt angle is facingl slightly south, thus negative. Calculations for several countries, particularly island countries, are based on the same meteorological station, since it is the nearest available, thus all output and tilt angles are the same. Such duplicate values are removed in all figures and in the derivation of all fitting curves. For some large countries geographically, results are shown for 2–4 locations.

data in each hemisphere. Fig. 1 also shows results from two linear estimates of optimal tilt angle versus latitude from Chang (2009) and Talebizadeh et al. (2011). For most mid-latitude values, the linear estimates and the polynomial fit track the PVWatts optimal tilt angles well.

However, for high latitudes in the Northern Hemisphere, the linear fits diverge substantially for most, but not all data. The reason is that the linear estimates ignore cloud cover and air pollution, but in reality, heavy cloud cover and haze exist in many high-latitude countries and regions. Greater cloud cover results in lower optimal tilt angles because clouds scatter solar radiation isotropically, so the closer a panel is to the horizontal under cloudy skies, the more diffuse solar radiation it will receive that is scattered by clouds above them. Further, the direct component of solar radiation, which depends significantly on tilt angle, is largely blocked by clouds, so the diffuse component becomes more important when clouds are present. In sum, on average, the 3<sup>rd</sup>-order polynomial fit derived here appears to represent better the optimal tilt angle of solar panels above around 40° N latitude than some previous linear functions do.

However, the linear functions do estimate optimal tilt better than the polynomial fit at a few high-latitude locations that have relatively clear sky. For example, Calgary ( $51.12^\circ$  N), has a higher optimal tilt angle ( $45^\circ$ ) than does Beek, the Netherlands ( $34^\circ$ ), which is at a similar latitude ( $50.92^\circ$  N). The reason, as explained above, is that Calgary is exposed to less cloud cover so panels can more efficiently take advantage of overhead sun. In Beek, due to heavier cloud cover, panels are

exposed to less direct light, so must take advantage of isotropic diffuse light scattered by clouds above them and receive more of such light with a lower optimal tilt angle. Other data (Breyer and Schmid, 2010a) similarly indicate that optimal tilt angles vary substantially at the same latitude but different longitude, in many parts of the world.

Calgary, in fact, benefits the most from tilting and tracking among all locations examined with PVWatts. Solar output there is  $\sim 32.4\%$  higher with optimal tilting than with horizontal panels (no tilting) and 91.4% higher with 2-axis tracking than with no tilting. In Beek, optimal tilting yields only 14.6% greater output than with no tilting, and 2-axis tracking yields only 34.8% greater output than with no tilting. Tracking and tilting both benefit Calgary the most in January (ratio of 2-axis:no tilt of 3.44 and optimal tilt:no tilt of 2.68) and the least in June (1.51 and 0.93). Tracking and tilting benefit Beek the most in December (ratio of 2-axis:no tilt of 1.97 and optimal tilt:no tilt of 1.64) and the least in June (1.14 and 0.98).

The difference between Calgary and Beek is due entirely to the greater cloudiness (Anderson and West, 2017) and aerosol pollution (The World Bank, 2017) in the Netherlands than in Canada, and aerosol pollution enhances cloud optical thickness. Conversely, reducing aerosol pollution reduces cloudiness and increases surface solar radiation. For example, between 1980 and 2005, surface solar radiation in Europe increased about 10 W/m² (Ohmura, 2009). The reason is that, between 1985 and 2007, aerosol optical depth over Europe declined 69%, increasing surface solar radiation (Chiacchio et al., 2011). Fewer aerosol particles result in clouds being optically thinner due to the first

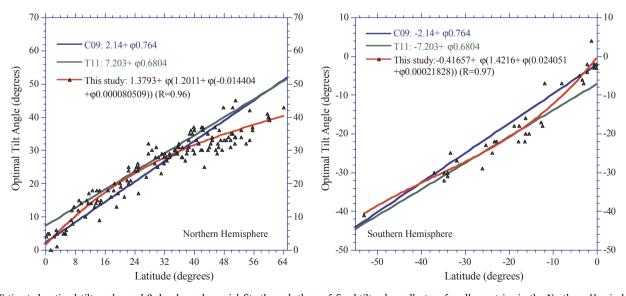


Fig. 1. Estimated optimal tilt angles and 3rd-order polynomial fits through them of fixed-tilt solar collectors for all countries in the Northern Hemisphere and Southern Hemisphere, as derived from PVWatts. Data for each country are from Table 1. Countries with identical tilt angles in Table 1, due to the fact that they rely on the same meteorological station as other countries, are excluded from the figure and curve fits. Also shown are linear equations from two previous studies, Chang [7, C09] and Talebizadeh [8, T11], where  $\phi$  is latitude (in degrees). To allow for rain to naturally clean panels, optimal tilt angles between -10 and  $+10^{\circ}$  latitude are usually limited to either  $-10^{\circ}$  (for negative values) or  $+10^{\circ}$  (for positive values).

