South African maize production: mitigating environmental impacts through solar powered irrigation

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ABSTRACT

Agriculture is among the largest contributors to global greenhouse gas emissions. Clean technologies, such as renewable energies, have the potential to significantly reduce these environmental repercussions of agriculture. Countries like South Africa have a coal intensive electricity mix, as well as high solar irradiation and a dry climate which is why agricultural crops are produced under fossil energy intensive irrigation. At the same time, the high solar irradiation could be used for the generation of photovoltaic electricity as a renewable power supply for irrigation. A joint research project between the University of Cape Town and the Zurich University of Applied Sciences quantified the environmental impacts of South African maize production (Zea mays) and the improvement potential of maize irrigation with photovoltaic electricity by means of life cycle assessment (LCA).

The LCA includes the whole value chain of maize production from cultivation to storage in a silo for six months, respectively with a functional unit of one kilogram of maize at silo storage produced either on dry land or under irrigation. Electricity consumption for irrigation was identified as an environmental hotspot in the impacts related to greenhouse gas emissions from maize production. Therefore, clean electricity would be the starting point to reduce the carbon footprint of South Africa’s maize. We calculated that replacement of South African electricity mix with photovoltaic electricity in the maize irrigation can reduce environmental impacts by up to 47%. The calculated greenhouse gas emissions per kilogram of maize on dry land without irrigation, under irrigation and under irrigation using photovoltaic electricity, are 0.50 kg CO₂-eq. and 0.82 kg CO₂-eq. and 0.54 kg CO₂-eq., respectively, with a potential reduction of 33% if the electricity is supplied from photovoltaics compared to the conventional fossil electricity mix. The analysis of further indicators reveals a reduction for non-renewable energy demand (nuclear and fossil), acidification, freshwater eutrophication and human toxicity of carcinogenic substances. The irrigation of a maize field of one hectare consumes 1’900 kWh of electricity per year, which, in turn, requires a solar power plant with an area of 9 m². We computed that a total area of 199 ha of solar panels would suffice to produce the total electricity requirement of the current maize production area under irrigation. This corresponds to more than approximately 500’000 t CO₂-eq. saved per year.

Compared to data representing maize production in the United States and in Switzerland, South African maize production has a higher global warming potential per kilogram of maize due to lower yields in South Africa.

The replacement of the South African electricity mix in the irrigation with electricity from photovoltaics has proven to be an effective clean technology to reduce environmental impacts associated with maize production in South Africa. Compared to the irrigated field area, land use for PV panels is almost negligible and is therefore no limiting factor in the implementation of irrigation using photovoltaic electricity.

Keywords: Photovoltaic, greenhouse gas emissions, crop production, emerging economy

1. Introduction

Maize is the major feed grain and the most important staple food for the majority of South Africa's population. South African maize production is largely dependent on sufficient and timeous summer rainfall and can reach 12 million tonnes per year, planted in an area of over 2.6 million hectares (Grain SA, 2014). Maize is produced throughout South Africa. The provinces Free State, Mpumalanga and North West are the largest producers, accounting for approximately 83% of the total production.

A distinction is made between maize production for feed and for human diet. White grain maize is primarily produced for human consumption and is on average 60% of the total maize production area in South Africa. Yellow maize is mostly used for animal feed and comprises about 40% of the total South African maize production area (DAFF, 2014).

In 2013 there was a shift towards higher maize production for animal feeding at the expense of maize production for human diet. The production volume of maize for feeding was 5'933'100 t spread over an area of 1'164'000 ha. The production of white grain maize for human diet is estimated to 5'580'300 t planted on 1'617'200 ha (Grain SA, 2014).

Agriculture is among the largest contributors to global anthropogenic non-CO₂ greenhouse gas emissions, accounting for 56% of emissions in 2005 (IPCC, 2014). While animal production contributes most by methane emissions, arable production is associated with dinitrogen monoxide emissions (Johnson et al., 2007).
In South Africa crop irrigation is typically operated with fossil fuel based energy. Using green and clean technologies, such as renewable energies, some of the environmental impacts of agriculture can be reduced.

