Assessment of cleantech options to mitigate the environmental impact of South African dairy farming

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Abstract Milk production in South Africa has increased substantially over the past ten years and is associated with various environmental impacts. These can be reduced by different means, four of which were analysed in this study: choice of breed, the use of methane emission reducing feed additives, solar power as well as variable frequency drive usage in fodder irrigation. The results showed that Holstein cows had a lower impact than Ayrshire cows per litre of milk, but that differences between farms were greater than between breeds alone. The feed additive 3-nitrooxypropanol (3NOP) led to an 18% reduction in the climate change impact category, and did not have negative effects in other categories. Using solar power for irrigation decreased the environmental impact by a larger degree than integrating a variable frequency drive to reduce the electricity demand of the water pump. All four are adequate means of reducing the environmental impact of milk.

1 Introduction

Agriculture is the main contributor to global anthropogenic non-CO_2 greenhouse gas emissions [1] and also contributes considerably to air pollution, land, soil and water degradation, and the reduction of biodiversity [2]. As in most emerging economies, livestock is one of the fastest growing sectors of the agricultural economy in South Africa. Milk production increased by 26% in South Africa from 2004 to 2014 [3] and rising meat consumption could exacerbate water stress in South Africa [4]. Given the considerable environmental impacts caused by dairy production systems and the industry's growth, environmental mitigation strategies are required.

Enteric emissions are responsible for the largest share of greenhouse gas emissions of milk at farm gate [5]. Effective measures to reduce enteric methane emissions

include the genetic selection of animals producing fewer emissions and having higher production efficiency (genetic approach), as well as management approaches, e.g. practices to reduce non-voluntary culling and diseases and improvements in nutrition [4]. In this paper, choice of breed as well as the use of feed additives are analysed.
The World Bank sees investing in more advanced technologies as an answer to the environmental problems caused by agriculture [6]. In a sustainability evaluation of 17 cleantech measures in agriculture, the two cleantech options analysed in this paper - solar electricity and the use of frequency converters - were rated among the five best approaches [7]. A joint research project of the University of Cape Town and the Zurich University of Applied Sciences was carried out, aimed at identifying environmental hotspots in the life cycle of South African agri-food products in order to determine the key intervention points for mitigating their environmental impacts. This paper specifically describes four clean technologies and their potential to reduce the environmental impact of South Africa's milk by applying life cycle assessment (LCA).

2 Methods

Data collection for the LCA of milk and maize were part of this research project: data on maize cultivation were collected from the major maize production corporations in South Africa (GWK AGRI,Grain SA). Manufacturing data, including fertiliser and pesticide use, diesel consumption, production area and yield are average values from the Grain SA planning models of three different regions (Eastern Highveld; North West and Central; Northern Free State) of maize production in South Africa from 2006-2013 [8]. The modelling is based on different methods of production (rainfed and irrigated) and three different maize varieties: genetically modified (GM)-insect tolerant trait (RR, only rainfed); GM- genetically modified herbicide tolerant trait and GM-free (Bt, only irrigated) and GM-free. Both multi-nutrient fertilisers (NPK-fertilisers) and cattle manure are applied.
Data for the milk model was collected in 2014 from five dairy farms in the province of KwaZulu-Natal (KZN) [9], one of the three main milk production areas South Africa [3].

Allocation between beef and milk was conducted according to the approach recommended by the International Dairy Federation (IDF) that reflects the underlying use of energy from fodder by the dairy animals and the physiological feed requirements of the animal to produce milk and meat (IDF, 2015, p. 29). To distribute the beef's environmental impact between calves and cull dairy cows, economic allocation was performed.

Based on the results of these LCAs, four different measures to reduce the environmental impact of raw milk were considered: choice of suitable breed: comparison of Ayrshire and Holstein cows (A); reduction of enteric emissions with feed-additives: feeding 3NOP to lactating cows (B) and producing maize feed with two types of cleantech for irrigation (C): solar power (C1) and integration of a variable frequency drive that reduces the electricity demand of the water pump (C2). The measures are described in more detail in Chapter 3. All scenarios of clean technologies were based on the same raw milk LCA model [9] that includes infrastructure, water, electricity and feed input (see Fig. 1).

