The Role of CSP in the Electricity System of South Africa – Technical Operation, Grid Constraints, Market Structure and Economics

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Abstract. This paper analyses the role of solar technologies (CSP and PV) and their interaction in the South African electricity system by using a fundamental electricity system modelling (ENTIGRIS-SouthAfrica). The model is used to analyse the South African long-term electricity generation portfolio mix, optimized site selection and required transmission capacities until the year 2050. Hereby especially the location and grid integration of solar technology (PV and CSP) and wind power plants is analysed. This analysis is carried out by using detailed resource assessment of both technologies. A cluster approach is presented to reduce complexity by integrating the data in an optimization model.

1. Introduction

South Africa`s electricity supply is characterised by structures, that can not sufficiently meet the demand requirements. The demand has strongly increased over time. For this reason renewable energy technologies became an attractive alternative to conventional power plants such as coal. Today, coal is the major energy source which supplies about 85% of the total electricity demand. In 2014, only about 5% of the electricity demand is generated by renewable energy sources (RES).

First renewable energy projects have successfully led to the REIPPPP (Renewable Energy Independent Power Producer Procurement Program) [1]. Currently, a total of 92 projects have been awarded which will contribute 6,327 MW of renewable electricity supply by 2025 [1]. Under these projects, a major part is installed as Photovoltaic (PV) and Concentrated Solar Power (CSP) plants. By 2030, the energy strategy of South Africa includes a generation capacity extension from 45 GW to 81 GW. In terms of generated electricity, about 30% is targeted to be supply by RES in 2030. In the future, the increasing share of renewable energy leads however to an increasing demand for grid strengthening and balancing of the fluctuating renewable resources. Moreover, the different levels of wind resource and solar radiation provide technical and economic questions that are addressed in this paper regarding the overall system benefits from PV and CSP in the South African electricity system. Furthermore, in a system based on renewables, a large amount of decentralized power plants operate in the market. This issue increases certainly the complexity of interactions and dependencies in the system and similar in the quantitative analysis of this system.

The following overall research question is targeted with this paper: What are the effects of high share of large-scale solar power plants on the energy system in terms of total system cost, the cost optimal technology mix, the security of supply, the necessary grid extensions and the unit commitment as well as the power flow?

However, this paper gives a first introduction on the potential role of CSP in terms of resource potential in comparison with PV. This comparison is necessary to be able to carry out a comprehensive system analysis based on high resolution data for renewable energy feed-in, grid constraints and location planning.

2. Resource Data and Link to Energy System Model

To answer the research question all potential areas for the implementation of photovoltaic (PV) and concentrating solar power (CSP) are identified within an in-depth, spatial-temporal GIS (geographic information system model) analysis for integration in the energy system model ENTIGRIS [2]. Onshore wind power is also analyzed in the model, but it is not focus in this paper.

Within the GIS model, all potential areas for the implementation of photovoltaics (PV), concentrating solar power (CSP) and onshore wind power are identified. The following overview shows the used data in the analysis.

- Spatial-temporal solar radiation data (GHI and DNI) with 20 x 20 km resolution is derived from the National Centers for Environmental Prediction (NCEP) Climate Forecast System[2]

- Suitable areas for large-scale solar power plants are determined from several criteria to select the optimal site:
    - Distance to substations and transmission lines (GCCA by ESKOM [3])
    - Slope and aspect (DEM by NASA with 90 x 90 m spatial resolution[4])
    - Land use profile (Land-Cover Dataset by GEOTERRAIMAGE with 25 x 25 m spatial resolution[5])
    - Nature conservation areas and other unsuitable areas have been excluded

The basis for the resource assessment is the analysis of the renewable electricity generation potential as well as the transmission capacity potential. The data for these potentials (PV and CSP) is derived from solar radiation data [6] by GeoModel Solar, wind speed data [7] by the NASA (United States National Aeronautics and Space Administration), the land use profile data [5] by GEOTERRAIMAGE and the transmission development plans GCCA-2022 (Generation Connection Capacity Assessment of the 2022 Transmission Network) [3] by Eskom. The following figure 1 shows the basic data on solar data, suitable land and transmission grid for PV and CSP in South Africa.