In a joint research project between the University of Cape Town and the Zurich University of Applied Sciences the environmental impact, as well as the potential for improvement through the use of clean technologies, was assessed for South Africans maize production.

2. Goal and Scope

In order to define optimization strategies through the use of clean technologies, a Life Cycle Assessment (LCA) of the status quo of the grain maize production in South Africa for human diet was performed, following the ISO 14040 and 14044 standards (ISO, 2006a; 2006b). The system boundaries of the LCA include the whole value chain of grain maize production, from seed bed preparation, to maize cultivation and harvesting, to storage of the harvested maize in a concrete silo for approximately six months. The LCA considers the production and application of fertilizers and pesticides, as well as the particular use of irrigation water. Land use, direct field emissions, the production and use of tractors and agricultural machines and consequential diesel consumption of tractors in use as well as transport are also taken into account. The most relevant production data, including production area, application of fertilizers and pesticides, diesel consumption and yield, were taken from planning models provided by Grain SA, the national representing and consulting institution for grain producers in South Africa (Grain SA, 2014). The planning models, which give a detailed compilation of any costs in the maize production, cover the circumstances of grain maize production in three different regions of South Africa: Eastern Highveld, North West, and Central and Northern Free State. As a functional unit one kilogram of grain maize at silo storage produced either on dry land or under irrigation for human diet was defined.

South Africa has a high level of solar irradiation and a dry climate, which leads to an agricultural crop production under irrigation. Electricity supply for irrigation is a coal intensive electricity mix, leading to high environmental impacts, which are associated with irrigation. The goal of this study was to quantify the reduction potential by using solar irradiation for the generation of photovoltaic electricity as a renewable power supply for irrigation.

The environmental impacts were assessed using five different impact indicators, namely climate change according to IPCC (2013), the cumulative non-renewable energy demand according to Hischier et al. (2010), acidification and freshwater eutrophication according to the European Commission (2011), and human toxicity (cancer) according to Rosenbaum et al. (2008).

3. Life Cycle Inventory

In 2013, 82'000 ha with grain maize for human diet were irrigated in South Africa. Under irrigation yields are higher but also the use of fuel and need for fertilizers increase. An overview of the key inventory data for South African maize production for human diet on dry land and under irrigation is given in Table 1. Transport distances are estimated using online distance calculators for sea and land routes.

Field emissions to air as nitrous oxides (N₂O) and ammonia (NH₃) and leaching of nitrate to ground water (short and long term) are calculated according to Meier et al. (2012; 2014). Phosphate emissions to ground water through leaching and to surface waters through run-off and water erosion, as well as emissions of heavy metals to soil are modelled according to Nemecek et al. (2007). In addition, all pesticides applied for maize production were assumed to end up as emissions to the soil (Nemecek et al., 2007). Background data for the life cycle inventories were taken from the international ecoinvent v3.2 database using the system model “allocation, recycled content” (ecoinvent Centre, 2015).

Seed, pesticides and fertilizers are transported by lorry from retailers to the farm (650 km) and harvested maize is transported from the field to the farm and further to a silo co-operation by tractor (5 km and 40 km, respectively). Tractor and agricultural machines are imported from the United States, Canada, Europe and Japan, whereas 1'700 km and 650 km are assumed representative for
inland transportation by lorry in the export land and in South Africa, respectively. Overseas transport is an average distance from the mentioned export countries above to South Africa, accounting for 14'400 km by a transoceanic ship. The life cycle inventories and the impact assessment were modelled with the SimaPro software v8.2 (PRé Consultants, 2016).