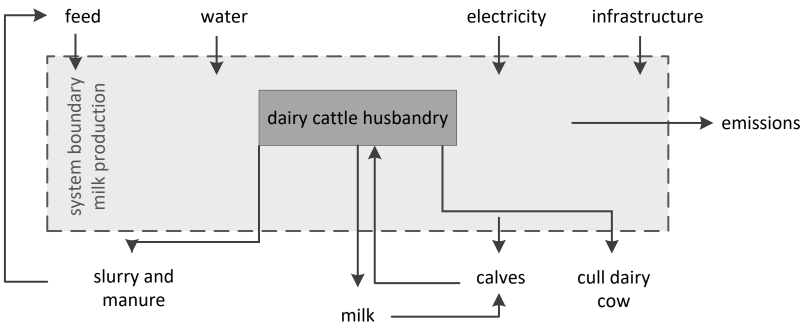

Fig. 1: System boundary of raw milk production

The functional unit was defined as one kilogramme of fresh milk at the farm gate in South Africa. For a sensitivity comparison of breeds, one kg of fat and protein corrected milk (FPCM) as well as price were included as additional functional units. Ecoinvent v.3.3 data with the system model cut-off [11] were used as background data. The details on the foreground data are described in the sub-chapters. The results were calculated and analysed in SimaPro v8.3. To assess the environmental impacts associated with South African dairy farming and processing, five impact categories and respective methods were used:

1) **Climate change** (abbr.: GHG emissions) with the method IPCC 2013, GWP 100a [1].
2) **Non-renewable energy** (fossil + nuclear) (abbr: CED non-ren.) with the method Cumulative Energy Demand (CED) [12]. In this study, only fossil and nuclear energy resources were considered.
3) **Freshwater and marine eutrophication** (abbr. Freshw. / Marine Eutr.) with the EUTREND model as implemented in ReCiPe [13].

4) **Ecotoxicity (fresh water)** (abbr. Ecotox.) with the USEtox model [14]. The version "USEtox (recommended + interim) v1.04" was used.
5) **Land use** with the method Ecological Scarcity 2013 (global model) [15].

3 Life cycle inventory

This study uses the "Tier 2" approach described in the IPCC Guidelines to calculate methane emissions from enteric fermentation [16]. Thereby, the methane emissions from enteric fermentation of a dairy cow during its lifetime are calculated from the gross energy intake (GE), the methane conversion rate (Ym) and the energy content of methane (55.56 MJ/kg). Based on the IPCC standard, the methane conversion rate (Ym) was assumed to be 6 %, the value for dairy cows in developing countries. Further details of modelling are described for each measure individually.

Different breeds (A)

The four major dairy breeds in South Africa are Holstein, Jersey, Guernsey and Ayrshire [3]. This study analysed the environmental impact of raw milk from Ayrshire and Holstein breeds.

A production mix of the five farms where data was collected (see chapter 2) with an equal share from each farm was modelled. Three farms keep only Holstein cows and two farms keep both Holstein and Ayrshire cows. The number of dairy cows per farm varied between 260 and 1345. Data on feed quantities were collected from each farm. Silage maize and grain maize in concentrated feed was modelled based on kg input and published inventories [8]. The quantity of hay, pasture grass and kikuyu silage was included based on the production area on each farm. Ryegrass was irrigated on all farms, whereas kikuyu grass was cultivated under rainfed conditions. For silage and grain maize, the share of irrigation was based on the average share in South Africa from 2006 to 2013 [17].

Addressing enteric fermentation (B)

Enteric fermentation was responsible for about 20% of the worldwide greenhouse gas emissions from agriculture, forestry and other land use (AFOLU) from 2000 to 2010, of which cattle contributed the largest share (75%). The enteric emissions increased most in Africa during this period (by 2.4% per year) [1].