indirect effect of aerosol particles on clouds. Because aerosol pollution is likely to drop further between now and 2050, solar output is likely to increase further by 2050. Since PVWatts relies on 30 years of past meteorological data and recent solar radiation data, it may thus underestimate 2050 solar resource in any currently polluted region of the world.

In practice, when the optimal tilt angle is between -10 and  $+10^\circ$ , which occurs primarily in the tropics, installers generally tilt the panel either -10 or  $+10^\circ$  to allow for rainfall to naturally cleanse the panels. The locations that this affects are denoted in Table 1.

# 4. Calculating incident solar radiation with GATOR-GCMOM

The 3rd-order optimal tilt polynomials as a function of latitude (Fig. 1), derived from PVWatts data, were input worldwide into every grid cell in the global weather-climate-air-pollution model GATOR-GCMOM (Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model) (Jacobson, 2001a, 2001b, 2005, 2012; Jacobson et al., 2007, 2014; Jacobson and Archer, 2012). All individual optimal tilts from Table 1 within 700 km to the west or east and within 250 km to the south or north of a grid cell horizontal center were then interpolated to each cell center using a 1/R2 interpolation (where R = distance from the cell center to the data point) and using the background value as one data point  $700\,\mathrm{km} \times 250\,\mathrm{km}$  away. This interpolation resulted in values from Table 1 dominating near the locations in Table 1 but also in background values dominating over ocean water and over land away from the locations in Table 1. Fig. 2 shows the resulting worldwide field, which was input into GATOR-GCMOM. Fig. 2 does not reflect GATOR-GCMOM meteorology, only values from PVWatts. Fig. 2 does not show more variation with longitude because the number of locations with specific optimal tilt values in Table 1 is relatively small, particularly for big countries, and no locations are over the ocean. PVWatts itself was not used in GATOR-GCMOM.

GATOR-GCMOM was then run for the year 2050 to calculate radiation normal to flat-plate (horizontal) panels (Fig. 3), normal to optimally-tilted panels, normal to 1-axis vertically tracking panels, normal to 1-axis horizontally tracking panels, and normal to 2-axis panels. Ratios of incident radiation in each tilting or tracking case to that in the horizontal panel case were then plotted (Figs. 4 and 5).

In general, GATOR-GCMOM simulates feedbacks among meteorology, solar and thermal-infrared radiation, gases, aerosol particles, cloud particles, oceans, sea ice, snow, soil, and vegetation. GATOR-GCMOM model predictions of wind and solar resources have been compared with data in multiple studies (e.g., Jacobson, 2001a, 2001b, 2005, 2012; Jacobson et al., 2007, 2014), including here. With respect to energy, it predicts output of time- and space-dependent electricity

from onshore and offshore wind, rooftop and utility scale PV, and CSP; and heat from solar-thermal equipment. It accounts for competition among wind turbines for available kinetic energy, tilting and tracking of PV panels, the temperature-dependence of PV output, the reduction in sunlight to rooftops and the ground due to extraction of radiation by solar devices, changes in air and ground temperature due to power extraction by PV and use of the resulting electricity, and the impacts of time-dependent gas, aerosol, and cloud concentrations on solar radiation fields. Below, the model is briefly described only with respect to radiation transfer and treatment of solar PV.

