Comparative Experimental FWA & FOWA Aggregated VLCSPPs' LUR Estimation for GIS Based VEED

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Abstract- Solar power conversion technologies are photovoltaics (PV), concentrated solar power (CSP), and concentrated photovoltaics (CPV). These technologies need sufficient amount of appropriate land. In super grids and Global Grid, large sized power plants play the key role, so that this study only focuses on very large solar power plants (VLSPP). VLSPPs are defined as the power plants that have the installed power of 1,000 MW (peak in PV) or more in this study. Solar land use requirements (LUR) should be studied, analyzed and estimated for each solar power technology. This study investigates only the LUR of very large concentrated solar power plants (VLCSPPs). Under unsharp conditions, a fuzzy weighted average/weight averaging (fuzzy WA: FWA) aggregated and an ordered fuzzy weighted average/weight averaging (fuzzy OWA: FOWA) aggregated solar LUR models on a worldwide basis are built for LUR prediction on the geospatial information systems (GIS) at the very early engineering design (VEED) phase. These two models are presented in a comparative way. Five experimental criteria (direct normal irradiance: DNI, engineering design year, net installed power, cooling method, storage capacity) are only included in these models. The mean absolute percentage error (MAPE) of land area (hectares) and solar field aperture area ($m^2$) are respectively %331.35 (FWA), %505.14 (FOWA) and %914.86 (FWA), %1374.45 (FOWA).

Keywords Concentrated solar power, FuzzME, Fuzzy Ordered Weighted Average, Fuzzy Weighted Average, land use requirement.

1. Introduction

Solar power can supply the largest electricity amount to humans by 89,000 TW_p (terawatt equivalent photonic fuel power), 58,000 TW_c (terawatt equivalent chemical fuel power) [1]. It is presented that only 0.00015 TW_c was supplied in 2001 [1].

The research, development, demonstration, and deployment (RD&D) engineers try to increase the usage of this resource. In today's capabilities, there are three solar power technologies: photovoltaics (PV) [2], concentrated solar power (concentrating solar power, concentrated solar thermal) (CSP) [3], concentrated photovoltaics (CPV) [4].

Today, the CSP technology is usually classified under parabolic trough, linear Fresnel, power tower, and parabolic dish technologies [5,6] as shown in Fig.1. This study investigates all of these CSP technologies at once.

![Fig. 1. CSP technology families (Source: [5,6]).](Image)

The most efficient investment approach in solar power plants is by economies of scale approach (see [7] for economies of scale). As a result, large size solar power plants shall first be investigated in detail.

Very large concentrated solar power plant (VLCSPP) concept is researched in this manner. The definition isn't
clear yet, but it is discriminated as the CSP plants that have the installed power of 1.000 MW or more [8].

The most effective way of generating and consuming of electricity is also by considering economies of scale. Therefore, super grids and Global Grid are researched and tried to be modelled and designed (e.g. European Supergrid [9], Supergrid for America [10], DESERTEC [11], Gobitec [12,13], Asian Super Grid [12,13], Global Grid [14]).

A detailed literature review on Google Scholar [15] and Directory of Open Access Journals [16] was performed by some key terms in this study. It had been observed in previous studies that Google Scholar had been the most dominant academic publication online database (highest number of documents for each search term: author's experience). Moreover, both of these online websites had "open access" publications, so that all RD\(^3\) engineers would be able to find these publications.

The search term of this study was "land use" and "concentrated solar". Only English documents were searched on Google Scholar (1930 results) and Directory of Open Access Journals (0 results) until 21/12/2015. The titles and abstracts were first reviewed and the related documents (papers, reports, presentations, etc.) with this study were saved in their specific folder (only 19 studies). After this observation, previously known documents on some websites (e.g. [17-21]) were also once more checked. Only a few documents could be added, but one of them was the most important one (Ong et.al.'s study at the National Renewable Energy Laboratory (NREL): author's point of view).