Due to the importance of bovine enteric methane emissions, research has been carried out to determine means of reduction. Feed supplements have been found to achieve a significant reduction in methane emissions from enteric fermentation. The effect of administering the methane inhibitor 3-nitrooxypropanol (3NOP) was analysed during a 12-week experiment in Pennsylvania (US): 48 Holstein cows were fed 60 to 80 mg of 3NOP per kg dry feed [18]. The feed consisted mainly of maize silage (42.2%) and alfalfa haylage (18%). The rumen methane emissions were measured five times during this period. An average reduction of 30% in rumen methane emissions was observed for the cows that were fed with 3NOP, while the milk yield was not affected.

To estimate the effect of the methane inhibitor 3NOP on the environmental impact on South African milk, 3NOP supplementation was modelled for one farm with Holstein cows (Farm 5). For the model, the average methane reduction achieved using 60 and 80 mg 3NOP per kg dry feed in the experiment was 30% [18] was used.

The original input data of Farm 5 and modelled data for the theoretical administration of 3NOP were evaluated. The 3NOP supplement contains 8.85% 3NOP mixed with silicon dioxide and propylene glycol [18]. The share of silicon dioxide and propylene glycol was assumed to be 50% each. The quantity of 3NOP added to cow feed was calculated per litre of milk: based on the average concentration of 3NOP used in the experiment (70 mg/kg dry feed) and the total feed (the sum of maize and concentrated feed) per kilogram of milk. The input of 3NOP was modelled as the production of organic chemicals. Emissions of hydrogen increased 64 fold due to the treatment [18] and this was included in the model (see table below). The emission of hydrogen is not environmentally relevant and thus not assessed by any impact assessment method used in this study.

Tab. 1: Input per litre of milk at Farm 5 with feed additive 3NOP

Type of flow	Dataset	Origin	mg/kg raw milk
Input	Chemical, organic (3NOP)	Global	47
Input	Silica sand	Global	265
Input	Propylene glycol, liquid	Global	265
Output	Hydrogen emissions	-	25

Addressing animal feed production (C)

Direct emissions play a major role in the greenhouse gas emissions of raw milk. All other impact categories are dominated by the production of concentrated feed and the housing system [9]. Fig. 2 shows the contribution analysis of milk from a South African farm for the six impact categories.

Feed (i.e. silage maize, concentrated feed and grass) is responsible for 15% to 24% of the climate impact of milk. In all other categories considered, feed dominates the impact (see Fig. 2). Measures reducing environmental impacts from the production of animal feed are therefore a way to decrease the life cycle impact of milk.

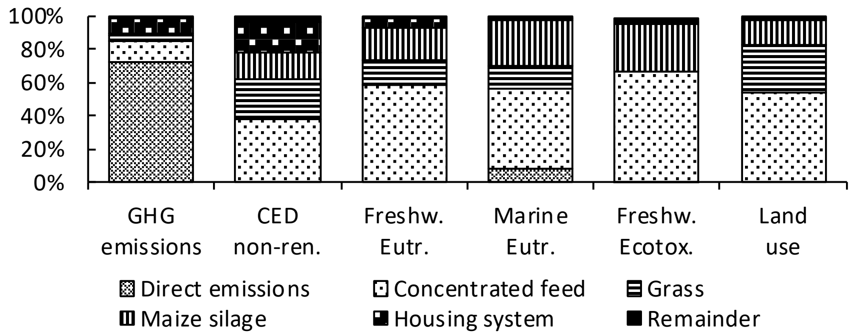

Fig. 2: Contribution analysis of raw milk from Holstein cows at a farm in KwaZulu-Natal analysed in our study (Farm 2) for six impact indicators.

In this study, two cleantech measures in the production of cow-feed were considered: the reduction of electricity demand by integrating a variable frequency drive for the electric motor of a centre pivot irrigation system ("VFD") and the use of solar electricity for irrigation ("solar").

