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Solar Photovoltaic Energy Production Conditions in the Urban Environment of Athens, Cairo, Granada and Vienna †

Stavros Vigkos [1], Panagiotis G. Kosmopoulos [2,*] and Alexandros Papayannis [3,4]

1 Department of Physics, National Technical University of Athens (NTUA), Zografou Campus, 15780 Athens, Greece; stavrosvigkos@gmail.com
2 Institute for Environmental Research and Sustainable Development, National Observatory of Athens (IERSD/NOA), 15236 Athens, Greece
3 Laser Remote Sensing Unit (LRSU), Physics Department, National Technical University of Athens, 15780 Zografou, Greece; apdlidar@central.ntua.gr
4 Laboratory of Atmospheric Processes and Their Impacts (LAPI), École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland
* Correspondence: pkosmo@noa.gr

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Abstract: This study deals with the effect of clouds and aerosols on solar photovoltaic energy in the urban environments and conditions of Athens, Cairo, Granada and Vienna, so that there is diversity in terms of cloud presence, aerosol types and irradiation levels. To this direction, satellite-based remote sensing data were used for a decade (2010–2019) from Eumetsat in conjunction with Copernicus and radiative-transfer-modelled data. Furthermore, an idealized solar energy planning scenario, making the most of photovoltaics installed on the roofs of city buildings, was investigated in order to cover the electricity needs of the pilot cities and to promote local energy security and transition.

Keywords: solar energy; cloud and aerosol effect; urban environment

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1. Introduction

The increasingly intense effects of climate change observed in recent years combined with the energy crisis in the last year, triggered by the recent developments in Ukraine, have made the imperative need for an energy transition and a transformation of cities into autonomous smart ones more evident than ever, with renewable energy sources—especially solar—to be the cornerstone. According to the International Renewable Energy Agency (IRENA), at the end of 2022, global renewable generation capacity amounted to 3372 GW, with solar accounting for almost one third of it (1053 GW; 31%) [1]. When it comes to discovering renewable energy sources (RES), geospatial analysis has received a lot of attention in the last several years. Typical studies examine feasible areas for the creation of RES, site selection, and the energy consumption and performance of residential buildings [2]. In this study, the focus was placed on the cities of Athens, Granada, Vienna and Cairo to have a representative geographical and climatic sample of Europe, North Africa and the Mediterranean basin in general. All four of these cities, following the latest global trends, invest more and more in the development and use of photovoltaics (PV) in order to cover as much of the energy needs as possible from the exploitation of solar radiation and energy.

2. Materials and Methods

2.1. Data Sources

For the benefit of this study, Earth Observation data sources and technologies were utilized to calculate the climatological levels of the solar energy potential as well as the impact of atmospheric factors. In this context, we employed the Copernicus Atmosphere Monitoring Service (CAMS) [3] with the total Aerosol Optical Depth (AOD) at 550 nm to study the impact of aerosols on solar energy production. We integrated modeling aerosols and MODIS satellite AOD data assimilation to ensure consistent data correction [4,5]. The optical features of the clouds were retrieved using EUMETSAT's Satellite Application Facility for Nowcasting (SAFNWC) and extremely short-range forecasting [6].

In addition, the urban fabric density data from the Urban Atlas [7] and the cities' maps downloaded from OpenStreetMap [8] that we processed appropriately with the QGIS [9] system were also used to estimate the building footprints of the 4 cities of interest.

2.2. Solar Energy Simulation

The sun irradiation that reaches the PV panels must be known in order to determine the power output from solar plant systems. The global horizontal irradiance (GHI) is the irradiance that PV uses. Lower GHI values indicate a higher incidence of clouds, higher air pollution, or just lower solar elevation levels. The SODAPRO service [10,11] was used for the climatological solar radiation simulations. The Photovoltaic Geographic Information System (PVGIS) [12] was also utilized to collect data on solar radiation and PV system energy generation, as well as to perform realistic numerical calculations.