### 4.1. Radiative processes in GATOR-GCMOM

In GATOR-GCMOM, each model column for radiative calculations is divided into clear- and cloudy-sky columns, and separate calculations are performed for each. Radiative transfer is solved simultaneously through multiple layers of air and one snow, sea ice, or ocean water layer at the bottom to calculate, rather than prescribe, spectral albedos over these surfaces. For vegetated or bare land surfaces, no layer is added. The 2-stream radiative code (Toon et al., 1989) solves the atmospheric radiative transfer equation for radiances, irradiances, atmospheric heating rates, and actinic fluxes through each of 68 model layers in each column, over each of 694 wavelengths/probability intervals in the ultraviolet, visible, solar-infrared, and thermal-infrared spectra (Jacobson, 2005), accounting for gas and size- and compositiondependent aerosol and cloud optical properties (Jacobson, 2012). The intervals include 86 ultraviolet and visible wave intervals from 170 to 800 nm, 232 visible, solar-infrared, and thermal-infrared probability intervals from 800 nm to 10 µm, and 376 thermal-infrared probability intervals from  $10\,\mu m$  to  $1000\,\mu m$ . Solar radiation calculations here span from 170 nm to 10 µm. The solar panel efficiency accounts for the portion of this spectrum that the panel actually absorbs in. The model calculates both downward and reflected upward direct and diffuse radiation.

Cloud thermodynamics in GATOR-GCMOM is parameterized to treat subgrid cumulus clouds in each model column based on an Arakawa-Schubert treatment. Aerosol particles of all composition and size and all gases are convected vertically within each subgrid cloud. Aerosol-cloud interactions and cloud and precipitation microphysics are time-dependent, explicit, and size- and composition-resolved. The model simulates the size- and composition-resolved microphysical evolution from aerosol particles to clouds and precipitation, the first and second aerosol indirect effects, the semi-direct effect, and cloud absorption effects I and II (which are the heating of a cloud due to solar absorption by absorbing inclusions in cloud drops and by swollen absorbing aerosol particles interstitially between cloud drops,

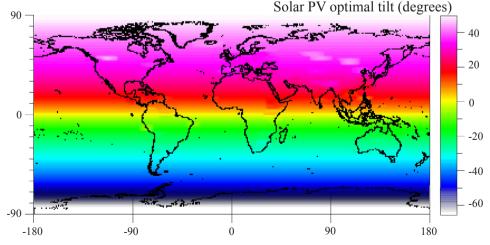


Fig. 2. Optimal tilt angles for PV panels worldwide that are input into GATOR-GCMOM. These are calculated as described in the text.

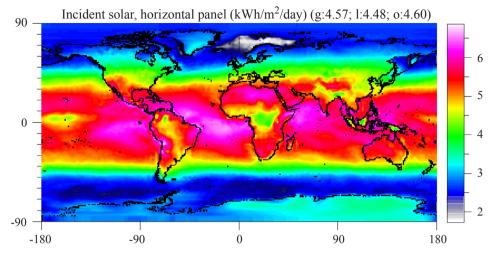


Fig. 3. Annually averaged (2050) modeled downward only (not downward minus reflected upward) direct plus diffuse solar radiation incident on and normal to a flat, horizontal panel.

### respectively) (Jacobson, 2012).

Aerosol and cloud optical properties for radiative purposes are calculated by integrating spectral optical properties over each size bin of each aerosol and hydrometeor particle size distribution. Aerosol spectral optical properties of a given size are determined by assuming that black carbon, if present, is a core surrounded by a mixed shell and that the aerosol liquid water content is a function of the ambient relative humidity and aerosol composition. Cloud spectral optical properties of a given size are determined accounting for scattering by aerosol particles between cloud particles, where aerosol particle liquid water content is determined at the relative humidity of the cloud. Cloud drop, ice crystal, and graupel optical properties are determined accounting for the time-dependent evolution of black carbon, brown carbon, and soil dust inclusions within the drops, crystals, and graupel. Ice crystal and graupel optical properties also account for the non-sphericity of these particles (Jacobson, 2012).

### 4.2. Treatment of solar PV in GATOR-GCMOM

GATOR-GCMOM predicts time-dependent direct and diffuse solar radiation as a function of wavelength, accounting for time-dependent predicted gas, aerosol particle, and cloud particle concentrations. The radiative transfer calculation also accounts for surface albedo (and predicts albedo over water, snow, and ice surfaces), building and vegetation shading, angle of the sun, Earth-sun distance, Earth-space refraction, and solar intensity versus wavelength. As such, the model predicts the variable nature of solar radiation fields.

