Evaluation of Rooftop Potentiality for Solar Energy Generation Using Geographic Information Systems

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Abstract
Considering the environmental impacts of fossil fuel usage, the possibilities of oil depletion and world development needs, many efforts investigate the possibilities and feasibilities of replacement the current traditional fuel resources by clean energy resources. The geographic and climatic settings of the Kingdom of Saudi Arabia (KSA) represent an advantage in the field of solar energy generation. The issues of solar energy discussed in the terms of governmental and national actions but not in the domestic levels for the individual and family usage.

The objective of this study is to investigate the feasibility of rooftops for solar energy generation using geographic information system. Three dimensions model for an urban area in Dammam Metropolitan was built, solar energy income calculate for rooftops based on the location and elevation for every roof considering the different other possible usage for the rooftops.

The model developed in this study to evaluate the possible solar energy generated from rooftops of the building may use anywhere without restrictions, and present the result of modeling in both graphical and tabular forms.

Keywords

Introduction
Considering more than one and half centuries, since Industrial Revolution in England, of using fossil fuels worldwide, the environmental subsequences are very complicated and serious. For example, air pollution induced by cars and thermal power generation stations in great metropolitans around world, decreases the quality of life in these metropolitans. Rapid increasing of anthropogenic greenhouse emissions is another serious threat for all human kind, as a main player in the processes lead to world climatic changes.

In the other hand, human kind is no longer able to support his community’s usage of fossil fuels. There are many projections for near future depletion in oil and gas. Human kind shall choose between back to steam ages, or to modify his life style to match a world without oil (Administration, 2016).

Renewable energy is the corner stone to solve the potential energy crisis. Many researchers had investigating replacement of oil and other forms of fossil fuels by renewable energy like hydro
energy, solar energy and wind energy. Policy makers and planners have recommended strongly using renewable energy in and development plan, and they have pointed to the share of renewable to fossil energy as a mark for sustainability (Mardani, et al., 2015).

Most of renewable energy forms are dependent strongly on its spatial context. For this reason, the spatial studies are to investigate the potential of renewable energy generation. Site selection studies are wide GIS application in the field of renewable energy studies. For example, (Miller & Li, 2014) presented a geospatial approach for prioritizing wind farm development in Northeast Nebraska, USA. They applied weighted multi criteria overlay analysis to find the suitable area to host the wind farms. In the field of hydropower, (Gergepová, et al., 2013) studied the hydropower planning and environmental assessment on a watershed level. (Georgiou & Skarlatos, 2016) had using multi-criteria decision analysis and geographical information systems to find optimal site selection for sitting a solar park on a regional level. These show how the most of spatial studies in the field of renewable energy are site selection studies aims to find the best locations to host renewable energy instalments.

In the Kingdom of Saudi Arabia, policy makers, scientific community, and a regular people were developed well awareness about the energy issues. For example, King Abdullah City for Atomic and Renewable Energy has launched a Renewable Resource Atlas of Saudi Arabia to support the policy and decision makers ((K.A.CARE), 2016). Still, the approach used for this study is regional approach.

The aim of this study is to present a model to investigate the potential solar energy generation on the level of the rooftops of the buildings to support the individual and family use in the urban area. The study area chosen in the southern Dana in Dammam Metropolitan in KSA. Geographic information system (GIS) used to model the annual total radiation received by rooftops in the study area, then the electric power, which may generated by four common photovoltaic systems were calculated for each rooftop.

**Methodology**

**Total Solar Radiation Mathematical Model**

The solar radiation that received by any point on earth ground is composed of three components; direct, diffuse and reflected radiation. Direct radiation ($R_{dir}$) is a radiation that projected directly from sun to the land. Diffuse radiation ($R_{dif}$) is a radiation that scattered by clouds. Reflected radiation ($R_{ref}$) is a radiation that reflected from other landscape features. The total or global solar radiation ($R$) is the sum of these three components.

$$ R = R_{dir} + R_{dif} + R_{ref} \quad (1) $$

Each component is a function in the space.

When sun located at zenith angle ($\theta$) and azimuth angle ($\alpha$), the direct radiation received in this point, given by the following equation.

$$ R_{\theta,\alpha} = S \cdot \beta^m(\theta) \cdot T \cdot F \cdot \cos \phi \quad (2) $$

Where:

$S$ the solar constant and it is equal to 1367 W/m$^2$;

$\beta$ the transmissivity of the atmosphere;

$m(\theta)$ the relative optical path length, given by equation 2;

$T$ the time duration;
the gap fraction for the sun path; and

\( \phi \) the angle of solar radiation incidence.

The relative optical path length is a function in elevation \((z)\) and solar zenith angle \((\theta)\), given as:

\[
m(\theta) = \frac{e^{-z(k+lz)}}{\cos \theta}
\]

(3)

Where \(k\) and \(l\) are dimensionless constants equal 0.000118 and 1.638*10^{-9} respectively.