To assess the influence of the cleantech on the environmental impact of milk, it was assumed that cleantech is used in all irrigated feed production, i.e. silage maize, grain maize (in concentrated feed) and grass irrigated on the farms. For purchased feed, the share of irrigated feed on total is based on the South African average share between 2006 to 2013 [17].

Electric motors are most efficient when they are running at their maximum capacity. Current irrigation systems running at their maximum capacity, regardless of the current water demand, use more electricity than needed for irrigation. Variable speed drives allow the regulation of speed and rotational force – or torque output – of the motor in accordance with the actual demand. The centrifugal pump on irrigation systems has particularly high potential to save power. A subcategory of variable speed drives are variable frequency drives: they combine a converter and an inverter with a control unit in between to allow adjustment of the frequency, which changes the speed of the motor. A 30% reduction in electricity use of the water pump [19] was used for this model.

Photovoltaic electricity for irrigation in South Africa was modelled based on a 570 kWp open ground multi-crystalline silicon power plant in the ecoinvent database [11, p. 3]. The city Welkom, lying in the main maize production region (Northwest and Free State), was used for the estimation of the photovoltaic yield. An annual photovoltaic yield of 1 770 kWh/kWp is expected for that city according to PVGIS of the Joint Research Centre [20]. For the calculations, a lifetime of 30 years for the photovoltaic modules was used, with a yield degradation of 0.7% per year. This corresponds to an average loss of 10% of the yield per year (1 593 kWh/kWp, including degradation). These assumptions correspond to the recommendations of the IEA [21]. The module (22.1 m^2) has an efficiency of 13.6% (module area of 7.4 m^2/kWp), resulting in an annual yield of 216 kWh/m^2 of module. It was assumed that the total electricity demand for irrigation was met using solar electricity, replacing grid electricity from South Africa.

4 Life cycle impact assessment

Different breeds (A)

The greenhouse gas emissions associated with the production of raw milk on the five farms in KZN varied between 1.2 kg CO_2-eq/kg and 2.0 kg CO_2-eq/kg. A study on milk from Western Cape supports these findings, with 1.0 to 1.6 kg CO_2-eq/kg raw milk [5]. The production mix for raw milk had a carbon footprint of 1.5 kg CO_2- eq/kg. Direct emissions (methane and dinitrogen monoxide) accounted for 67%-71% of the overall greenhouse gas emissions.

On Farms 2 and 4, where both Ayrshire and Holstein cows are kept, the climate impact is lower for milk from Holstein cows (see Fig. 3). This is mainly a result of the higher milk yields of Holstein cows [22]. However, the variability between farms was greater than that between breeds. High variability is common in agriculture [23]. In addition to the yield, feed amount and type and longevity of the cows are crucial factors influencing the results.

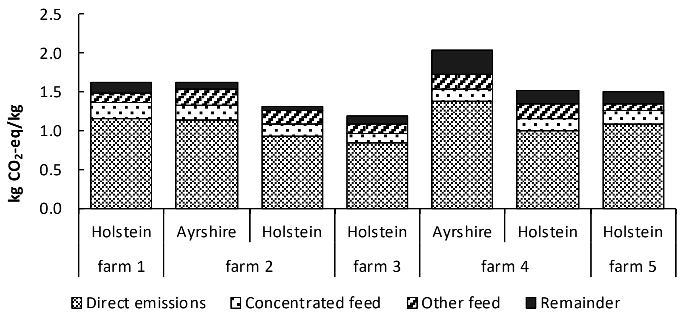

Fig. 3: Greenhouse gas emissions per kilogram of raw milk at five different farms, by breed.

Ayrshire milk is sold at a higher price and has a higher fat content than standard milk. The comparison of the two types of milk according to price (South African rand, ZAR) and fat and protein corrected milk (FPCM) does not alter the results: the milk from Holstein cows still had a lower impact on climate change than that from Ayrshire cows.