Photovoltaics in the model are either horizontal (flat on the ground), optimally tilted (for rooftop PV) or tracked (for utility PV). Each time step that the two-stream radiative transfer code (Toon et al., 1989) is called in the model, zenith angles in a vacuum ( $\theta_z$ ) are calculated for each PV tilting case as follows:

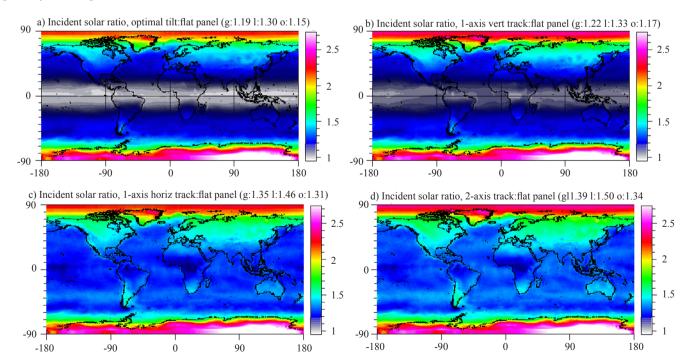


Fig. 4. Ratio of incident direct plus diffuse solar radiation normal to a panel surface for PV panels that are either (a) optimally tilted, (b) tracking the sun vertically (swiveling vertically around a horizontal axis), (c) tracking the sun horizontally (at their optimal tilt and swiveling horizontally around a vertical axis), or (d) tracking the sun both vertically and horizontally, relative to downward (not downward minus reflected upward) radiation (shown in Fig. 3) normal to flat (horizontal) panels.

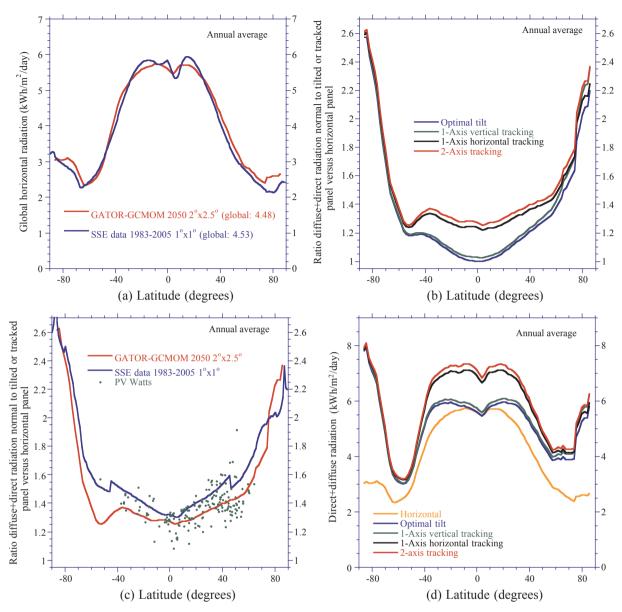


Fig. 5. (a) Comparison of zonally- and annually-averaged GATOR-GCMOM 2050  $2^{\circ} \times 2.5^{\circ}$  resolution model predictions with NASA Surface Meteorology and Solar Energy (SSE) 1983–2005  $1^{\circ} \times 1^{\circ}$  resolution satellite estimates (NASA, 2018) of global direct plus diffuse solar irradiance impinging on (normal to) a flat (horizontal) panel parallel to the surface of the Earth. (b) Zonally- and annually-averaged ratios of incident direct plus diffuse solar radiation normal to a panel surface for PV panels that are either optimally tilted or tracking the sun relative to flat (horizontal) panels, Results are obtained from GATOR-GCMOM by averaging data for each latitude in Fig. 4(a)–(d) over all longitudes. (c) Comparison of the modeled 2-axis tracked curve from Fig. 5(b) with an estimate from NASA (2018), derived here as the ratio of the sum of direct normal radiation (radiation to a flat surface normal to the sun's beam) plus diffuse radiation, to global horizontal radiation, and with estimates from PVWatts for each country of the world. Whereas, the RMS error in comparison with ground measurements for the SEE global radiation data is 10%, those for diffuse and direct normal radiation are 29% and 23%, respectively (NASA, 2018). (d) Direct plus diffuse solar radiation to horizontal, optimally tilted, or tracked panels. The global horizontal radiation is the modeled curve in Fig. 5(a). The remaining curves are the product of the horizontal radiation and the ratios in Fig. 5(b).

