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Solar photovoltaic powered on-site ammonia production for nitrogen fertilization

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Abstract

Ammonia synthesis is the most important step for nitrogen-fertilizer production and consumes approximately 1% of the world's energy production and energy-related greenhouse gas emissions. In addition to the concomitant emissions caused by ammonia and nitrogen fertilizer synthesis, centrally produced fertilizer that must be distributed to farms also harms the environment because of the embodied energy of transportation. An environmentally-optimal nitrogen fertilizer system would be distributed on farms themselves using only renewable inputs. Recent developments in solar photovoltaic technology and subsystems for ammonia production have made non-organic on-site ammonia production physically possible. This study provides a technical evaluation of the process for on-site nitrogen-fertilization of corn using solar photovoltaic electricity as the energy input. The system consists of a water electrolysis system to generate hydrogen and a membrane system to generate nitrogen needed as material inputs. Total power consumption for syngas preparation to generate a unit of ammonia is calculated. System total energy consumption is calculated while compensating syngas preparation with heat recovery. Five case-study locations are evaluated to determine their suggested nitrogen fertilizer addition (N-rate) for corn growth and the energy consumption for suggested N-rate is calculated. The System Advisor Model (SAM) is then used to simulate the PV system output for those five locations. Finally, the PV land use required as a fraction of the corn field area is determined. The results indicate that because PV is so much more efficient at solar energy conversion than organic methods, even the worst case evaluated in Indiana requires less than 1% of the corn field converted to a PV system to provide enough energy to generate sufficient amounts of ammonia for fertilizer for the remaining corn. The system was modeled to provide ammonia to fertilize for corn fields larger than 1079 acres with the worst soil conditions, the area of which applies to more than half of cropland in the U.S. in 2011. As the finiteness and emissions of fossil fuel production of nitrogen become more important, this renewable system should become economical and future investigations into its overall viability are warranted.

Keywords: Photovoltaic; Ammonia; Fertilizer; Electrolysis; Distributed generation; Distributed production

1. Introduction

Ammonia synthesis is the most important step for nitrogen-fertilizer production and consumes 1% of the world's energy production and resultant energy-related greenhouse gas emissions (Kitano et al., 2012). Ammonia

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consists only of nitrogen and hydrogen. Both hydrogen and nitrogen are widely available in earth's atmosphere, but currently, according to U.S. Environmental Protection Agency (EPA) natural gas is used as a primary hydrogen generation source, and this process results in carbon dioxide (CO_2) emissions (EPA, 2009). Carbon dioxide emissions have well-known environmental problems and there are efforts underway to replace fossil fuels with renewable sources of energy (Flavin, 1990; Steinberg, 1999; El-Fadel et al., 2003; Sims, 2004; Stern, 2006; Granovskii et al., 2007; Tsoutsos et al., 2008). In addition to the emissions caused by ammonia and nitrogen fertilizer synthesis, there are also negative environmental externalities caused by the transportation of the centrally produced good to distributed farms (Brentrup et al., 2004; Horvath, 2006; Facanha and Horvath, 2007; Pearce et al., 2007). Thus the environmentally optimal nitrogen fertilizer system would be distributed on farms themselves using only renewable inputs. Historically, the only means of doing this was with natural nitrogen fixation following the practices used by organic farmers (Havlin et al., 1990; Drinkwater et al., 1998; Badgley et al., 2007). Unfortunately, this process has a significant productivity penalty with nonproductive (or less than optimal) crop rotations and potentially lower than optimal nitrogen levels. However, the nitrogen and hydrogen needed for ammonia synthesis can be obtained by using an air membrane system and water electrolysis, respectively. Commercial water electrolyzers can reach energy efficiency (higher heating value) as high as 73% (Ivy, 2004), making them feasible for hydrogen generation. Both of these methods—membrane and water electrolysis have the potential to be environmentally friendly as they use renewable natural resources as inputs (air and water); however, the sustainability is dependent on the energy used to run the processes. Solar photovoltaic (PV) technology, which converts renewable solar energy directly into electricity is a long-established sustainable energy technology (Pearce, 2002). As solar energy is available in all agriculturally relevant geographic locations, it represents a prime candidate for a sustainable solution for powering a distributed system for nitrogen fertilizer (N-fertilizer) production.

According to the United States Department of Agriculture (USDA), corn consumed 45.67% of N-fertilizer in United States in 2010 (USDA, 2013). Thus, corn fertilization in the United States is used as a case study here to determine the energetic feasibility for on-farm distributed N-fertilizer production using solar-generated electricity. First, the required N-fertilizer amounts are determined for five locations as the N-rate for corn strongly depends on the soil condition, which is greatly influenced by weather conditions (Fernández et al., 2012). Then the total power consumption for syngas preparation to generate a unit of ammonia is calculated. System total energy consumption is calculated while using heat recovery with syngas preparation for suggested N-fertilizer amounts. The System Advisor Model (SAM) is then used to simulate the PV system output for those five locations. Finally, the PV land use required as a fraction of the corn field area is determined. The results are presented and the technical and energetic viability of distributed on-farm nitrogen-fertilizer production are discussed.

2. Methods

The proposed ammonia generation system is shown in Fig. 1. The nitrogen membrane generator (2) works with the air compressor (1) to generate nitrogen, using air as source material. Hydrogen is generated from the water electrolyzer system (3). Hydrogen and nitrogen gases are then compressed and heated as syngas, which is combined in the ammonia converter (6). The heat generated in the converter will be recovered either to electrical energy or thermal energy, unconverted syngas will also be separated from ammonia and recycled as syngas again.

The ammonia synthesis conversion rate is limited by temperature. Industrially the temperature used to speed up reaction is usually around 400–500 °C and the conversion rate is around 10–15% at this temperature (Lovell, 1981). However, unconverted syngas can be recovered, so the total conversion rate can eventually reach 97% (Barclay and Leigh, 2000). The primary criteria for selecting sub-components of the system was to achieve maximum energy efficiency.

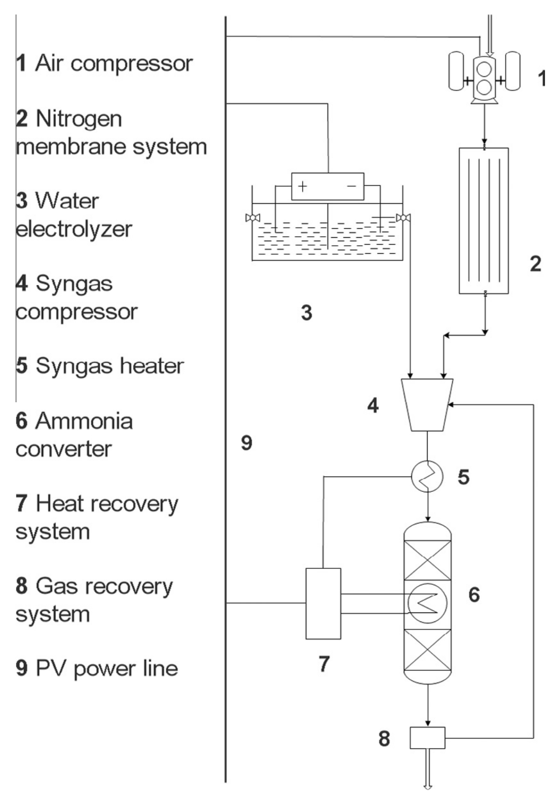

Fig. 1. System diagram.