In other impact categories, milk from Ayrshire cows also had a higher impact than the milk from Holstein cows from the same farm (see Fig. 4). Here too, the differences between farms overshadow the differences between the two breeds.

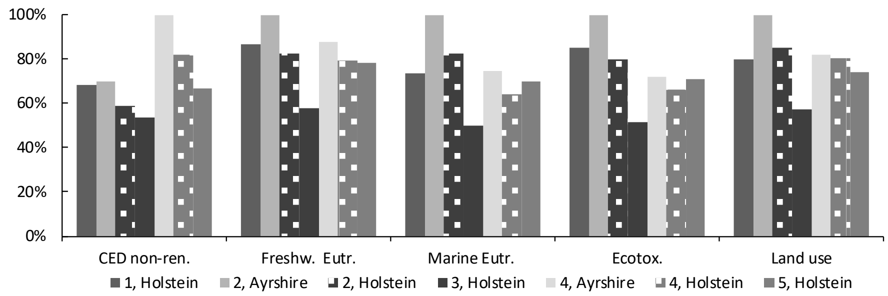

Fig. 4: Comparison of the environmental impact of raw milk at five farms per kilogram milk

Addressing enteric fermentation (B)

Adding the methane inhibitor 3NOP to feed led to an 18% reduction in the life cycle greenhouse gas emissions of milk, with only very small changes in the other impact categories (see Fig. 5).

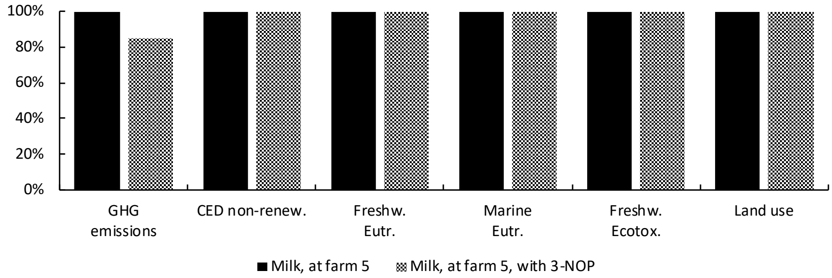

Fig. 5: Impact of feeding 3NOP to cows, calculated using Farm 5 as an example (South African farm with Holstein cows)

These predicted reductions took the direct emissions of cows into account but not potential change in emissions from the manure. Long-term observations are necessary to rule out potential negative effects on the animals, the milk and the meat produced: the possible accumulation of hydrogen in the rumen, the potential nitrite toxicity and adaptation of the animals to the supplements have to be considered [24]. If there is no change in the emissions from the manure and if there are no negative effects on the cows' health, the administration of 3NOP can be recommended to decrease the environmental impact of milk production.

Addressing animal feed production (C)

Fig. 3 shows that between 8% and 13% of the climate impact of raw milk can be attributed to concentrated feed and 6%-15% to other feed such as grass, silage or milk powder. The sum of silage, grass and concentrated feed is responsible for 15% - 24% of the climate impact.

Using cleantech in the irrigation of feed led to a reduction in the environmental impact of milk in the categories greenhouse gas emissions, non-renewable cumulative energy demand, freshwater eutrophication and freshwater ecotoxicity. No change was observed for the categories land use and marine eutrophication (see Fig. 6). The replacement of the electricity mix with solar electricity ("solar") leads to a larger reduction in environmental impacts than the implementation of a variable frequency drive ("VFD").