Horizontal  $\cos\theta_z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos H$ Optimal tilt  $\cos\theta_z = \sin\phi \sin(\delta+\beta) + \cos\phi \cos(\delta+\beta)$   $\cos H$ 1-Axis vertical tracking  $\cos\theta_z = \sin^2\phi + \cos^2\phi \cos H$ 1-Axis horizontal  $\cos\theta_z = \sin\phi \sin(\delta+\beta) + \cos\phi \cos(\delta+\beta)$ tracking  $\cos\theta_z = \sin^2\phi + \cos^2\phi = 1$ where  $\phi =$ latitude,  $\delta =$ solar declination angle, H =hour angle, and

where  $\phi$  = latitude,  $\delta$  = solar declination angle, H = hour angle, and  $\beta$  = optimal tilt angle. Each zenith angle is then corrected for the air's refraction according to Snell's law with

$$\theta_{z,air} = \arcsin(\sin\theta_z/r_{air})$$
 for  $\theta_z \le \pi/2$ 

$$\theta_{z,air} = \theta_z + \theta_{crit} - \pi/2 \text{ for } \theta_z > \pi/2$$

where  $\theta_{crit} = \arcsin(1/r_{air})$  is the critical angle and  $r_{air} = 1.000278$  is the real part of the index of refraction of air at 550 nm. Solar radiative transfer calculations are performed only when  $\cos\theta_{z,air} > 0$  for horizontal panels. Otherwise, it is assumed that the sun is beyond the horizon, so no more refraction over the horizon occurs for any tilt angle. Each time step, the total spectral direct  $(F_{diff;\lambda}, W/m^2 \mu m^{-1})$  plus diffuse  $(F_{diff;\lambda}, W/m^2 \mu m^{-1})$  solar flux normal to a panel is calculated for each solar wavelength  $\lambda$  as

$$F_{tot,\lambda} = F_{diff,\lambda} + \cos\theta_{z,air} F_{dir,\lambda}$$

The calculation is repeated for each zenith angle corresponding to

each type of panel tilting. Results are summed over all solar wavelengths and probability intervals (from 170 nm to 10  $\mu$ m) for each zenith angle to get the total flux ( $F_{tot}$ ,  $W/m^2$ ) normal to each panel.

Panel output equals the total flux normal to the panel multiplied by the panel efficiency, the panel loss factor, and the solar cell temperature correction factor. Panel efficiency is the panel's rated power (W) divided by one sun  $(1000 \, \text{W/m}^2)$  and by the panel surface area  $(\text{m}^2)$ . The example panel used for this study (assuming 2050 panels) has a rated power of 390 W and surface area of  $1.629668 \, \text{m}^2$ , giving an efficiency of 23.93% (Jacobson et al., 2017). This efficiency accounts for the fact that PV cells utilize only a portion of the total solar spectrum.

The panel loss factor equals one minus panel losses (as fractions). Panel losses (not including transmission and distribution losses) are assumed to be a total of 10%, which accounts for soiling (2%), mismatch (2%), wiring (2%), connections (0.5%), light-induced degradation (1.5%), nameplate rating (1%), availability (0.5%) and shading (0.5%) (e.g., NREL, 2017).

The solar cell temperature correction factor is estimated roughly as

$$C_{temp} = 1 - \beta_{ref} \max(\min(T_c - T_{ref}, 55), 0)$$

where  $T_c$  (K) is the solar cell temperature,  $\beta_{ref}$  (K<sup>-1</sup>) is the temperature coefficient, and  $T_{ref}$  is the reference temperature. For this study,  $\beta_{ref} = 0.0025 \, \text{K}^{-1}$  and  $T_{ref} = 298.15 \, \text{K}$  (Razykov et al., 2011). Although  $\beta_{ref}$  ranges from 0.0011 to 0.0063, depending on the type of cell (Razykov et al., 2011; Dubey et al., 2013), only one value is used for simplicity. Another issue with the equation is that it does not account for the possible increase in solar cell efficiency for cell temperatures below 298.15 K, which are rare but more relevant at high latitudes during winter. However, because  $C_{temp}$  is applied to all panels, regardless of tilting or tracking, its value has no impact on the ratio of incident solar radiation to a tilted or tracked panel to a horizontal panel. The temperature dependence appears in both the numerator and denominator of a ratio, thus cancels out.

The solar cell temperature depends on the solar flux and mean wind speed W (m/s) through

$$T_c = T_a + 0.32*F_{tot,}/(8.91 + 2*W)$$

Skoplaki et al. (2008). PV panels are placed in GATOR-GCMOM on rooftops at optimal tilt angles and in utility-scale PV power plants with either 1-axis vertical tracking, 1-axis horizontal tracking, 2-axis tracking, or a combination of all three. For the present study, all three types of tracking are assumed to be present in utility PV plants in the model. The electricity produced by all PV panels in the model is assumed ultimately to dissipate as heat, which is released back to the grid cell where the panels exist. Because the PV panels extract solar power, they reduce solar radiation to the rooftop or ground below them, thereby reducing rooftop and ground temperatures. These factors are accounted for in the model.

