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A review of potential innovations for production, conditioning and utilization of biogas with multiple-criteria assessment

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ABSTRACT

Biogas is a relatively mature renewable energy technology but still most commercial biogas power plants require significant financial incentives. Additionally, local shortages of very cheap digestible feedstocks limit biogas productivity, especially for larger biogas power plants (> 1 MW_e). Innovations that could improve cost-effectiveness and resource efficiency of biogas energy technology are therefore required.

Over the last few years a number of potential process innovations for biogas technology have been proposed and investigated. However, the majority of these novel concepts has minimal or no impact on technology development. Disruptive innovations are very rare, but only they really matter for the economy. Therefore review reports that systematically compare, analyze and evaluate the suitability of these emerging methods with emphasis on technological excellence and realistic commercial potential are needed.

This study presents potential process innovations from most recent patent and academic literature proposed for biogas (i) production, (ii) conditioning, (iii) utilization and (iv) industrial symbiosis. Within these four highly interdisciplinary categories the review attempts to provide short practical comments on selected methods and briefly analyzes their perspectives and constraints. Further, relevant biogas process innovation criteria are designed and multiple-criteria assessment of pre-selected potential process innovations is made. The paper concludes with the characterization of innovativeness of selected solutions and suggests future research needs for biogas energy technology that could bring new innovations in near term.

Contents

Abbreviations: AD, anaerobic digestion; AER, absorption enhanced reforming; AFEX, ammonia fiber explosion; AHPD, autogenerative high-pressure digestion; ARP, ammonia recycle percolation; AwR, alkaline with regeneration; BA, bottom ash; BM, biomethane; BS, biosyngas; C, degree of Celsius; CCR, CO_2 capture and recycling; CCS, carbon capture and sequestration; CH_4, methane; CHHP, combined heat, hydrogen and power; CHP, combined heat and power; CI, compression ignition; C/N, carbon/nitrogen; CO_2, carbon dioxide; COD, chemical oxygen demand; COG, coke oven gas; CP, commercialization potential; CPB, cryogenic packed beds; CSTR, continuous stirred tank reactor; CY, number of citations per year; DF, dark fermentation; DME, dimethyl ether; EECI, energy, environment and climate impact; Ef, factor of energy; EP, electrochemical pretreatment; F–T, Fischer–Tropsch; FVW, fruit and vegetable wastes; GHG, greenhouse gas; GT, gas turbine; HCCI, homogeneous charge compression ignition; HHV, higher heating value; HMF, hydroxymethylfurfural; HPRSS, high-pressure reactive solvent scrubbing; HRAP, high rate algal pond; HRT, hydraulic retention time; HTL, hydrothermal liquefaction; IEA, International Energy Agency; IF, impact factor; IT, information technology; KOH, potassium hydroxide; KSAMBR, Kubota Submerged Anaerobic Membrane Bioreactor; kW_e, electrical kilo Watt; L, liter; LBM, liquid biomethane; LCA, Life Cycle Assessment; LHW, liquid hot water; LNG, liquid natural gas; MBR, membrane bioreactor; MCA, multiple-criteria assessment; MCFC, Molten carbonate fuel cell; MEC, microbial electrolysis cell; MFC, microbial fuel cell; MFR, microbial film reactors; MJ, Mega Joule; MOM, metal-organic material; MeOH, methanol; MSW, municipal solid waste; MW_e, electrical Mega Watt; NaOH, sodium hydroxide; NMMO, N-methylmorpholine-N-oxide; Nm^3, cubic meter at standard temperature and pressure; NP, number of publications; NPK, nitrogen/phosphorous/potassium; OLR, organic loading rate; ORFC, oxy-reforming fuel cell; O&M, operating and maintenance; PAH, polycyclic aromatic hydrocarbon; PEIO, primary energy input to output; PEMFC, proton exchange membrane fuel cell; PSAP, patent status or academic performance; SCFA, short-chain fatty acid (or volatile fatty acids (VFA)); SI, spark ignition; SNG, synthetic natural gas; SOC, soil organic carbon; SOFC, solid oxide fuel cell; SRT, solids retention time; SS-AD, solid-state anaerobic digestion; *T*, temperature (K); t, tonne; TCOE, thermoeconomic cost of electricity; TRL, technology readiness level; TS, total solids; UASB, upflow anaerobic sludge blanket; USD, US dollar; Wh, Watt hour; WWTP, waste water treatment plant; VPSA, vacuum pressure swing adsorption; VS, volatile solids; VSS, volatile suspended solids; %wt, percent by weight.

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1. Introduction

Biogas is attracting significant attention as an increasingly interesting renewable and sustainable energy technology. Although biogas technology seems relatively mature it is not considered fully economically viable and usually requires significant financial incentives to successfully compete with commercial fossil fuel based energy technologies [1–3]. Three major factors limit expanded adoption of biogas energy technologies: (i) high cost of digestible feedstocks, (ii) limited local availability of such feedstocks and (iii) limited availability of innovations that could make biogas energy more economically attractive.

In some highly developed countries such as Germany biogas production receives significant financial support which has led to rapid expansion of this renewable energy technology over recent years. Attractive German financial incentives facilitate the use of several raw materials as feedstocks for anaerobic digestion (AD) (e.g. dedicated energy crops) and therefore the overall production potential of biogas has significantly increased over the past two decades. Also some other European countries like Denmark, Austria, Italy or Sweden have legislation and financial incentives beneficial for investments facilitating expanded use of biogas energy. Unfortunately, most other countries offer insufficient or no financial support for the production, conditioning and utilization of biogas. Importantly, these countries usually cannot adopt most of existing biogas technologies directly from highly developed countries (e.g. technologies utilizing expensive energy crops) because such biogas plants would make a loss. Consequently, for those numerous countries [3–7], especially if they have limited access to cheap digestible biomass, availability of innovations that could facilitate cost-effective production, conditioning and utilization of biogas is of particular importance.

An innovation is the implementation of a new or significantly improved: (1) product (good or service), (2) process, (3) marketing method, or (4) organizational method in business practices, workplace organization or external relations. The minimum requirement for an innovation is that the product, process, marketing method or organizational method must be new (or significantly improved) to the enterprise [8]. This study reviews only process innovations in the field of biogas technology. A process innovation is the implementation of a new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software [8]. In general, many new concepts are being constantly proposed for all commercial technologies. However, only very few of them have or might have realistic commercialization potential. Although breakthrough or disruptive innovations with significant commercialization potential are very rare, in practice only they matter for the economy. Scientists should therefore constantly filter emerging concepts with potentially innovative character in order to find most promising ones and to facilitate their diffusion and possibly future commercialization. Academic [9–11] and patent