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Nitrogen fertilizers manufactured using wind power: greenhouse gas and energy balance of community-scale ammonia production

Joel Tallaksen [a,*], Fredric Bauer [b], Christian Hulteberg [b], Michael Reese [c], Serina Ahlgren [d]

[a] West Central Research and Outreach Center, 46352 State Highway 329, University of Minnesota, Morris, MN 56267, USA
[b] Department of Chemical Engineering, Lund University, P.O. Box 124, SE-221 00 Lund, Sweden
[c] West Central Research and Outreach Center, University of Minnesota, Morris, MN 56267, USA
[d] Department of Energy and Technology, Swedish University of Agricultural Sciences, P.O. Box 7032, SE-750 07 Uppsala, Sweden

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ABSTRACT

The paper presents a cradle-to-gate life cycle assessment of production of ammonia using wind power. The ammonia is intended to substitute for nitrogen fertilizer produced from fossil resources. The studied system is designed to supply a rural community with fertilizer based on renewable energy and is, therefore, smaller than industrial fossil ammonia production systems. Two contrasting cases examine the impact of the location of the system, investigating the dependence on the regional energy system (background system) to balance demand and supply of energy in the ammonia production system (foreground system). The results show that wind-based ammonia production can significantly decrease fossil energy inputs and greenhouse gas emissions compared to conventional production, but that the use of energy from the background system severely impacts the environmental performance, especially in regions where fossil fuels dominate the energy system.

1. Introduction

Since the establishment of industrial-scale production of mineral nitrogen fertilizers in the 1950s, the yield of plant biomass per hectare has increased dramatically. The demand for fertilizers is also bound to increase in the future, as a growing world population will need to produce more food and biomass for energy purposes on a finite amount of land (Smeets and Faaij, 2005). Nitrogen gas accounts for 78% of the volume of the atmosphere. However, converting the nitrogen to a form that is useful for agricultural purposes requires significant amounts of energy. Currently the production of nitrogen fertilizer accounts for 1.2% of global primary energy demand (IFA, 2014). Globally about 110 million metric tonnes of nitrogen fertilizer is used every year (Heffer and Prud'homme, 2013) and the demand is projected to grow 1–1.5% annually during the next five years, with the majority of the growth in demand occurring in Asia (FAO, 2012).

Ammonia is a precursor for all synthetically manufactured nitrogen fertilizers and is produced using nitrogen and hydrogen gases, with the overall reaction being $N_2 + 3H_2 \rightarrow 2NH_3$. Although nitrogen purification is relatively simple and energy efficient, hydrogen generation is a very energy intense process. Currently, the hydrogen is most often derived from natural gas, heavy oil or coal, and the nitrogen from air (EFMA, 2000). While anhydrous ammonia can be directly injected into the soil where it is dissolved; ammonia can also be processed further into other liquid or solid fertilizers which are easier to handle. These can be used in combination with other nutrients or as nitrogen-only formulations. Of the solid nitrogen fertilizers, nitrates – ammonium nitrate (AN) and calcium ammonium nitrate (CAN) – and urea are the most commonly used in Europe, accounting for 78% of the nitrogen fertilizer consumption (Fertilizers Europe, 2013). In the US, and in the US Corn Belt particularly, liquid anhydrous ammonia is a commonly used nitrogen fertilizer (Bierman et al., 2012).

Because current nitrogen fertilizer production is based on fossil energy, agricultural life cycle assessments have documented that nitrogen fertilizer inputs contribute significantly to the total greenhouse gas (GHG) emissions of agricultural output at the final product stage, e.g. when calculating the carbon footprint of food or liquid biofuels. A study by Börjesson and Tufvesson (2011)

* Corresponding author.
E-mail addresses: tall0007@umn.edu (J. Tallaksen), fredric.bauer@chemeng.lth.se (F. Bauer), christian.hulteberg@chemeng.lth.se (C. Hulteberg), reesem@morris.umn.edu (M. Reese), serina.ahlgren@slu.se (S. Ahlgren).

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concluded that nitrogen fertilizers represented 3–26% of the total GHG emissions from Swedish wheat based ethanol production and for rapeseed biodiesel the nitrogen fertilizer production represented up to 29% of the GHG emissions. GHG emissions from corn production in the US are also heavily impacted by emissions from nitrogen fertilizer related production activities (Kim and Dale, 2008), which were the single largest component of cropping system emissions.

The dependence of agricultural production on nitrogen fertilizer directly links food supplies with fossil energy and the high carbon footprint of fossil resource use. This strong dependency leads to unsustainable food production chains and is a risk to price stability as increasing fossil energy prices could lead to rapidly increasing food prices. Thus, studying and deploying alternative fertilizer production systems with lower carbon footprints is a critical issue. The concept of alternative fertilizer production was considered in the post oil crisis era, i.e. the late 1970s and 1980s. Reducing the dependency on imported oil by producing ammonia from electrolysis-based hydrogen was part of US goals (Dubey, 1978; Grundt and Christiansen, 1982). Other technologies for production of hydrogen from renewable resources for ammonia synthesis include steam reforming of biogas, biomass pyrolysis oil or bioethanol, biomass gasification, direct fermentation of biomass, thermal or photoelectronic chemical water splitting, and water electrolysis using renewable electricity, e.g. from wind power (Turner et al., 2008). In fact, ammonia has been produced from electrolytic hydrogen in countries where electricity was available at low cost, e.g. from hydropower in Norway, India, Egypt, Peru and Canada. However, these plants were closed after the development of efficient technologies for using hydrocarbon feedstocks (UNIDO and IFDC, 1998).