Whereas a radiative transfer code (Toon et al., 1989) is used here to calculate direct and diffuse radiation with different tilting cases, other studies have often relied on satellite data combined with geometric equations to estimate radiation to surfaces of different tilting (Breyer and Schmid, 2010a, 2010b; Breyer, 2012; Bogdanov and Breyer, 2016; Kilickaplan et al., 2017; Breyer et al., 2017a, 2017b; Sadiqa et al., 2018; Duffie and Bechman, 2013).

Finally, since GATOR-GCMOM simulates meteorology here in 2050 upon transitioning all energy to 100% clean, renewable wind, water, and solar power for all purposes (Jacobson et al., 2017), greenhouse gas mixing ratios in the atmosphere are higher than today, but anthropogenic aerosol emissions are virtually zero. Natural aerosol emissions still occur.

# 5. GATOR-GCMOM model results

GATOR-GCMOM was run for the year 2050 at 2.5° W-E  $\times$  2.0° S-N

horizontal resolution with 68 vertical layers between the ground and 0.219 hPa (~61 km) to estimate the ratios of incident solar flux normal to PV panels with tracking or tilting relative to flat (horizontal) panels. Fig. 3 shows the vertical component of diffuse plus direct downward radiation impinging on horizontal panels. Whereas the model calculates both downward and upward reflected radiation, only the downward components of direct and diffuse radiation are relevant for radiation impinging on a horizontal surface. Fig. 5(a) compares 2050 model predictions of zonally averaged global (direct plus diffuse) horizontal (parallel to the Earth's surface) downward radiation with 1983–2005 satellite-derived data (NASA, 2018). The uncertainty in the data is given as 10%. Considering the coarser resolution of model and the difference in years, the globally averaged difference between model and data of only 0.8% is encouraging.

Figs. 4 and 5(b) and (c) show global and zonal ratios of the radiation impinging normal to tilted or tracked panels relative to horizontal panels. For these calculations, direct solar plus diffuse radiation hitting the panels are accounted for, but the upward component of ground-reflected radiation is ignored due to the additional complexity of that calculation. This omission is likely to affect results primarily at high latitudes with higher tilt angles. However, the significant benefit of tracking and tilting without accounting for such reflection seen here suggests that omitting that part of the calculation should have no impact on the conclusions of this study.

Fig. 5(b) shows that the benefits of tilting and tracking relative to horizontal panels generally grow with increasing latitude north or south of the equator. Further, in the global and annual average, 2-axis tracked panels, 1-axis horizontal tracked panels, 1-axis vertical tracked panels, and optimally tilted panels receive  $\sim 1.39$ ,  $\sim 1.35$ ,  $\sim 1.22$ , and  $\sim 1.19$  times the incident solar radiation as do horizontal panels, respectively. As such, on average, 2-axis tracked panels receive 39% more incident solar radiation than do horizontal panels and 17% more than do optimally tilted panels. However, these ratios vary substantially with latitude (Fig. 5(b)).

At virtually all latitudes, 1-axis horizontally tracked panels receive within 1–3% the radiation as 2-axis tracked panels (Fig. 5(b)); thus, 1-axis horizontal tracking panels appear more optimal than 2-axis tracking panels because, although not calculated here, 1-axis -tracked panels likely require less land and cost less for the same output as 2-axis panels. Breyer (2012) similarly found that 2-axis tracking did not improve solar output much over a specific 1-axis tracking tested therein. 1-axis vertical tracking and optimal tilting are less beneficial than 1-axis horizontal or 2-axis tracking. 1-axis horizontal tracking receives much more incident solar than does 1-axis vertical tracking below 65° N and S, whereas above 65° N and S, the incident solar is similar for both.

Above 75° N and 60° S, there seems to be little added benefit for any type of tracking relative to optimal tilting. This result is supported further by results from Breyer (Breyer, 2012). Thus, in the absence of more local data and costs, the default recommendation here for utility-scale PV is for 1-axis horizontal tracking for all except the highest latitudes, where optimal tilting appears sufficient.