Based on the aforementioned data and methods, the aerosol influence on solar energy was quantified in terms of aerosol modification factor (AMF), which is computed as follows:

$$\mathrm{AMF} = \mathrm{GHI0}/\mathrm{GHI00} \tag{1}$$

where GHI0 represents clear sky radiation, and GHI00 represents clean (from aerosols) and clear (from clouds) sky radiation. Furthermore, the cloud's optical thickness (COT) is a dimensionless measure of irradiation attenuation induced by scattering and absorption caused by the cloud's optical characteristics and microphysics. Clouds do not absorb visible light wavelengths but rather scatter and reflect the majority of visible light. To evaluate the impact of clouds on solar energy, the cloud modification factor (CMF) is calculated using the following formula:

$$\mathrm{CMF} = \mathrm{GHI}/\mathrm{GHI0} \tag{2}$$

where GHI stands for radiation under all sky circumstances, and GHI0 stands for radiation under clear sky conditions. The AMF and CMF variables have values ranging from 0 to 1, with 1 indicating clear sky GHI0 (i.e., no cloud influence) and all lower values indicating GHI with cloud effect. A GHI00 grade of 1 denotes that the sky is clean and clear. This approach estimates the independent effects of aerosols and clouds on solar energy.

3. Results

Aerosol and Cloud Effect on Solar Radiation

Figure 1 presents the monthly sums of energy lost due to the attenuation of solar irradiation due to clouds (Figure 1a) and aerosols (Figure 1b), respectively, for the decade of 2010–2019. Figures 2 and 3 summarize the annual change of each city's CMF and AMF during the same decade. From the observed data, we can conclude in terms of cloudiness that out of the four cities in Vienna, there are generally the greatest energy losses due to clouds, while the energy losses due to clouds in the other three cities fluctuate at lower levels; especially from the end of spring and until mid-autumn, we observe low to very low values, which means less effects on irradiation and therefore lower levels of cloudiness. More generally, as shown in Figure 2, over the course of the decade, the CMF for Athens, Vienna and Granada keeps increasing, while it tends to decrease for Cairo, which indicates a decrease and an increase in cloud cover, respectively. The disturbance of the phenomena of seasonality, such as mild rainfall over longer periods of time and their replacement by intense weather phenomena of very short duration, becomes indirectly evident, as well as the increasing number of prolonged drier and consequently warmer summers too, especially in the areas around the Mediterranean basin—characteristic effects of climate change. At the same time, regarding the levels of aerosols, as shown in Figure 1b, the energy losses due to aerosols reached a maximum in Cairo. As shown in Figure 3, during the decade 2010–2019, the AMF for Athens, Vienna and Granada kept increasing (decreasing air pollution), while for Cairo the AMF tends to decrease, which indicates an increase in air pollution, respectively.

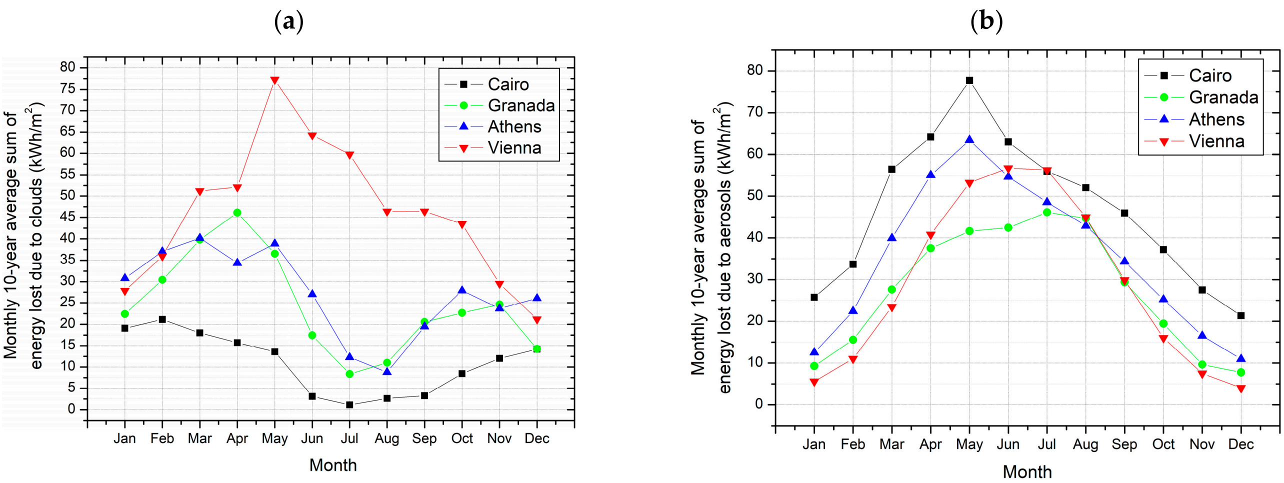

Figure 1. Monthly panels plot for (**a**) average sums of energy losses due to clouds and (**b**) average sums of energy losses due to aerosols in the 4 cities of interest during the decade 2010–2019.