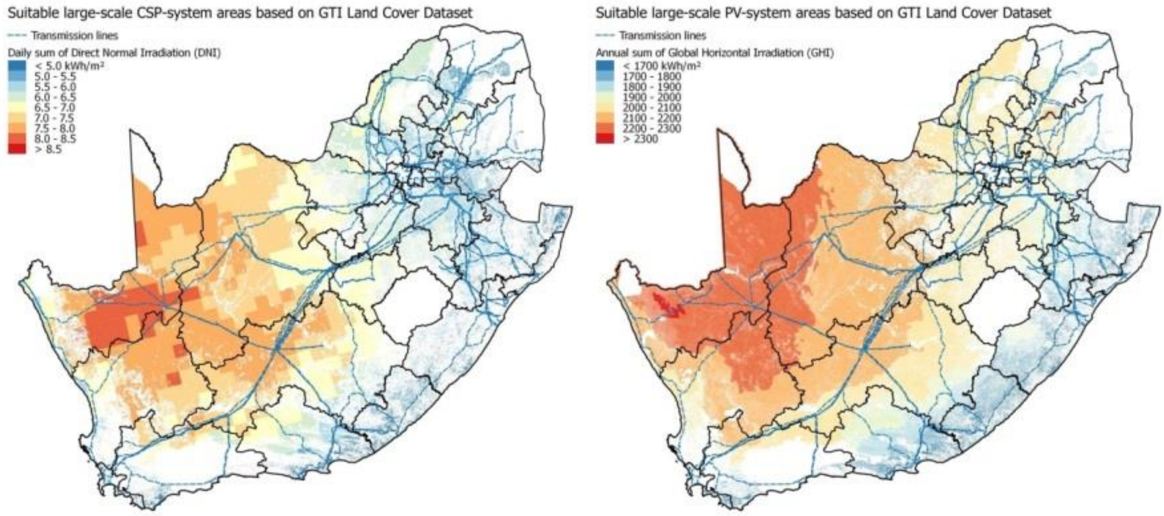


Figure 1. Suitable areas for CSP and PV, solar radiation and grid in the South Africa electricity system

In this paper, an approach is shown how this data is then proceeded to be able to integrate these data in an optimization model for power plant expansion and system operation for the electricity system in South Africa.

The energy system model is able to model the role of CSP and PV in the electricity system. Consequently, the user receives quantitative data to be supported by analyzing this role in the electricity system. The objective of the optimization formulated as a linear problem in GAMS is to compare different electricity generation and transmission technology options while minimizing the system and operation costs of the required technology mix and infrastructure for the electricity supply in South Africa. The model optimizes the expansion and the unit-commitment of CSP plants in the overall power system by considering the grid constraints and geographical typology.

The South African version of the optimization model ENTIGRIS is a modification of the European version and covers the electricity system in detail [2,8]. It optimizes the connection between the existing conventional power plant systems with a high resolution of renewable energy generation. Furthermore an endogenous expansion planning for power plants and transmission lines between the South African regions over the next 40 years are key features within the model. The expansion problem of the electricity generation technologies and the transmission grid is modeled with a high geographical resolution. South Africa was divided in 24 different regions for electricity demand and production. The Figure 2 shows the general input and output data of the optimization model which optimizes total cost for expansion planning and system operation over a specific time horizon (e.g. 20 years). The models has the advantage to be able to include CSP potentials (but also other renewable energy technologies) per region and optimizing the PV, CSP and wind onshore and conventional power plant portfolio under demand, supply and transmission capacity constraints at the same time.

