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Technology overview of biogas production in anaerobic digestion plants: A European evaluation of research and development

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ABSTRACT

Anaerobic digestion (AD) technology is used commercially around the world, especially in Europe, which has set some challenging targets to diversify its energy mix with more renewable energy. This study intends to demonstrate, through technology prospecting, the relation between academic research (published articles) and technology development (patent applications) evolved from 1990 to 2015. Published articles were classified under the topics and wastes they cover, which include manure, agricultural and food waste, wastewater, sewage sludge and the organic fraction of municipal solid waste, with the last of these often being associated with co-digestion processes. Meanwhile, the patents in the area are mostly for equipment of the AD process and new methods or means of purifying the biogas obtained. It was found that the patents filed in Europe tend to protect their innovations only occasionally in countries outside the EU. Germany is the clear leader in all the areas of research and the commercial applications of the technologies, followed by Italy, Spain and Sweden. This study also demonstrates the immense potential of biogas throughout Europe, not just for energy generation, but also as a fuel and a by-product of the treatment of different kinds of waste.

1. Introduction

In 1630, Jan Baptist van Helmont (1580–1644), pointed that organic material in decomposition produced flammable gases. Some years later (1776), Alessandro Volta (1745–1827) discovered methane by collecting gas emerging from Lake Maggiore (Italy) and in 1804, John Dalton (1766–1844) established the chemical constitution of methane [1]. The concept of anaerobic digestion has been introduced around 1870 with the development of the septic tank system by Jean-Louis Mouras. It was Louis Pasteur (1822–1895) who reported that biogas could be used for heating and lighting. Indeed, in 1895 Donald Cameron design led to light up the streets of Exeter (England). Biogas development presented an inflection point in the energy shortages of the Second World War and during petroleum crisis in 1970. From then to now, anaerobic digestion has been studied, microbiologically identified and converted into a technology that, nowadays, is being used either for the treatment of wastewaters and solid wastes. In this sense, anaerobic digestion (AD) has become an interesting alternative for energy production, not only for the environmental advantages, of using waste as a raw material to produce biogas and a high-quality fertilizer (digested material) as its main products, but also for their relative low cost when compared to other techniques [2]. In fact, any kind of biomass has potential to be a substrate for biogas production as long as they contain carbohydrates, proteins, fats, cellulose and hemicelluloses as main components [3].

Briefly, anaerobic digestion is a biological process running under anaerobic conditions (strict absence of oxygen) in which a consortium of microorganisms breaks down complex biodegradable organic matter to methane 50–80%) and carbon dioxide 30–50%): biogas. Consequently, biogas can be used as a valuable energy source 5.5–7 kWh/m^3 of biogas).

According to De Baere and Mattheeuws [4], AD is not a new technology. It was already known in the 17th century, but it was only in the 1980s that it started to be used more widely for treating industrial and municipal wastewater, sewage sludge or municipal solid waste. As it is now a mature technology, it could be key to reducing organic waste, recovering the energy contained in biomass, and generating biofuels and energy [5].

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This process is therefore seen as a profitable treatment procedure, and it is increasingly being used, especially in Europe, to the detriment of other methods like incineration and disposal in landfill sites. Also, the use biogas promotes a sustainable society, reducing the dependence on oil, reducing the pollution and supplies energy with less impact on the environment [6]. Anaerobic digestion technology for biogas production, constitute today the most sustainable way of using the energy present in biomass and other wastes, because it also increases nutrient recovery and reduces greenhouse gas emissions. According to this potential, countries such as Germany, The United Kingdom and The USA established new legislation introducing alternative sources of energy including biogas [7]. Some biogas applications are reported in literature, for example, biogas has been used to efficiently heat a greenhouse during the typical winter conditions in eastern Turkey [8] or for heating households in India [9] or been used in a biogas-powered train (Sweden).

In parallel with these environmental advantages, AD could be also an instrument in helping countries to meet the new targets set by the European Union (EU), whose members have the overall goal of generating 20% of all their energy from renewable sources and of having 10% of their transport sector run on renewable energy by 2020 [10]. The state members must also cut their disposal of municipal solid waste by 50% by 2020 [11]. Reinforcing the importance of biogas in Europe, in 2013 the biogas production was comparable approximately to 13.4 M tons oil equivalent, 15.5 Mrd m^3 methane and 3% of natural gas consumption, also a production of 39.5 Mtoe is estimated for 2020, which corresponds to approximately 10% of EU natural gas consumption [12]. Finally, one extra advantage of using this technology has to do with the versatility of biogas, which can be used to generate electricity as well as a vehicle fuel. Consequently, it is attracting increasing interest on the part of researchers from academia and the public and private sectors.