Fig. 5(c) compares the ratio of output from 2-axis panels to horizontal panels, from Fig. 5(b), with SSE data NASA, 2018 and PVWatts calculations for all countries in Table 1. The SSE curve is derived here as the sum of direct normal radiation (radiation to a flat surface normal to the sun's beam) plus diffuse radiation, all divided by global horizontal radiation. All three datasets are available from NASA (2018). Whereas, the RMS error in comparison with ground measurements for the SSE global radiation data is given as 10%, those for diffuse and direct normal radiation, which are derived from the global radiation data over 1°  $\times$  1° areas, are given as 29% and 23%, respectively. The greater uncertainty in the SSE datasets of the diffuse and direct radiation than of the global horizontal radiation may explain why the 2-axisto-horizontal radiation ratios between GATOR-GCMOM and the SSE data are less similar in Fig. 5(c) than are the global horizontal comparisons in Fig. 5(a). The fact that the PVWatts results cluster closer to

the GATOR-GCMOM model curve further suggests that the GATOR-GCMOM results in Fig. 5(c) may be slightly more accurate than the derived SSE curve.

Finally, Fig. 5(d) shows the annual average direct plus diffuse solar radiation impinging normal to panels of different orientation. The figure is obtained by multiplying the ratios in Fig. 5(b) by the modeled global horizontal radiation in Fig. 5(a). The significant result of this figure is that, over the Antarctic, although horizontal panels receive relatively little radiation, optimally tilted and tracked panels receive more sunlight than anywhere else on Earth. This is primarily due to the facts that the Antarctic receives sunlight 24 h a day in the Southern Hemisphere summer and much of the Antarctic is at a high altitude, thus above more air and clouds than over the Arctic or other latitudes, on average. Tilted and tracked panels over the Arctic receive more radiation than between 40° and 80° N, but less than over the Antarctic, due to the lower altitude and greater cloudiness above the surface of the Arctic than the Antarctic.

#### 6. Conclusions

In this study, optimal tilt angles for solar panels were first calculated for every country of the world using NREL's PVWatts program. A 3rd-order polynomial fit to the optimal tilt angles as a function of latitude was developed from the data for the Northern and Southern Hemispheres. This fit appears to give a better fit to PVWatts data above 40° N than do previous linear estimates of optimal tilt as a function of latitude. Whereas, this function and the country-specific optimal tilt angles calculated here are useful for general PV resource analyses, solar installers should calculate optimal tilt angles for their specific location for greater accuracy.

Optimal tilts found here for all countries were then input into the global 3-D GATOR-GCMOM climate model. Radiative transfer calculations were modified to calculate incident radiation normal to optimally tilted, 1-axis vertical tracking (swiveling vertically around a horizontal axis), 1-axis horizontal tracking (at optimal tilt and swiveling horizontally around a vertical axis), and 2-axis tracking panels. Ratios of incident radiation normal to panels in each of these configurations relative to that normal to horizontal panels were calculated worldwide. In the global and annual average, these ratios are  $\sim 1.19$ ,  $\sim 1.22$ ,  $\sim 1.35$ , and ~1.39, respectively. At virtually all latitudes, 1-axis horizontal tracking receives within 1-3% the incident solar radiation as 2-axis tracking. 1-axis horizontal tracking provides much higher solar output than does 1-axis vertical tracking below 65° N and S, whereas above 65° N and S, output is similar. There is little added benefit of any type of tracking relative to optimal tilting above 75° N and 60° S. The benefits of tilting and tracking versus horizontal panels virtually always grow with increasing latitude. Optimally tilted and tracked solar panels over the Antarctic receive more sunlight than anywhere on Earth, in the

In sum, when considering only optimal output (not the cost of tracking or land) for a single panel in a utility PV plant, 1-axis horizontal tracking is recommended for all except the highest latitudes, where optimal tilting is sufficient. However, final decisions about what panel to use also require knowing tracking equipment and land costs, which are not evaluated here.

Cities near the same latitude, such as Calgary, Canada and Beek, the Netherlands, can have vastly different benefits of tilting and tracking relative to horizontal panels because of the greater aerosol and cloud cover in one (Beek) over the other. An important topic for future research is to study how changes in aerosol pollution and resulting cloud cover have affected and will affect global solar radiation incident on PV panels.

Finally, because tilting and tracking are found to increase incident solar radiation at all latitudes, even near the equator, models that do not treat optimal tilting for rooftop PV and tracking for utility PV may underestimate significantly country or world PV output.

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