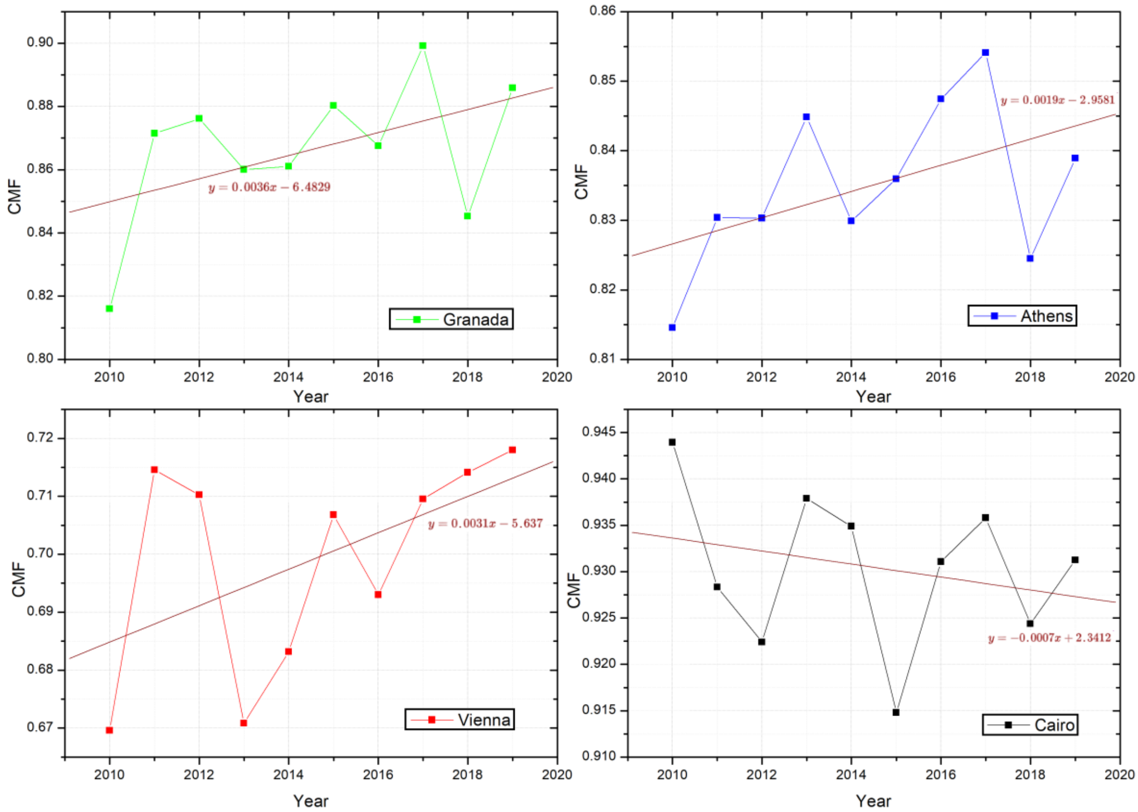

Figure 2. Annual average CMF in the 4 cities of interest during the decade 2010–2019.