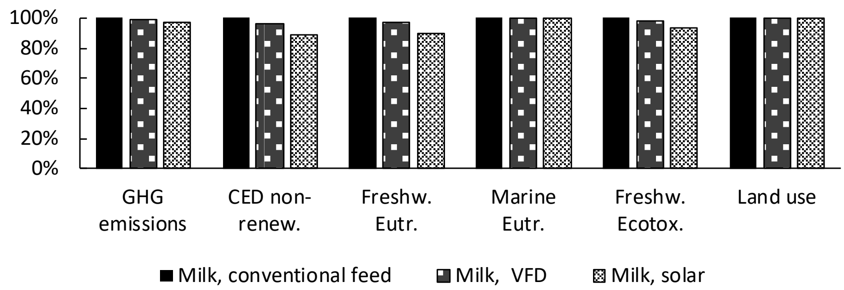

Fig. 6: **Influence of cleantech in the irrigation of feed on the environmental impact of milk.**

The highest reduction occurred for the non-renewable cumulative energy demand, where a reduction of up to 4% (VFD) and 11% (solar) compared with average milk was reached. For freshwater eutrophication, an average reduction of 3% (VFD) and 10% (solar) was achieved. Depending on the share of irrigated feed and electricity use per farm, the reduction for individual farms differed, ranging from 2% to 4% (VFD) and 6% to 14% (solar) for freshwater eutrophication.

Theoretically, a reduction in global warming potential of 34% is possible if grid electricity is replaced with photovoltaic-generated electricity [8]. Due to the high share of coal (92%) in South Africa's electricity production [25], greenhouse gas emissions can effectively be decreased by reducing grid electricity demand. Since methane emissions of cows are responsible for the largest share of the global warming potential, the indirect effect of cleantech on the global warming potential of milk remained small.

5 Conclusions

On the five farms analysed, milk from Holstein cows had a lower impact than milk from Ayrshire cows. However, the influence of farm management was more relevant than the choice of breed. For climate change, enteric emissions are responsible for the highest share of impact. Therefore, the reduction of direct emissions of cows can generally be recommended. However, only the impact of one environmental category is reduced and the long-term safety of 3NOP has not yet been demonstrated. Reducing impacts associated with feed production may be a more suitable approach, as it dominates the other impact categories. Addressing animal feed production with the use of a variable speed drive or the production of solar electricity decreased the impact in three of the six impact categories considered while there was no trade-off in the other categories. These can therefore be recommended. Using solar electricity for irrigation reduced the impact to a higher degree than the integration of a VFD and is therefore more effective.

In view of the importance of agriculture for sustainable development and the rise in production and consumption of animal products in South Africa, early implementation of cleantech could potentially have a considerable influence on the state of the environment both in South Africa as well as worldwide.

Many measures are available that decrease the environmental impact of milk and different means should be combined to reach the goal of environmentally sound production. Both the cost of implementation of these technologies and potential monetary benefits for the farms, i.e. arising from the reduction of grid electricity consumption, have to be analysed to evaluate the financial sustainability of these measures. Since the lack of acceptance from consumers or farmers could be a potential barrier to the implementation of improvement strategies, the acceptance of these technologies also has to be investigated. Finally, the analysis of social effects would complete the sustainability evaluation of these measures.

6 References

[1] IPCC, Climate Change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2013.

[2] Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., and Haan, C. da, Livestock’s long shadow - environmental issues and options, FAO, Rome, 2006.

[3] DAFF, A profile of the South African dairy market value chain 2014, Department of Agriculture, Forestry and Fisheries, 2015.

[4] Harding, G., Courtney, C., and Russo, V., When geography matters. A location-adjusted blue water footprint of commercial beef in South Africa, Journal of Cleaner Production, 2017, Vol. 151, pp. 494–508.

[5] Notten, P. and Mason-Jones, K., Life cycle assessment of milk production in the Western Cape, 2011.

[6] The World Bank, World development report 2008 - overview, Washington D.C., USA, 2007.

[7] Scharfy, D., Boccali, N., and Stucki, M., Clean technologies in agriculture – how to prioritise measures?, Sustainability, 2017, Vol. 9, No. 8, p. 1303.

[8] Wettstein, S., Muir, K., Scharfy, D., and Stucki, M., The environmental mitigation potential of photovoltaic-powered irrigation in the production of South African maize, Manuscript submitted for publication, 2017.

