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A feasibility study of microgrids for reducing energy use and GHG emissions in an industrial application

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HIGHLIGHTS

- A life cycle assessment is conducted on the microgrids for an industry application.
- The effect of renewable energy on the LCA performances of microgrids is illustrated.
- The minimal life cycle energy use and GHG emissions of microgrids are evaluated.
- The LCA of different pathways for electricity, heat and hydrogen are presented.

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ABSTRACT

Microgrids provide a new energy paradigm with the benefits of higher energy supply reliability, lower greenhouse gas (GHG) emissions through a higher penetration of renewable sources, higher energy efficiencies through the use of local waste heat and the avoidance of losses in transmission and distribution. This study reports a life cycle assessment (LCA) of microgrids for an industry application of an ammonia plant in central Inner Mongolia, China. The life cycle energy use and GHG emissions of the microgrids are evaluated and compared to the existing fossil fuel-based energy system. The electricity, heat and hydrogen fuel loads of the ammonia plant are all modelled in the study. An optimization model is developed to estimate the minimum life cycle energy use and GHG emissions with the microgrids under three scenarios (natural gas (NG)-based, optimized, and maximum renewable energy microgrids). The results indicate that the use of wind and solar in the NG-based microgrid can only slightly reduce the energy use and GHG emissions. If there are no land area limitations on the deployment of solar and wind power, the maximum renewable energy microgrid offers significant reductions of fossil fuel energy of up to 56.9% and GHG emissions reductions of up to 66.3% compared to the existing energy system.

1. Introduction

The current global energy supply is mainly generated from fossil fuel-based centralized power stations. Due to growing concerns about climate change and the longevity and security of the energy supply, alternative energy solutions based on distributed energy resources (DERs) is urgently requiring the evolution from traditional grids to smart grids. In China, the development of distributed energy generation based on new energy is of great importance to the Chinese government. In February 2006, the Ministry of Science and Technology of China issued the "National medium- and long-term plan for science and technology development (2006–2020)", in which the development and use of renewable energy at a low cost and on a large scale has been proposed as one of the priority domains of future government investment [1]. In September 2007, the National Development and Reform Commission (NDRC) of China launched the "Renewable energy medium- and long-term development plan", which clearly stated that renewable energy production would account for 15% of the total energy production in China by 2020 [2]. It is clear that the development of DER technology based on renewable energy in China is an inevitable trend.

Microgrids are emerging as a promising solution for combining clean energy resources (e.g., solar and wind power) with smart energy management technologies. Despite the challenges of their many disadvantages, such as high capital costs, irregular power supply and variable power quality [3], microgrids possess advantages that have continued to drive microgrid development. These advantages include the ability to provide power generation units closer to the end users and to integrate combined heat and

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power (CHP) technologies, increasing efficiency and reducing emissions [4].

A critical issue with the deployment of microgrids is to quantitatively evaluate the potential energy use and emission reductions before project implementation. There have been many studies on the energy efficiency and environmental benefits for both fossil fuel-based DERs (e.g., gas engines, diesel engines, gas turbines and micro-turbines) [5–8] and renewable-based DERs (e.g., wind power stations, solar power stations, biomass power generation and fuel cells) [9–15]. However, most of these studies focused on analyzing individual DERs. Microgrids are composed of different DERs, which are operated differently than individual DERs. The energy and environmental performances of microgrids also significantly differ from DERs.

Different management methods and operation modes were proposed by Refs. [16–21] to maximize the fuel efficiency and reduce the pollutant emissions for the actual operation scenarios of microgrids [16–18]. However, the evaluation of GHG emissions in these studies focused only on the operation stage. The emissions associated with the upstream stages, such as the manufacturing process and transportation process, were not considered in those studies. To comprehensively evaluate and minimize the energy use and GHG emissions of microgrids, the operation stage has to be extended to the life cycle.

A few studies analyzed the life cycle assessment (LCA) of microgrids in terms of energy use or GHG emissions [22–24]. However, none of these studies are in China. The literature survey shows that few studies focus on the LCA of microgrids in the context of China. One of the originalities of this work is evaluating the life cycle energy and environmental benefits of microgrids based on the actual conditions in China.