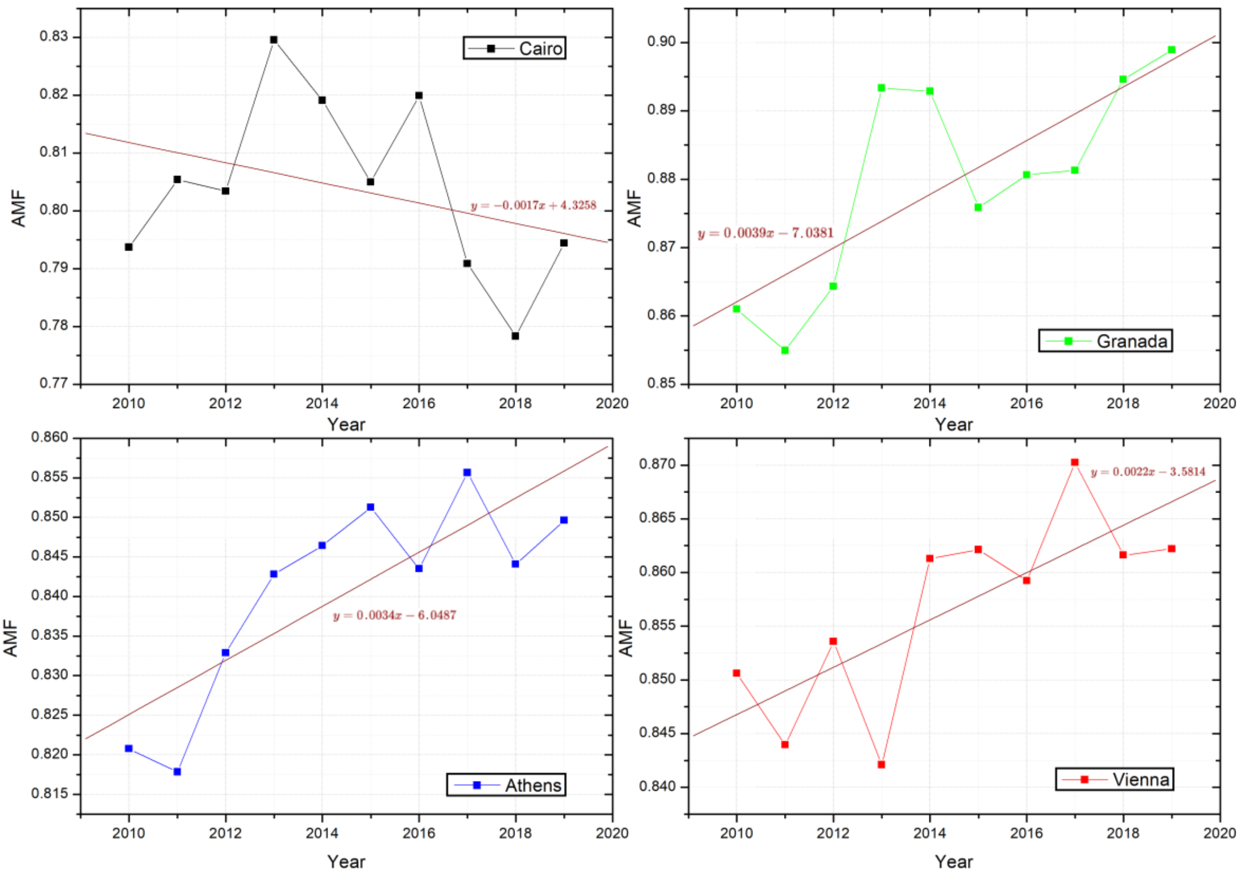

Figure 3. Annual average AMF in the 4 cities of interest during the decade 2010–2019.

4. Discussion

Summarizing the climatological results of the study, in Europe in recent years, pollution and cloud cover have both decreased, while in Egypt there is more pollution. Maximum attenuation of solar irradiation due to clouds is observed in Vienna, and the maximum attenuation due to aerosols in Cairo, Egypt after all the dust is indeed more frequent and intense than clouds during the year because of the Western Desert. These findings are in agreement with the recent literature [13–15].

Finally, an attempt was performed in rough lines to explore a rather idealized, but at the same time quite realistic, possible scenario of energy sufficiency for each city. Our ideal energy planning scenario concerns the theoretical maximum possible exploitation of the buildings' rooftops for PV installation. For this purpose, firstly, each city's building footprint (bf) was calculated using OpenStreetMap and QGIS and was subsequently multiplied by a total PV exploitability and compatibility ratio to get the exploitable and compatible bf area and the total PV production levels. Then, while assuming that an area of approximately 20,500 m^2 corresponds to 1 MWp [12,16], the final PV energy production was estimated by converting each city's PV capacity (GWp) into energy (GWh) based on the corresponding annual cumulative PVGIS 1 kWp energy output for a slope equal to the latitude for optimum energy production [16]. The following Figure 4 presents the monthly energy output from a fixed-angle PV system, using the PVGIS online tool that was set to the default performance settings of grid-connected PV systems, as well as the slope that was first set to 0° then set equal in degrees to each city's latitude coordinate. Table 1 brings together the main key points of this study's energy planning scenario.