[9] Eymann, L., Stucki, M., Schwab, S., and Wettstein, S., Environmental impact of South African milk: A comparison of Ayrshire and Holstein breeds, in 10th International conference on Life Cycle Assessment of Food, University College Dublin, Ireland, 2016, pp. 99–105.

[10] IDF, A common carbon footprint approach for the dairy sector. The IDF guide to standard life cycle assessment methodology, International Dairy Federation, 2015.

[11] ecoinvent Centre, ecoinvent data v3.3, Swiss Centre for Life Cycle Inventories, Zürich, 2016.

[12] Hischier, R., Weidema, B., Althaus, H., Bauer, C., Frischknecht, R., Doka, G., Dones, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerinck, Y., Margni, M., and Nemecek, T., Implementation of life cycle impact assessment methods, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, 2010.

[13] Goedkoop, M., Heijungs, R., Huijbregts, M. A. J., De Schryver, A., Struijs, J., and van Zelm, R., ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition. Report I: Characterisation, NL, 2013.

[14] Rosenbaum, R. K., Bachmann, T. M., Gold, L. S., Huijbregts, A. J., Jolliet, O., Juraske, R., Koehler, A., Larsen, H. F., MacLeod, M., Margni, M., McKone, T. E., Payet, J., Schuhmacher, M., van de Meent, D., and Hauschild, M. Z., USEtox - the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life

cycle assessment, International Journal of Life Cycle Assessment, 2008, Vol. 13, No. 7, pp. 532–546.
[15] Frischknecht, R. and Büsser Knöpfel, S., Swiss Eco-Factors 2013 according to the Ecological Scarcity Method. Methodological fundamentals and their application in Switzerland, Federal Office for the Environment, Berne, 2013.
[16] IPCC, IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories - Chapter 4 Agriculture, 2006.
[17] Grain SA, Operational planning of white maize grain production in the production year 2011/2012 in Eastern Highveld, Northwest, and Central and Northern Free State, South Africa; Maize production in South Africa from 2006 - 2013, 2014.
[18] Hristov, A. N., Oh, J., Giallongo, F., Frederick, T. W., Harper, M. T., Weeks, H. L., Branco, A. F., Moate, P. J., Deighton, M. H., Williams, S. R. O., Kindermann, M., and Duval, S., An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production, Proceedings of the National Academy of Sciences, 2015, Vol. 112, No. 34, pp. 10663–10668.
[19] Eskom, Variable Speed Drives: Reducing the energy cost of irrigation on farms, Eskom Integrated Demand Management, 2015.
[20] European Commission, Photovoltaic Geographical Information System (PVGIS) - geographical assessment of solar ressource and performance of photovoltaic technology, 2012.
[21] Fthenakis, V., Frischknecht, R., Raugei, M., Chul, K. H., Alsema, E., Held, M., and Scholten, M. de W., Methodology guidelines on life cycle assessment of photovoltaic electricity, Subtask 20 "LCA", IEA PVPS Task 12, 2011.
[22] Moore, R. K., Kennedy, B. W., Schaeffer, L. R., and Moxley, J. E., Relationships between age and body weight at calving and production in first lactation Ayrshires and Holsteins, Journal of Dairy Science, 1991, Vol. 74, No. 1, pp. 269–278.
[23] Hersener, J.-L., Baumgartner, D. U., and Dux, D., Zentrale Auswertung von Ökobilanzen landwirtschaftlicher Betriebe (ZA-ÖB)., Agroscope, Forschungsanstalt Agroscope Reckenholz-Tänikon ART, Zürich/Ettenhausen, 2011.
[24] Hristov, A. N., Oh, J., Firkins, J. L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H. P. S., Adesogan, A. T., Yang, W., and Lee, C., Special topics—Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options, Journal of Animal Science, 2013, Vol. 91, No. 11, pp. 5045–5069.
[25] International Energy Agency, South Africa: electricity and heat for 2014, 2017, <https://www.iea.org/statistics/statisticssearch/report/?country=SouthAfric &product=electricityandheat>, (Accessed 25.05.2017).