Ong et.al. studied the direct land use ("disturbed land due to physical infrastructure development") and the total land use ("all land enclosed by the site boundary") requirements of the utility scale ground mounted small and large photovoltaic (PV) and concentrating solar power (CSP) plants in the United States [22]. There were 25 projects with a capacity (MW\(_AC\)) of 3747 in the total land use requirements for CSP plants (parabolic trough, tower, dish Stirling, linear Fresnel) analysis. The capacity weighted average land use (acres/MW\(_AC\)) was presented as 10 and the generation weighted average land use (acres/GWh/yr) was given as 3.5. There were 18 projects with a capacity of 2218 in the direct land use requirements analysis. The capacity weighted average land use was presented as 7.7 and the generation weighted average land use was presented as 2.7. In their dataset, the least installed power (MW\(_AC\)) was 1.5 (Maricopa Solar Project with Stirling Engine) followed by 5 (Sierra SunTower with tower). The most installed power was 370 (Ivanpah all with tower) followed by 354 (SEGS all with parabolic trough) and 280 (Solana all with parabolic trough) [22]. Purohit et.al. investigated the possibility of generating electricity from CSP technologies (parabolic trough collector, linear Fresnel reflector, central receiver system: tower with heliostats, parabolic dish) in the Northwestern India [23]. They presented that the area (collector/heliostat (m\(^2\)) was 34–550 (parabolic trough), 40–120 (central receiver), 92 (dish). They also added that the land requirement (m\(^2\)/MW) was 40000 (parabolic trough), 83600 (central receiver), 18000 for linear Fresnel and 16000 for dish [23]. Other studies also gave some similar information (see [24-29]).

It was understood that fuzzy WA and OWA aggregated based models hadn't been applied in any CSP LUR analysis study until 21/12/2015. Hence, this study is also one of the first studies that step up VLCSPP designs on the World, however, it had to be underlined that there were already some announced intentions (Morocco's Noor-Ouarzate Solar Complex aimed 2000 MW, designed as only for 510 MW by I, II, III at a cost of US$ 2677 million [30,31,32], Oman's Miraah aimed 1021 MW thermal only for steam at a cost of US$ 600 million [33,34], China's Ordos aimed 2000 MW at a cost of US$ 5 billion [35,36], Tunisia's TuNur CSP farm aimed 2250 MW at a cost of US$ 13.8 billion, with a note of the DESERTEC's cancellation/withdrawal at a cost of US$ 530 million [37,38,39,40]). Thus, VLCSPP designs are only remained as intentions today.

Shortly; it is deducted that by looking at figures E-1 to E-4 on [22], LUR and capacity of CSP plants in the U.S.A. don't show any linear characteristics. It is stated that this study is most probably a unique (the only one and first) in this field in this respect. There are five aims of this study as to start helping to model Global Grid, to start helping design process of VLCSPPs in Global Grid and other grids, to start helping to find possible alternative VLCSPPs locations in Global Grid by geographic information system (GIS) tools (e.g. ArcGIS, Google Earth, Netcad) in very early engineering design (VEED) stages, to start studying LUR estimations of VLCSPPs and CSPPs, to start modelling LUR estimations by fuzzy weighted average/weight averaging (fuzzy WA) aggregated models and ordered fuzzy weighted average/weight averaging (fuzzy OWA) aggregated models, to start a GIS tool RD\(^3\) for VLCSPP design process.

2. Preliminaries & Experimental Fuzzy WA & OWA Models for VLCSPP Design GIS Tool

These experimental proposed fuzzy WA and OWA aggregated models have 5 factors/inputs and 2 outputs/finding (Factor 1: F\(_1\): Direct Normal Irradiance, F\(_2\): engineering design year, F\(_3\): net installed power, F\(_4\): cooling method, F\(_5\): storage capacity factors, Finding 1: O\(_1\): solar field aperture area, O\(_2\): land area). The author believes that simple models obeying strictly main principles and approaches will show the RD\(^3\) progress direction (factor reduction or increment, defining membership functions). One of the important modelling principles in this subject is the magical number 7 (George Armitage Miller (1920–2012) (magical number 7) [41], Richard M. Shiffrin (1968–alive) and Robert M. Nosofsky (alive) (magical number 7, 7±2 rule) [42]). Accordingly, only 5 factors are used in this study as:

- F\(_1\): Direct Normal Irradiance (DNI) (kWh/m\(^2\)/year):