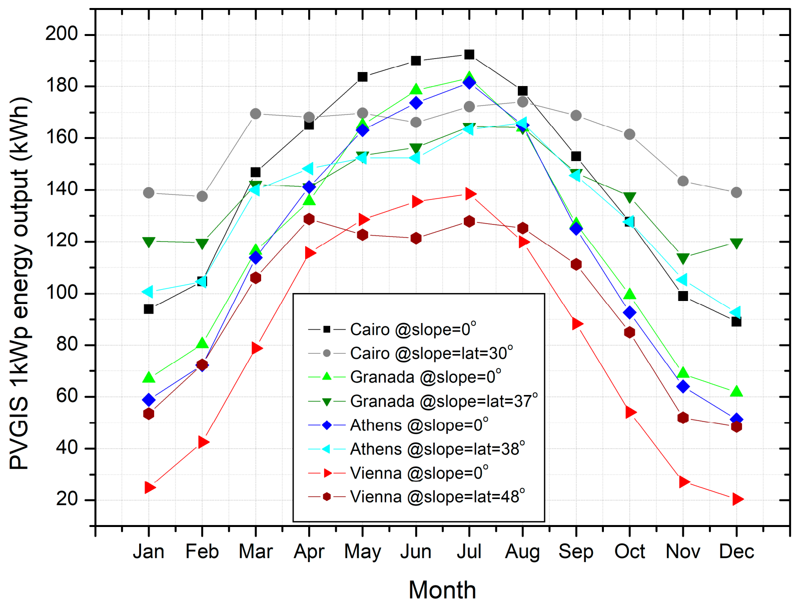

Figure 4. Monthly energy output from fixed-angle PV system using the PVGIS online tool.

Table 1. Summary table of the key elements of the energy planning scenario for each city.

City	Area (km^2)	Building Footprint (km^2)	Percentage Coverage (%)	Rooftop Exploitable/Compatible Ratio [17]	Consumption (GWh)	PV Production (GWh)	Adequacy Percentage (%)
Athens	412.00 [18]	75.35	18.0	0.42	8817.00 [19]	2962.35	33.60
Cairo	2734.00 [20]	164.04	6.0	0.56	30,897.47 [21]	8553.51	27.68
Granada	88.02 [22]	11.11	13.0	0.49	2086.48 [23,24]	445.84	21.37
Vienna	414.90 [25]	92.38	22.0	0.35	40,048.00 [26]	1821.57	4.55

Regarding the ideal energy planning scenario to examine the energy sufficiency rate of the cities through the maximum possible exploitation of all building roofs and the installation of PVs on them, as indicated in Table 1 above, Athens and Cairo have the highest adequacy percentages with rooftop solar panels producing energy equal to about a third and just over a quarter of the city's consumption, respectively (Athens is on top despite the area and consumption differences). Then, Granada follows with a PV production percentage of around one-fifth of the city's consumption, and lastly, Vienna with an energy efficiency of just 4.5%. It is therefore observed that although Athens and Vienna—in terms of area and building footprint—range at similar levels, the former can achieve almost 7.5 times more energy efficiency than the latter. This happens of course because Vienna has 4.5 times more energy consumption but is also quite reasonable and expected if we already consider the intensity of the incident solar irradiation in these cities and the PV exploitability and compatibility ratios since the architecture of Athens and even Cairo too, for example, allow a greater benefit compared to the architecture of Vienna.

5. Conclusions

In terms of solar irradiation and climatic conditions, the greatest attenuation of solar irradiation (and therefore the greatest losses in energy) due to clouds is observed in Vienna, while the greatest attenuation of solar irradiation due to aerosols is observed in Cairo. In European cities, there is a general trend towards reduced cloud cover, but at the same time, better and cleaner air quality as indicated by decreasing pollution levels, in contrast to Cairo, which experiences higher levels of air pollution.

Concerning PV production, the percentages of energy sufficiency that on-roof solar panels in Athens, Cairo and Granada would lead to are not negligible and could contribute to the transformation into green, autonomous smart cities. Especially for Athens, it is a strong indication that the city could greatly benefit from an upgraded urban design that will take into consideration the exploitation of solar energy through the roofs of its buildings to cover a fairly significant part of the daily energy demands.

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