Unlike most other microgrids studies for applications in schools, hotels, offices, residential buildings or isolated islands [5–24], this paper presents energy and environmental performances of LCA for the microgrids of industrial application. Fuel demand is seldom considered in studies [5–24]. However, similar to electricity and heat, fuel is also one of the most important energy carriers. To achieve a more complete and accurate evaluation, the mass fuel demand also needs to be included in the LCA calculations, particularly for some industry applications, e.g., a synthetic ammonia factory. It should be noted that a feature of a future energy network is that it allows a higher level of interaction between the fuel grid, electric grid, and thermal grid [25]. Therefore, in this study, in addition to the thermal and electric loads, the hydrogen demand as the fuel load is also included in this LCA.

In this study, life cycle analysis is conducted to investigate the life cycle energy use and GHG emissions of the conventional energy supply system and microgrids for an ammonia plant located in central Inner Mongolia, China. The case study aims to show the feasibility of the microgrid for replacing the conventional energy supply system and to quantitatively present its potential benefits for industrial applications. The electricity, heat and fuel are all considered as the energy demands of microgrids. As a reference, the life cycle performances in terms of energy use and GHG emissions for the existing coal-based energy supply system are also presented. The comparison between the conventional energy supply systems and the microgrids under three scenarios (NG-based, optimized, and maximum renewable energy microgrids) shows the theoretical maximum benefits of microgrids in energy efficiency improvement and GHG emissions reduction.

2. Methodology

LCA is a tool that assesses the amount of materials and energy used throughout a product's complete supply chain and quantifies the emissions and wastes associated within its life cycle [26]. For a given process or product, the upstream and operation stages are included in the LCA scope. In this work, all evaluations of the energy and environmental performances of the energy supply systems are based on LCA.

2.1. The study subject

In this study, a synthetic ammonia plant located in central Inner Mongolia (E°119, N°46), China, was selected for the case study.

Ammonia is the product of the exothermic reaction of hydrogen and nitrogen. The reaction formula is expressed as:

$$0.5N_2 + 1.5H_2 \rightleftharpoons NH_3 \quad \nabla H = -46.22 \text{ kJ/mol} \tag{1}$$

The reaction occurs at high temperature and high pressure with a catalyst. The energy demands of a synthetic ammonia plant are electricity, heat and hydrogen, respectively.

This synthetic ammonia plant was officially in operation in 2012, and its annual output of synthetic ammonia is designed to be 460 thousand tons. There are a few advanced technologies adopted in the production process such as coal gasification, acid gas removal, ammonia synthesis, and urea production. These technologies are widely applied in the newly built ammonia plants in China.

The total electric load of the ammonia plant is 5.72×10^4 kW. Assuming that the annual operation hours are 8000 h, the power consumption of the plant is 4.57×10^8 kW h per year.

Coal is used to generate the high temperature (540 °C) and high pressure (9.8 MPa) steam via a high-temperature and high-pressure circulating fluidized boiler. The plant requires 652.4 thousand tons of coal annually to meet the heating load. There is rich lignite in the central Inner Mongolia area. The heat value for the lignite is 15.57 MJ/kg. Accordingly, the annual heating load of the ammonia plant is approximately 1.02×10^{10} MJ.

When operating under the design load, the hydrogen–nitrogen compressor consumes approximately 120,000 N m^3/h of hydrogen. The overall annual hydrogen demand is approximately 1.22×10^{10} MJ.

2.2. Microgrid model description

A microgrid, as shown in Fig. 1, is proposed to meet the electricity, heat and fuel demand of the ammonia plant. The microgrid system is composed of NG CHP generators, boilers, solar photovoltaic panels, and wind turbines. The electricity requirements can be met by the CHP generators and solar photovoltaic panels. The batteries are adopted in the microgrid model to provide electricity in a completely secure and reliable manner. The recovered heat from the CHP generators and the boiler can be used to meet the heating load of the plant. The hydrogen can be supplied by the reforming of NG and the electrolysis of water using the solid polymer electrolyte (SPE).

2.3. Life cycle boundary and functional nits

Figs. 2 and 3 illustrate the boundary of the conventional energy system and microgrid for the ammonia plant, respectively. As shown in Figs. 2 and 3, the LCA stages for each type of energy demand begins with the extraction of the primary energy and ends with the operation of the generators. The upstream process of the LCA consists of the feedstock and fuel stages, including fuel feedstock extraction, transmission, distribution and storage. The operation process captures the energy use and GHG emissions during the generator operation.

From a life cycle perspective, the energy use and GHG emissions during the generator set production process are negligible compared