  "direct irradiance received on a plane normal to the sun over the total solar spectrum" [43]. DNI is used for CSP and concentrating photovoltaic (CPV) systems [8,43,44]. Solar spectrum discrimination isn't taken into account in this study.
CSP minimum DNI rule of thumb or application (kWh/m²/year): 2000 [6], 1800 (technical), 2000 (economical), 1600 (future technical) [23], 902 (demonstration solar tower), 2012 (commercial example) [26], 2000 (commercial) [28], 1800 (5 kWh/m² day) [29], 800–900 W/m² (normal incident radiation), 1600–2800 kWh/m² (annual normal incident radiation) [45], 2.2 MWh/m²/year or 6.0 kWh/m²/day (annual average) [46], limited suitability below 1800, suitable 1800–2000, highly suitable 2000–2500, excellent 2500–3000 [47], 800 W/m² (normal incident radiation) and range 1600–2800 [48].

Location & design constraint: DNI ≥ 1600 kWh/m²/year (decision in this study).

It can be seen on Fig.2, that the possible VLCSPPs' regions are dispersed on the World very smoothly just like created for only super grids and Global Grid. The Creator wants us to think on a worldwide basis (only one piece, spacious enough). Hence, super grids and Global Grid is seemed very possible.

Fig. 2. Rule of thumb representation on DNI World Map for following GIS investigation studies (white regions) (Basemap: GeoModel Solar [49]) (generated by Microsoft Office Excel 2007 https://products.office.com/en-us/home or Apache OpenOffice 4.1.5 http://www.openoffice.org/ & Paint.NET http://www.getpaint.net/index.html).

F3: Engineering Design Year:

The RD³ engineer (author) thinks that technical and technological breakthroughs are important in CSP technology, so that it should be taken into account during modelling.

The author (also by his own conceptual design studies) very well knows and experiences that design date and grid connection date has more than some decades duration gap. Technical and technological capabilities are related to design. Hence, engineering design years are tried to be estimated in this study (10 years earlier than generation start date).

F4: Net Installed Power (Net Turbine Capacity in MW):

This factor is the most important factor in this study. When the installed power of a CSP plant increases the LUR increases. The net installed power and the net turbine capacity are used in the same manner in this study. The unit is taken as megawatt (MW). The current model covers up to 5.000 MW according to design of 1.000 MW at first.
A few preliminaries of fuzzy WA and OWA:

Fuzzy weighted average (see original [61] to avoid any misinterpretation or shift):

normalized fuzzy weights ∀ fuzzy numbers

\[ V_i \in [0,1], i = 1, 2, ..., m \text{ if} \]

∀α ∈ (0,1) ∧ ∀ i ∈ [1,2, ..., m] following holds

\[ v_i \in V_\alpha \text{ there exists} \]

\[ v_j \in V_\alpha, j = 1, 2, ..., m, j \neq i \text{ s.t.} v_i + \sum_{j=1,j\neq i}^{m} v_j = 1 \]

fuzzy weighted average ∀ fuzzy numbers

\[ U_i \in [0,1], i = 1, 2, ..., m \land W_j \in [0,1], j = 1, 2, ..., m \]

membership function

\[ U(u) \forall u \in \mathbb{R} \text{ is} \]

\[ U(u) = \max \{ \min(U_1(u_1), U_2(u_2), ..., U_m(u_m), W_1(w_1), W_2(w_2), ..., W_m(w_m)) \}

\[ u = \frac{w_1u_1 + w_2u_2 + \cdots + w_mu_m}{w_1 + w_2 + \cdots + w_m} = \frac{\sum_{i=1}^{m} w_i u_i}{w_i \neq 0} \]

For the computing algorithm of its calculation see [61,62].

Fuzzy ordered weighted average (see original [62,63]):

\[ u = \frac{w_1u_{G(1)} + w_2u_{G(2)} + \cdots + w_mu_{G(m)}}{w_1 + w_2 + \cdots + w_m} = \frac{\sum_{i=1}^{m} w_i u_{G(i)}}{w_i \neq 0} \]

where \( \emptyset \) a permutation of the set of indices

\[ u_{G(1)} \geq u_{G(2)} \geq \cdots \geq u_{G(m)} \]

For the computing algorithm of its calculation see [62,63].

These preliminaries are all founded on the ordered weight averaging (OWA) operator by Ronald Robert Yager (alive) [64] and the fuzzy set and logic by Lotfali Askar Zadeh (1921–alive) [65]. The fuzzy logic operators are clearly presented by Henrik Legind Larsen [66] (Fig.4).

