Journal of Cleaner Production 80 (2014) 252–261

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Optimal year-round operation for methane production from CO_2 and water using wind and/or solar energy

William Davis, Mariano Martín*

Department of Chemical Engineering, University of Salamanca, Pza. Caídos 1-5, 37008 Salamanca, Spain

A R T I C L E I N F O

Article history:
Received 28 March 2014
Received in revised form
26 May 2014
Accepted 27 May 2014
Available online 5 June 2014

Keywords:
Wind power
Solar energy
Synthetic methane
Hydrogen
Power

A B S T R A C T

In this paper we present the optimal year round production of synthetic methane from water electrolysis and CO_2 comparing the use of solar PV systems and wind turbines on a monthly basis. The process starts obtaining electricity in a wind farm or a solar field, which is then used to produce oxygen and hydrogen in a system of electrolyzers. The oxygen is purified and stored, and the hydrogen, after being purified using a deoxygenating reactor, reacts with CO_2 to synthesize methane. We study the operation of the plant for a year considering the wind or solar availability. The use of wind or solar energy depends on the region and the area available for the installation of solar panels or wind turbines. Europe and the US have been screened for the use of both sources of energy, being solar preferable in most regions. We present a detailed case of study in the South of Europe, Gulf of Cádiz. Solar is cheaper than wind in terms of inversion (240 M€ vs. 363 M€) and production costs (0.33 €/m^3 vs. 0.49 €/m^3), while the monthly operation differs due to the availability of renewable energy.

1. Introduction

The increasing demand of energy and current concerns on sustainability are supporting the development of technologies which use solar radiance, wind and biomass. While biomass is a carbon source and thus, it can be considered as a source of chemicals, the use of wind and solar energy is typically devoted to the production of electricity. One of the main features of renewable sources of energy is their variability across regions and over time. In particular, renewable sources constitute a major challenge due to their availability during the day and during the year. Recently, Martín and Martín (2013) optimized the year long operation of a solar power facility determining the optimal operating conditions for the production of electricity, taking into account the variability of solar radiation. In order for the facilities based on renewable energy to operate under steady state, storage systems, supplementary sources of energy or a combination of some of them are needed. Weekman (2010) and Yaun and Chen (2012) presented overviews regarding the integration possibilities as a perspective for the future combination of different sources of energy. Furthermore, Davis and Martín (2014) evaluated the production of methane from CO_2 using wind energy over a year. Solar or wind based facilities on their own cannot maintain the production level without combining different energy sources. The advantage of producing chemicals directly out of the renewable energy is that they can be stored and can be used downstream in a continuous basis.

The idea of using renewable energy to produce hydrogen can be traced back to 1923 (Haldane, 1923). Back then, wind energy was the first choice for the production of the electricity needed for water electrolysis. Since the early attempts, there was not much further development until the 70's. At this time, solar technologies were gaining attention and the first experiments using solar energy and photovoltaic systems were carried out (Bockris, 1975). Levene et al. made several studies on the production capacities of hydrogen from solar (Levene et al., 2005) and wind energy (Levene et al., 2006) in the US, revealing that the access to cheaper electricity is needed for the hydrogen to have a competitive price. Regarding Europe, apart from the UK, other interesting locations for the production of electricity from wind are the coast of Spain, France, Germany, and Denmark, (AWS Truepower, 2014). The solar incidence for its use in PV systems can be also seen in (JRC, 2014). Recent studies have used life cycle assessment (LCA) to evaluate different renewable technologies for the production of hydrogen. Hajjaji et al. (2013) used LCA to compare eight alternatives without considering water electrolysis. Among them, biomethane reforming generated the lowest impact. Water electrolysis was evaluated by Bhandari et al. (2013). Their conclusion was that

* Corresponding author. Tel.: +34 923 294479.
E-mail address: mariano.m3@usal.es (M. Martín).

http://dx.doi.org/10.1016/j.jclepro.2014.05.077
0959-6526/

water electrolysis is one of the most environmental friendly options to produce hydrogen, as long as the energy for the electrolysis comes from renewable sources such as wind power. Finally, Ozbilen et al. (2012) evaluated the use of splitting water using thermochemical cycles. Furthermore, (Xydis, 2013) compared the use of solar and wind to produce power using an exergy analysis (Xydis, 2013).

The generation of CO_2 due to human activities, and in particular related to energy production and usage, is an important concern, since its concentration in the atmosphere has recently surpassed 400 ppm (Montaigne, 2013). While biomass is a source of carbon for the production of different chemicals, CO_2 can also be used for this purpose. This is seen in nature, where CO_2 is captured through photosynthesis to produce hydrocarbons and biomass. For instance, biodiesel facilities based on algae use these organisms to capture CO_2 and obtain biofuel. Although this process is slow when compared to the emissions of CO_2 in the transport and energy sectors, carbon capture technologies have been proposed and are under development, such as PSA, amine solutions, etc. The captured CO_2 can be used as a source of chemicals, contributing to reducing emissions and providing further value out of it.