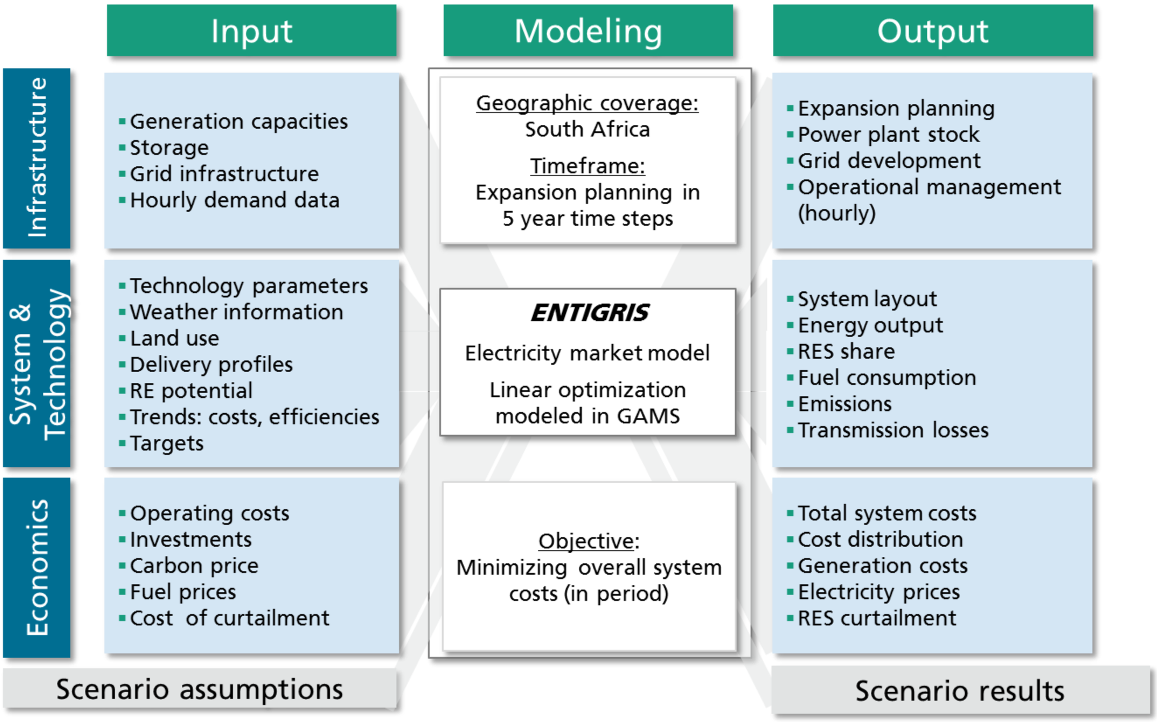


Figure 2. Input and output of the energy system optimization model ENTIGRIS-SouthAfrica

3. Method for Integration of RE Potential and Generation Profiles in Energy system Model

A cluster analysis is carried out to link radiation and area analysis with the electrical grid and demand structure by using electrical zones which represent the current electricity system. However, to reduce the data set, a suitability factor is introduced which rank the land use according to the current land use. E.g. flat areas with existing infrastructure, but without any buildings, streets or any other permanent use is ranked very high compared to agricultural land which receives lower suitability factors. Additionally, distance to transmission lines [3], slope and the land use profile [5] per region are analyzed to select optimal renewable energy sites.

For the aspect in decrees the following assumption is made (see TABLE1)

TABLE1. Suitability based on aspect and slope

Slope in Percent		Aspect in Degrees									
		North		East		South		West			North
min		0	22.5	45	90	135	180	225	270	315	337.5
	max	22.5	45	90	135	180.0	225.0	270.0	315.0	337.5	360.0
0	2	1	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	1
2	5	1	0.8	0.7	0.25	0.25	0.25	0.25	0.7	0.8	1
5	15	1	0.8	0.5	0	0	0	0	0.5	0.8	1
15	30	0.5	0.5	0	0	0	0	0	0	0.5	0.5

After CSP and PV suitability factors are based on slope and aspect, the following classification is defined by the authors:

- 0.75 high (Class 1)
- 0.75 – 0.5 medium (Class 2)
- < 0.5 not suitable

Regarding the suitability of areas in distance to the transmission grid, it was assumed that areas which have a distance with more than 100 km from the existing transmission grid (transformer station), receive only a suitability factor of 0.5.

In the following figures the suitability for PV and CSP is displayed. It can be found out that the existing grid structure has an important impact on the potential location as some region of the country suffers currently large transmission lines. However, it can be assumed that in these areas electricity demand will remain low as human population does not exist in these areas.