By 2030, it is estimated that Europe's biogas production capacity will have reached around 18–20 billion m^3, which corresponds to around 3% of European current natural gas consumption [13]. Reducing global warming, enhancing its energy grid, and diversifying its power generation capacity constitute the main priorities of the European Parliament's environmental policies. Europe's targets for renewable energy production, greenhouse gas emission reductions and the sustainable management of waste can all be attained by using AD technology. It is one of the few processes that has the capacity to fulfil these three main European priorities [14].

According to the Global Intelligence Alliance [15], the potential sources of biogas at world level are: 75% in agricultural crops, by-products, and manure; 17% in municipal and industrial organic waste and 8% in sewage wastewater treatment facilities. Fig. S1 (Supplementary Material) shows the general biogas production chain. The first link is the entrance of substrates (with a high biodegradable organic load) that can be degraded by AD. In theory, all biodegradable materials that are not composed exclusively of lignin (e.g. wood), which, because of their molecular structure, have to be pre-treated to expose the biodegradable material to microorganisms, can serve as a substrate for AD processes and direct biogas production. Agricultural waste, manure, municipal solid waste, food waste, sewage, wastewater, and different industrial effluents with a high organic load can also be used in biogas production plants. Sometimes, they need to go through a pre-treatment stage, or to be co-digested, when one material is combined to improve process efficiency and synergic effects [16]. The logistic stage of collection, storage and transportation should be kept as simple as possible to keep overall process costs down. In some cases, especially when agricultural wastes are subject to seasonality, a logistic stage is required where these materials are transported to AD units [17].

The production stage is the most complex and involves two sub-stages: pre-treatment of the raw material and the AD reaction per se. Pre-treatment is needed to remove any impurities from the feedstock, like metals, plastics, or stones, and also to adjust the physical and chemical process conditions. More specific pre-treatments may be required to break down materials with a high lignocellulosic content and improve their bioavailability to the microorganisms involved in the process [18]. Currently, the literature breaks the types of pre-treatment down into three groups: chemical, physical and biological. They can be used individually or in combination.

As the biogas constitutes a mixture of gases, a purification stage is also required. There are different ways to separate out the constituent gases, but physical and chemical absorption are the most efficient and less complicated [19]. The biogas purification stage is a crucial part of the process as a whole. Generally, biogas must be purified to avoid problems in the subsequent heat and power units. These purifications processes remove unwanted components, like H_2S, particulate matter, dust and water [20]. However, when biogas is intended to be used as a fuel for vehicles, injected into the natural gas distribution network or used in fuel cells, high purification grade must be achieved and CO_2 must also be removed. Purification costs are very high, and this is currently the stage that is the most challenging in the whole process. According to Yong-Woo and Dong-Hoon [21], using membrane for biogas purification has the advantages to be simple technique and easy to scaling up.

The objective of this study is to evaluate the potential innovation and commercial applications of biogas production through anaerobic digesters in the European Union by investigating academic papers published and patent applications in the area. Using a technology prospection and collecting data from patents and articles for a long period (1990–2015), the correlation between Research, Development and Production is presented. It is not the objective of this study to provide a review on the process parameters of anaerobic digestion, as the biogas yields, organic matter removals or quality of the biogas. This study, intends to demonstrate, through technology prospecting, the relation between research institutions (throughout analysing published articles), and the relation between research institutions and technology development (throughout analysing patent applications). Apart from providing and extended overview of the research carried out on the production of biogas in anaerobic digesters, the expected impact of this study is the diffusion of bibliometric studies as a tool to expand and consolidate new knowledge about biogas and anaerobic digestion research.

2. Methodology

This study is a foresight analysis involving the empirical study of academic publications and patents documents. Reference literature was used to give a picture of the state of the art in biogas production and research in terms of the leading country (production and articles publication), main assignees and main research institutions in biogas production. To perform this analysis indexed articles and patents have been evaluated between 1990-september 2015.

For articles evaluation, a search in the Web of Science database for academic papers indexed between 1990 and September 2015 was made using the following keywords (*biogas* or "*green gas*" or *greengas* or *biomethane* or "*digestated gas*" or "*renewable natural gas*"). Note that these keywords do not include the keyword "*Anaerobic Digestion*". This is due to the focus of this research is focused on the product "biogas", our search assumed that if the objective of the research was the production of biogas, keywords related to biogas should be present in the title or the abstract of the articles. Of course, papers related to the biogas purification step are also recovered, thus complementing our search on the use of the product "biogas".

After this, the data mining processes was started with the software Vantage Point®. This software allows organizing the documents and sorting them out by country, priority, year, author, etc. showing correlations between research institutions or companies that joins its efforts for research or patent inscription. As previously mentioned, for