A number of researchers have recently evaluated the usage of CO_2 as a carbon source. Most papers use a simulation based approach for the production of methane or methanol (Van-Dal, Bouallou, 2013; Trudewind et al., 2014a,b), but they do not include the analysis of the wind farm or solar field. Only recently, Davis and Martín (2014) used an optimization based framework to evaluate the operation of a process that uses wind energy for the production of hydrogen from water electrolysis that, together with CO_2, produces synthetic methane.

Since solar energy is widely available in the studied location, we compare the use of solar or wind energy to produce hydrogen from water electrolysis, which then reacts with CO_2 emitted from power plants to produce synthetic natural gas. The performance of this process is evaluated throughout a year using mathematical optimization techniques, as well as its economics.

The paper is organized as follows. The process is described in Section 2. Next, in Section 3 the main modeling assumptions and solution procedures for the MINLP multiperiod problem formulated are discussed. Subsequently, the results for a variable production of methane are presented in Section 4, ending with the economic evaluation for the optimal plant, which uses either solar or wind energy. Furthermore, a study on the limit for the selection among these two technologies, solar and wind, is also presented and used to determine the preferred technologies across Europe and the US. Finally, in Section 5 some conclusions are drawn.

2. Process description

The process consists of five stages, starting with the wind farm or solar field where the electricity is generated. The next stage is the electrolyzer used to split water into hydrogen and oxygen operating at 80 °C and atmospheric pressure. On the one hand, we have the line of oxygen that carries some water vapor and traces of hydrogen. Most of the water is condensed, and the resulting gas stream is then dehydrated using a zeolite adsorber. Finally, the oxygen is compressed and stored. On the other hand, we have the stream of hydrogen, containing traces of oxygen and water vapor, most of which is separated by condensation. The oxygen represents a challenge for the synthesis of methane, so it is eliminated using a de-oxygenation reactor producing some water. Next, a zeolite is used to dehydrate the stream. The hydrogen is now mixed with the CO_2 taking in consideration that, in order to avoid carbon deposition on the catalyst, a proper ratio of reactants is required (Bader et al., 2011). Then, the gas phase is adjusted to the optimal operating conditions required by the reactor, using a compressor and a heat exchanger, where methane and water are following the typical methane steam reforming equilibrium.

In order to reduce water consumption in the process, the water produced in the reactor together with the methane is condensed, separated and recycled in the electrolyzer. The produced gas which consists mainly of methane but also contains CO_2, CO and unreacted H_2, must meet the composition constraints so that it can be fed to the network that currently supplies natural gas. Fig. 1 shows the flowsheet for the plant.

3. Modelling

In this section the main assumptions used in modeling the process for the production of synthetic methane using wind power

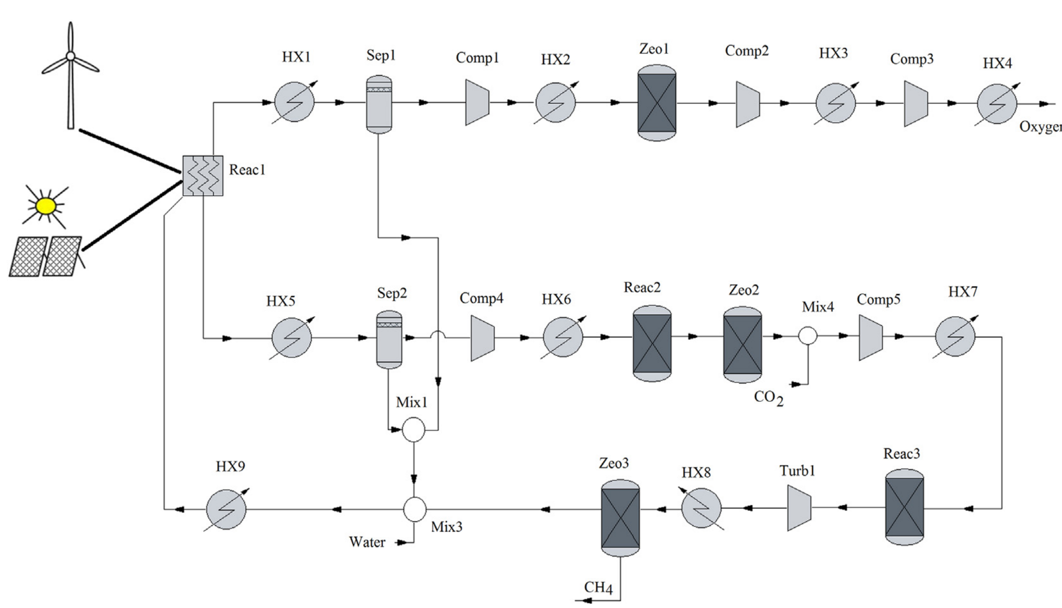

Fig. 1. Flowsheet for the production of synthetic methane.