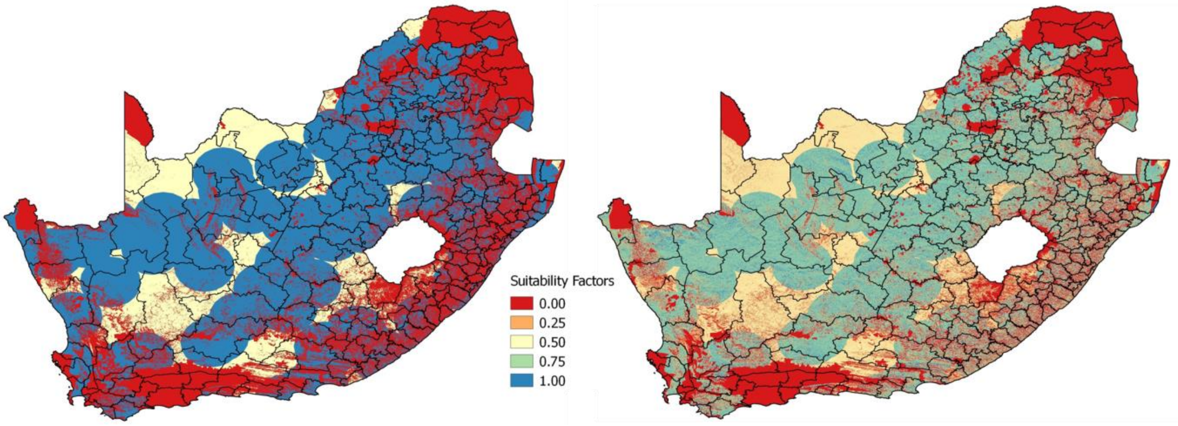


Figure 3. Map of South Africa with suitable factors for the installation of large-scale CSP plans (left, areas with a max slope of 4 % assumed suitable) and large-scale PV plants (right)

In the next step, this information is then clustered and linked with the electrical grid and demand structure by using electrical zones which represent the current system. Target is to obtain only 50 standardized generation time-series cluster regions which are related to the structure of the electrical grid and demand in South Africa. Of course, this approach can be transferred to other countries or electricity systems, but the clustering is always depending on the underlying data for demand and transmission grid.

The presented methodology helps to define similar weather and potential areas and to obtain provincial power generation potential. In the next step the local potential per model region (result of the clustering analysis) and the generation profiles are then integrated in the energy system model ENTIRGRIS.

4. Results

Analysing the weather data, demand structure and grid capacities, it turns out that for CSP and PV the regions displayed in Figure 4 are an optimal aggregation level to integrate them in an energy system model. Each region obtains a similar generation profile and a resource capacity. With this result, it is avoided to represent each single power plant in the model.