In this study, the models are directly built on the FuzzME Software (developed by Holecek, Talasova, Pavlacka and BebcaKova [57,58]). There are many modelling options on it (fuzzy weighted average, OWA, WOWA, Choquet integral, expert system). Fuzzy WA & OWA are only applied in this experimental study due to the inspiration of some studies by fuzzy WA and OWA in other fields (e.g. [59,60]).
method, storage capacity (Increasing), Land Area (1/1 scaled) & Solar Field Aperture Area (1,79 multiplied and 1/1000 scaled) on the FuzzME.

These experimental models are tested on the historical projects data and information (see ESM) by using FuzzME and Microsoft Office Excel or Apache OpenOffice 4.1.5 (Fig.7). The errors are calculated according to the absolute percentage errors (APE), the maximum absolute percentage error (MAP), and the mean absolute percentage error (MAPE) like demand forecasting studies (see [67-72]). The MAPE of land area (hectares) (O₈) is 331.35 (FWA) and 505.14 (FOWA). The main errors occur for very small land area projects or small installed power projects (land area: 8; 6.5; 5.3; 1). When these projects are removed from the data set the model performance for MAPE increases approximately 6 times better. When the installed capacities increase in this model, the performances increases very well (For 377 MW error rate is 4%). As a result, this model works well in bigger CSP plants rather than in small CSP plants in its current form (Fig.7). The MAPE of solar field aperture area (m²) (O₆) is 914.86 (FWA) and 1374.45 (FOWA). The same problem is observed in these models too. The main errors occur for very solar field aperture area projects or small installed power projects (solar field aperture area: 31860; 100000; 10000; 17650; 75000; 150000; 400). When these projects are removed from the data set the model performance for MAPE increases approximately 18 times better. When the installed capacities increase in this model, the performance increases very well (For 377 MW error rate is 4%). As a result, this model works well in bigger CSP plants rather than in smaller CSP plants in its current form (Fig.7). When these fuzzy WA and fuzzy OWA models are compared, it is observed that the current fuzzy WA model is performed better. However, it is very clear, that these models need very serious improvement efforts, but it is also thought that this study is a good start for this research aim. Finally, some very large concentrated solar power plants (VLCSPPs) designs’ land use requirement predictions are also made by the experimental FWA model (better performed model) on the Middle East and North Africa Region (F₁: between 2500 and 2600, F₂: between 2018 and 2020 (estimated early design calculations), F₃: 500, 1000, 1500, 2000, 3000, 4000, 5000 (six alternative designs), F₄: Dry, F₅: between 10 to 18) (Fig.7).

Fig. 5. Membership functions on FuzzME (open FuzzME models) * Note: from top to bottom: DNI (Increasing Scale: higher values are better), engineering design year (Increasing), net installed power (Increasing), cooling method, storage capacity (Increasing), Land Area (1/1 scaled) & Solar Field Aperture Area (1,79 multiplied and 1/1000 scaled) on the FuzzME.

Fig. 6. Weights of fuzzy WA & OWA on FuzzME (open FuzzME models) * Note: Fuzzy WA weights (top), Fuzzy OWA weights (bottom)
One of the main outputs of these R&D efforts shall be some GIS applications (online and offline) for personal, laptop and tablet computers and also mobile phones. The design studies will be performed according to GIS software, coding and cognitive ergonomics principles and constraints in some specially organized R&D studies in near to medium term (Fig.8).

3. Conclusions and future work
This study presents a new idea of developing some plugins and applications on the geographic information systems software for the concentrated solar power plants land use requirements and estimations.

A comparative experimental fuzzy weighted average (fuzzy WA) and ordered fuzzy weighted average (fuzzy OWA) aggregated VLCSPPs land-use requirement estimation model is presented for very early engineering design studies (only on FuzzME, no integration of any GIS yet).

It is believed that these kinds of plugins, applications, and tools will increase the efficiency and effectiveness in the early engineering stages.

The models should be studied in detail with different approaches and views. Afterwards, GIS plugins and tools can be developed and presented for real world applications of international organizations, multinational foundations, governments, and investors.

These tools will hopefully very helpful for developing Supergrids and Global Grid, that will urgently be a must in mid to long term, when some critical issues are taken into account (see critical issues [75,76]).

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