Several evolving factors have led to a resurging interest in renewable fertilizers for agriculture; the instability of natural gas costs (IEA, 2014), a limited availability of nitrogen fertilizers in some regions (Pates, 2014), the connection between food and energy security (Arizpe et al., 2011), and a growing awareness of the possibilities for renewable energy in agriculture (Bardi et al., 2013) all point in this direction (Tunå et al., 2013; Razon et al., 2014). Recent work has begun to focus on possibilities for reducing the use of fossil fuels in agriculture by using renewable sources of energy (Bardi et al., 2013), including wind power (Xydis, 2015). Several studies have reported results based on modeling the production of ammonia based on biomass gasification (Gilbert et al., 2014), different forms of bioenergy (Tunå et al., 2013), microbial production processes (Razon, 2014), as well as the hydrogen precursor (Bhandari et al., 2014). The results of the interest in the use of wind energy for ammonia production have been mostly confined to feasibility studies of wind-based ammonia production (Morgan et al., 2014). In addition to its use a fertilizer, ammonia (Zamfirescu and Dincer, 2008, 2009) and its hydrogen precursor (Lan et al., 2012) can be used as a means of storing the intermittent wind or solar energy in a form that does not dissipate and which can be transported. This would, in the future, allow for the development of integrated systems that use stored hydrogen and/or ammonia to generate electricity when there is low power production and produce extra gases when the power transmission grid cannot accept additional power from the area. The present paper reports on the life-cycle assessment of a community scale production of ammonia based on wind power.

At the West Central Research and Outreach Center, an agricultural research station operated by the University of Minnesota, a pilot facility is producing ammonia using wind power as an energy source to electrolyze water to generate the pure hydrogen needed in the Haber–Bosch ammonia production process. The facility was constructed in an intensively agricultural region of the US that uses significant amounts of liquid anhydrous ammonia as fertilizer. However, the area has no fossil energy resources and must, therefore, import all of its nitrogen fertilizer. At the same time, the region has a growing number of wind turbines and the power production capacity has now increased so much that the existing regional electrical grid cannot accept power from some turbines during peak production (Rogers et al., 2010). The goal in building the wind powered ammonia production pilot system was to examine local production of the much needed ammonia from the abundant wind resource. The recently completed ammonia production pilot facility is already being used to examine several interesting chemical, economic, and power production issues. However, another important research opportunity for the project is to identify the GHG emissions and fossil fuel impacts of using the renewable ammonia as fertilizer in agricultural cropping systems. The extent of these impacts depends not only on the operations of the ammonia production facility, but also on the fertilizers being replaced and the emissions from the power grid that serves as the facilities backup electricity source and energy sink for periods of over-production, i.e. the background system. This pilot facility served as inspiration for the study reported in this paper, in which similar production technology is modeled, but in continuous operation and in a larger scale than a research pilot.

The aim of this study was to analyze primary fossil energy use and greenhouse gas emissions for production of ammonia based on current wind and grid power technologies, compared to current conventional fossil fuel based nitrogen fertilizer production. The production systems differ from conventional processes in several aspects, e.g. feedstock, scale, and location. Models of systems were developed to represent decentralized community scale ammonia production facilities located in two distinct regions, the Midwest US and Sweden. These regions were chosen because both have limited fossil resources, significant demands for nitrogen fertilizers, and are actively researching the use of renewably produced nitrogen fertilizers. They also represent two very different energy systems. Minnesota is heavily reliant on fossil fuel for electricity production, while Sweden's electricity is primarily produced from hydro and nuclear power. The overall intention of this work is to contribute to the knowledge of different methods of reducing fossil fuel dependency and the carbon footprint of agricultural production systems and agricultural products.

The paper is outlined as follows; Section 2 introduces life cycle assessment methodology, Section 3 describes the studied systems in detail, Section 4 presents the main findings and results, in Section 5 a sensitivity analysis of key parameters is presented, Section 6 discusses the results in relation to scenario methodologies and the socio-techno-economical context, and Section 7 concludes the paper.

2. Methods

In this section the main methodological choices are outlined, focusing on the life cycle assessment methodology and the delimitation of the studied systems in terms of system boundaries.

2.1. Life cycle assessment modeling

For the calculation of energy use and GHG emissions, life cycle assessment (LCA) methodology was used. LCA is a technique for studying potential impacts on the environment caused during the production of a chosen product, completion of a service or operation of a system. The methodology for the assessment of life cycle impacts is standardized in the ISO series 14040 (ISO, 2006a) and 14044 (2006b).

The modeling was performed using a combination of SimaPro v7.3/EcoInvent v2 (Ecoinvent, 2013) for collating data on