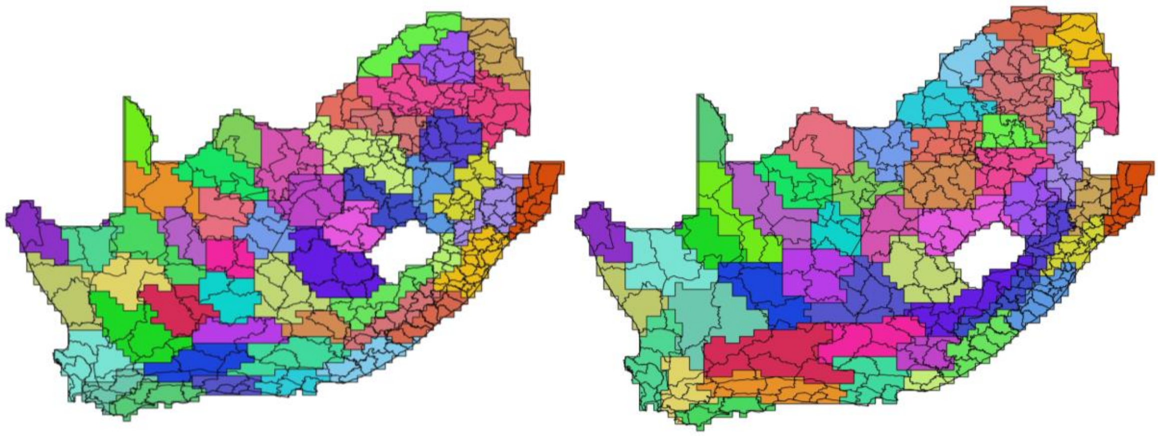
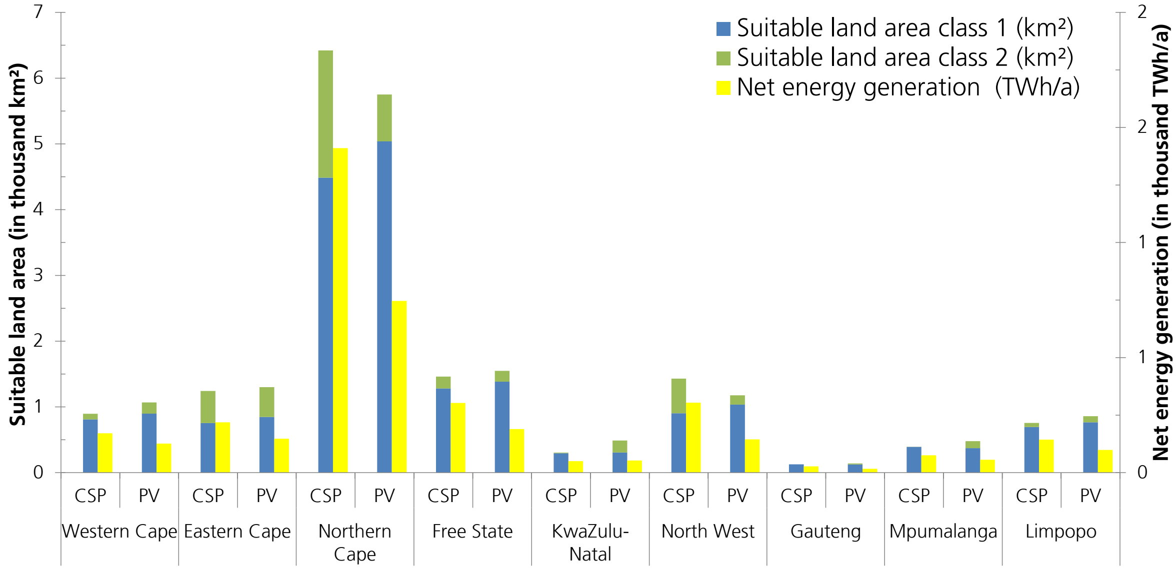


Figure 4. Cluster regions of CSP (left) and PV (right) representing the hourly standardized generation time series per technology in the ENTIGRIS model

In terms of potential area for solar power plant, the result is a huge area distributed all over the country. However, Northern Cape has the highest potential due to its size and current land use (Figure 5). The comparison between suitable class 1 and 2 shows for many regions in South Africa a positive result as most of the areas represent also suitable class 1. Potentially, thousands of TWh can be produced by CSP and PV on this potential areas.



5. Conclusions and Outlook

The spatial-temporal pre-analysis shows that there is indeed a huge potential for large-scale solar power plants in every South African province which will guide the way to the diversification of the power generation portfolio. Based on this analysis, different suitable classes per region are identified and local potential (in terms of potential land use) is quantified. In many regions, vast potential of renewables exists. However, Northern Cape shows the largest area for potential power plants. But only a combined analysis of demand structure, grid structure, and renewable resources can define the optimal structure of the future electricity system in South Africa. The clustering approach supports the analysis of RE potentials, location planning and defining a role in the energy system as complexity is reduced and similar power plants and locations are aggregated.

Energy system analysis supports the decision on an optimal portfolio mix and assists decision makers in investing in cost optimal energy technologies. Outlook on the next research steps show: Within such an analysis all elements of the system in South Africa, including demand, generation and the grid are optimized and as a result the role of CSP in an optimally planned future energy system of South Africa can be shown. Operating hours, storage size and location planning are the key issues for decisions in investing in CSP. This analysis leads to the answers how many CSP plants can be installed economically in the South African energy system and where they should optimally be installed. Furthermore, required large-scale grid extensions which are needed with an increase of renewable expansion are identified. From this analysis the optimal locations, CSP layouts, economics of the CSP integration as well as a cost optimal expansion path for CSP in the South African energy system can be concluded. Our results will show that in the long-term the South-African electricity system (with low CO2 emissions) requires the CSP expansion to balance the overall system and to dispatch electricity generation at every point of time.

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