Angle of solar radiation incidence \((\phi)\) is a function in surface zenith \((\theta_s)\) and azimuth \((\alpha_s)\) angle, given by:

\[
\phi = \cos^{-1}(\cos \theta \cdot \cos \theta_s + \sin \theta \cdot \sin \theta_s \cdot \cos(\alpha - \alpha_s))
\]

(4)

The direct radiation \((R_{dir})\) for any area is the sum of the direct radiation for every point in this area, given by:

\[
R_{dir} = \sum R_{\theta,\alpha}
\]

(5)

In the case of Saudi Arabia, where the cloud cover is usually absent, and there are not any reflective landscape inside urban area like iced cover area. Both diffuse and reflected radiation may ignored. So, the total radiation \((R)\) given as:

\[
R = R_{dir} = \sum R_{\theta,\alpha}
\]

(6)

**Spatial Analysis**

To evaluate the rooftop potentiality for solar power generation, a small area with considered topographic variation selected to be the study area. This area shown in figure 1, located in the southern Danna district. The elevation of any point in any rooftop is the sum of ground elevation and the building elevation. For that reason, a digital elevation model for the study area built using contour lines produced by surveying. Figure 2 shows the digital elevation model for the study area, where the maximum elevation is 73 m and minimum elevation is 60 m.

Building and other urbanized features like fence and neighbor park in the study area are mapped using surveying and field observation. These data used to create 3D model for the study area. Figure 3 shows this model. Using buildings data, a raster shows the elevation of rooftop for every building, is produced. Rooftop elevation raster added to digital elevation model to create a new raster with rooftop elevation up to sea level.

**Photovoltaic Production Calculation**

A monthly solar map for the study area using Area Solar Radiation provided by ArcGIS 10.2. An annual solar map produced by summing of all monthly solar map. The monthly solar maps used to investigate the temporal distribution of solar radiation in the study area. The annual solar map used to quantitative evaluation for solar energy evaluation, using the global equation to estimate the electricity generated of a most common photovoltaic systems. This global equation express the electric energy \((E)\) in the following form:

\[
E = A \cdot r \cdot H \cdot Pr
\]

(7)

Where:

\( E \) the generated electric energy in kW/h;

\( A \) total solar panel area \((m^2)\);

\( r \) solar panel yield (%)
annual average on titled panels; and

performance ratio or coefficient of losses.

To calculate the electric energy generated from rooftop of building in the study area, it will considered the rooftop area available for energy generation is the one third the total area of the rooftop. Performance ratio usually ranges between 0.5 to 0.9; and for this case study, the minimum value of performance ratio (0.5) will used to express very harsh conditions in the process of solar power generation.

Equation (7) will tested for the most four common photovoltaic systems. These systems are multi cells gallium arsenide photovoltaic system with 44% solar panel yield, single cell gallium arsenide photovoltaic system with 29% solar panel yield, crystalline silicon photovoltaic system with 25% solar panel yield, and the film copper indium gallium selenide photovoltaic system with 20% solar panel yield.

**Results**

Average monthly total solar radiation receiving by rooftops in the study area shown in the figure 4. It is obvious that, the yield of solar radiation most productive months are summer months (May, June and July), where the maximum total radiation may receive is approximately $1.8 \times 10^5$ Watt/m$^2$, and the minimum is $4 \times 10^4$ Watt/m$^2$.

The annual solar map, shown in figure 5, summarizes the monthly total solar radiation maps in one map, shows how the total radiation distribution on the rooftop of the buildings in the study area. According to this map, the maximum annual receiving of total radiation on rooftops of the study area is 1.61 MWatt/m$^2$, when the minimum annual receiving of total radiation is 0.27 MWatt/m$^2$.

The annual solar map used to produce four scenarios for solar power generation using common photovoltaic systems. Figure 6 shows the potential of solar energy generation from rooftop using different four photovoltaic systems. Table 1 summarizes the potential of energy generation from rooftop for each photovoltaic system in the form of maximum and minimum yield energy.

**Discussion**

Based on the pervious analysis and result, the study area has a considered potential for solar power generation from rooftops of the buildings, as conclusion, Dammam Metropolitan has a good potential fir solar generation from rooftops.

Four scenarios were tested to quantify potential power generation. These scenarios show the power potential ranging from 0.35 to 0.02 MWatt/m$^2$ annually. This means, application of photovoltaic system on 100 m$^2$ rooftop area, may provide electricity ranging from 35 to 2 MWatt annually. Comparing with the annual consumption of Saudi citizen, which is 80 MWatt, the electricity generated from photovoltaic systems on rooftops, may provide a considered share of power consumption at individual level and community level.

**References**


Table 1. Energy generated from rooftop for four photovoltaic system.

<table>
<thead>
<tr>
<th>Energy (Watt/m²)</th>
<th>multi cells gallium arsenide photovoltaic system</th>
<th>single cell gallium arsenide photovoltaic system</th>
<th>crystalline silicon photovoltaic system</th>
<th>film copper indium gallium selenide photovoltaic system</th>
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</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>353594</td>
<td>233051</td>
<td>200906</td>
<td>141438</td>
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<tr>
<td>Minimum</td>
<td>59189</td>
<td>39011</td>
<td>33630</td>
<td>23675</td>
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</tbody>
</table>

Figure 1: Location map for the study area.

Figure 2: Study area digital elevation model.
Figure 3: 3D Model for the study area.

Figure 4. Average monthly total radiation in the study area.
Figure 5. Annual Total Radiation Map for the Rooftops.

Figure 6: Energy Output from Photovoltaic System: (a) Multi-Cells Gallium Arsenide System, (b) Single-Cell Gallium Arsenide System, (c) Crystalline Silicon System, and (d) This Film Copper-Indium-Gallium-Selenide System.