Table 1: Summary of life cycle inventory of grain maize for human diet produced on dry land and under irrigation in South Africa (ZA), representing maize production in 2013

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Grain maize, dry land</th>
<th>Grain maize, irrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production area</td>
<td>ha</td>
<td>1'519'557</td>
<td>85'924</td>
</tr>
<tr>
<td>Yield</td>
<td>kg/ha</td>
<td>3'770</td>
<td>8'134</td>
</tr>
<tr>
<td>Seed</td>
<td>kg/ha</td>
<td>10.0</td>
<td>23.1</td>
</tr>
<tr>
<td>Fertilizers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lime</td>
<td>t/ha</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>NPK</td>
<td>kg/ha</td>
<td>84.7</td>
<td>282</td>
</tr>
<tr>
<td>manure</td>
<td>t/ha</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Pesticides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>herbicides</td>
<td>kg/ha</td>
<td>0.5</td>
<td>0.0001</td>
</tr>
<tr>
<td>insecticides, fungicides</td>
<td>L/ha</td>
<td>7.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Diesel consumption</td>
<td>L/ha</td>
<td>71.9</td>
<td>79.7</td>
</tr>
<tr>
<td>Irrigation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water</td>
<td>m³/ha</td>
<td>0</td>
<td>7'000</td>
</tr>
<tr>
<td>electricity</td>
<td>kWh/ha</td>
<td>0</td>
<td>1'900</td>
</tr>
<tr>
<td>Transports</td>
<td>km/t</td>
<td>281</td>
<td>179</td>
</tr>
</tbody>
</table>

South Africa, as an emerging economy, is used to irrigating its crops with fossil fuel based energy. Although only 10 % of the maize crop is produced under irrigation (DAFF, 2014), the potential to reduce environmental impacts by using green and clean technologies for irrigation is worth considering in more detail.

The main irrigation system in South Africa is a Centre Pivot system. In ecoinvent, inventory data for Centre Pivot irrigation systems are not available, therefore a new dataset was generated according the South African conditions concerning electricity supply and water use, based on personal communication with Jan Coetzee, extension officer at The South African Breweries.

A new inventory was also established for photovoltaic electricity. The dataset is based on a 570 kWp open ground installation with multi crystalline silicon panels. Annual yield is adapted to the main growing regions for maize (North West and Free State), and accounts for 1'770 kWh/kWp (European Commission, 2012). According to the IEA PVPS Methodology Guidelines, a life time of 30 years and an annual degradation of 0.7 % have been assumed (Fthenakis et al., 2011).

4. Life Cycle Impact Assessment

Production of fertilizers, direct field emissions, diesel consumption and (if present) electricity consumption for irrigation were identified as environmental hotspots in the South African grain maize production (Figure 1). The global warming potential (GWP) of irrigated grain maize in South Africa amounts to 0.82 kg CO₂-eq. per kilogram of grain maize and is 39 % higher than the global warming potential of grain maize produced on dry land (0.50 kg CO₂-eq. per kilogram grain maize). The higher yields of irrigated maize cannot compensate for the additional electricity and diesel consumption for irrigation (Figure 1). If irrigation is supplied by the South African electricity mix, the contribution of irrigation to the overall GWP accounts for 36 %. The replacement of the South African electricity mix in the irrigation with electricity from photovoltaics results in a reduction of 0.27 kg CO₂-eq. per kilogram of grain maize, which is equivalent to 33 % (Figure 1). The GWP of irrigated grain maize using photovoltaic electricity is similar to grain maize production on dry land.
Figure 1: Global warming potential in kg CO₂-eq. of the production of 1 kg of grain maize on dry land (left-hand column) and under irrigation. Irrigation is either supplied by the South African electricity mix (central column) or by electricity from photovoltaics (right-hand column).

The analysis of further indicators reveals a significant reduction for non-renewable energy demand (fossil and nuclear) of 47%. Acidification, human toxicity of carcinogenic substances and freshwater eutrophication are reduced by 21%, 19% and 13%, respectively (Figure 2). However, not all environmental and human domains are equally affected. Freshwater ecotoxicity, marine eutrophication, land use and human toxicity of non-carcinogenic substances remain almost unaffected by the change of electricity supply.

Figure 2: Comparison of selected environmental impacts for irrigated grain maize for human diet in South Africa using the South African electricity mix or electricity from photovoltaics for irrigation. All results are normalized by the results for maize irrigated using the national grid mix.
The high environmental impacts of the South African electricity mix are due to its composition: 88% of the electricity is supplied by hard coal power plants and 5% by nuclear power plants (ecoinvent Centre, 2015). By eliminating contributions of electricity with high environmental impacts, overall environmental impacts can be considerably reduced.

The irrigation of a maize field of one hectare consumes 19’000 kWh of electricity per year, which, in turn, requires a solar power plant with an area of 9 m². This means that in order to supply the power used for the irrigation of a field by means of photovoltaic panels, an area of only 0.09% of the irrigated maize field is required.

5. Interpretation

We estimated that a total area of 76 ha of solar panels would be needed to produce the electricity to supply the current grain maize production area for human diet under irrigation (85’924 ha). This corresponds to about 190’900 t CO₂-eq. saved per year. Including the maize production under irrigation for feed, which covers a production area of 139’964 ha in South Africa, a total of more than 502’000 t CO₂-eq. could be saved per year (additional 311’200 t CO₂-eq. from feed). The required solar panel area to supply the total current maize production area under irrigation in South Africa, including maize for human diet and for feed, would increase up to 199 ha or 0.09% of the irrigated maize area. The calculations about land use revealed that the installation area of PV panels is almost negligible compared to the irrigated production area. Consequently, land use is no limiting factor in the implementation of photovoltaics to irrigate the whole maize production throughout South Africa.

Compared to inventory data in ecoinvent, the modelled South African grain maize inventory has a higher global warming potential (0.82 kg CO₂-eq./kg maize) than maize produced in the United States (0.54 kg CO₂-eq./kg maize), in Switzerland (0.51 kg CO₂-eq./kg maize) or interpolated in global maize production (0.60 kg CO₂-eq./kg maize). System boundaries of the data inventories in ecoinvent are comparable to the maize inventory in the present study, including inputs of seeds, fertilizers, pesticides and irrigation water, as well as machine operations, field emissions and transport, and are therefore not crucial for the discrepancies regarding global warming potential. In contrast to our study, drying of grains at the farm is included, but not storage in a concrete silo. In South Africa, yields of 8’134 kg per hectare are lower than the yields of 9’315 kg per hectare gained in the United States, in Switzerland or in global maize production, leading to the higher greenhouse gas emissions per kilogram of maize, as mentioned above.

A further clean technology process, which is not yet widely used, is wireless sensor irrigation networks (WSIN). WSIN involve soil moisture sensors, specialized software interfaces and decision-supporting tools, which allows a more efficient and precise ‘water on demand’ irrigation. Water-saving technological processes are very important, especially where water is scarce and yield is highly dependent on proper irrigation, as is the case in South Africa. Majsztrik et al. (2013) show a decline in average water consumption of approximately 50% compared to traditional irrigation in ornamental plant production in the USA. A reduction in fertilizer application, nutrient runoff and related greenhouse gas emissions can be attributed to the implementation of wireless sensor irrigation networks in horticulture. Further study is required to estimate the reduction potential through the implementation of WSIN in agronomic crops such as maize in open field production. By applying a combination of WSIN and renewable energy, the potential for mitigating environmental impacts could possibly be maximized.

6. Conclusion

The replacement of the South African electricity mix in irrigation with photovoltaic electricity has proven to be an effective clean technology to reduce environmental impacts associated with irrigated maize production. As the calculations showed, land use is no limiting factor for installing PV panels in order to generate solar energy for the large scale irrigation of maize fields in South Africa.

Depending on the impact indicator, up to 47% of the environmental impacts can be saved with irrigation supplied by photovoltaic electricity compared to energy supply by fossils. The
environmental benefit would be even higher if renewable energy were expanded to further irrigated crops and additional clean technology processes like WSIN were implemented in South Africa.

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