Synergistic Carbon Sequestration for Sustainable Sludge Conversion

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Abstract. Due to the sludge treatment processes such as anaerobic digestion processes release substantial amounts of biogenic CO2, Wastewater treatment plants (WWTPs) represent significant carbon emission sources consequently. On the one hand, existing carbon capture technologies generally lack effective integrated, on the other hand, due to the green tides cause severe damage on ecological, their biomass remains an underutilized potential carbon sink resource yet. Thereby, this review trying to coupling supercritical water gasification (SCWG), organic rankine cycle (ORC), and Ulva biochar sequestration into a synergistic technological framework. SCWG technology which is at above 374°C and the pressure at 22Mpa situation to directly processes wet sludge, and produce hydrogen and liquid co2, the whole processes can save high energy consumption drying step. In order to achieving system self-sufficiency, through the ORC recover waste heat 30% of input energy which is generated by exothermic reaction to driving carbon capture units. Then use containerized systems transport the captured liquid co2 to Ulva farms, in order to promoting algal photosynthesis, use micro-bubble aeration enhances dissolution. The obtained Ulva undergoes pyrosis to form high stability biochar, the whole operation completing a carbon closed loop. Comparing conventional methods this comprehensive methods can reduces greenhouse gas emissions by 3.8–8.2 kg CO_2/kg dry sludge, coordinate policy mechanisms such as carbon tax and subsidies can improve economic feasibility. This review indicates to promoting industries significance reduce emissions thereby promoting the process of carbon neutrality there is a feasible approach which through elimination of sludge drying, achievement of energy self-sufficiency, and establishment of a carbon closed-loop.

Keywords: Carbon Capture and Storage, Supercritical Water Gasification, Organic Rankine Cycle, Ulva Biochar

1. Introduction

Carbon Dioxide Capture and Storage (CCS) technology as key method particularly apply in energy intensive industries and waste management area which hard to reduce emissions that is well known can achieve global net zero emissions. Although demonstrated technical feasibility in carbon capture, there still facing persistent and significant obstacles that widespread apply of integrated

CCS chains. Main problem is worried about sustainable and economic feasibility of the longtime operation which cause cannot implementation within huge scale [1]. Municipal and industrial wastewater treatment plants (WWTPs) also face this challenge. The main method of treating sludge is anaerobic digestion, this process will emission amount of methane and biogenic CO2 which emission 0.5-1.2kg CO2 per kg need to treating 1kg dry sludge. Currently most infrastructures lack of technology of the integrated carbon capture that is the reason caused leakage from such emissions [2]. Additionally, environmental issues gradually become worse due to exacerbating the rapid proliferation of green algae by the ocean warming, excessive consumption of oxygen and habitat destruction also severe damage to the marine ecosystem. The paradox point is such problematic green algae biomass as kind of great potential and huge scale apply in the carbon storage effective resources which not fully utilized [3]. To connect bridges between these technologies, this review proposes a new collaborative approach by coupling three technologies. Method of SCWG applied in dealing wet sludge which achieve improved value of sludge and produced liquid CO2 that easy to collect, this method also can avoid conventional thermal drying method which cause large amount of energy loss. ORC method used amount of waste heat from SCWG process produced, converted electric power that can supply power to carbon capture system so that enhance whole system energy efficiency and self-sufficiency. Method of Ulva biochar storage utilizes amounts of algae from aquaculture system, by microbubble technology accelerate the dissolution of CO2 that can promote the growth of algae, then through pyrolysis technology convert the algal biomass to the high stability and sustainability biochar. The whole comprehensive framework convert sludge to the valuable hydrogen sources, utilizes the emission CO2 convert algae biomass to the biochar. Such closed carbon cycle system not only can deal with sustainable waste management and effective emission reduction dual requirements, but also supply the decarbonization methods and approaches which extensible and replicable.

2. Integrated SCWG-ORC system for carbon capture

SCWG directly treat 80% water content wet sludge within temperature over 374 ℃ and pressure reach 22MPa extreme condition, utilizes the water have unique properties for dissolving organic components at critical point, through hydrothermal reaction let macromolecular substances such as proteins and lipids from sludge occurs cleavage and recombination, produces high purity hydrogen and over 90% purity liquid CO2 which collected by AI optimized ionic liquid membrane by the liquefaction reaction and transport in a high pressure liquid form. ORC recycle be guided waste heat, convert heat energy to electric power supply power to carbon capture system which achieve self-sufficiency operation pattern.

2.1. Fundamentals of supercritical water gasification

SCWG technology directly convert high water content thing to the high purity hydrogen gas [4]. To improving whole system energy efficiency, method directly treating wet sludge rather than drying step. SCWG technology cannot successfully reaching this convert step without process optimizing which separate liquid CO2 and produce pure hydrogen ability. The liquid CO2 collected by an ionic liquid membrane which by AI optimized can substantially enhance CO2 and nitrogen selectivity and permeability, so that can collect liquid CO2 within cellular material [5]. It can greatly enhance whole system sustainability and economic efficiency in subsequent formation of hydrates, pipeline transportation and provision of high purity raw gas for biomass carbon storage in the future [6].

2.2. Waste heat recovery via organic rankine cycle

The SCWG system is mainly constituted of eight subsystems, heating and energy recovery unit (HERU), SCWG device, gas cooling unit (GCU), carbon capture unit (CCU), pressure swing adsorption unit (PSA), hydrogen compression unit (HCPU), combustion and flue gas heat recovery (CFHR) and carbon dioxide compression unit (CCPU). The whole system utilizes waste heat recycle method reason is to avoid consuming amount of energy in operation. GCU unit utilizes ORC technology effectively recycle waste heat from the syngas. SCWG convert amount of heat energy within high temperature and pressure condition to electric power to supply power in order to driving ORC. It can effectively reduce requirement for outside electricity power. Choosing halocarbon refrigerants such as Freon as ORC working medium, optimized heat exchanger design technology also can enhance effectively waste heat exchange. Guaranteed system self-sufficiency ability by ORC produces electricity power to driving units which requires amount of energy, so that can minimize the reliance on the power grid to the greatest extent. Therefore, the whole system reaches transition from SCWG to ORC and then to CCS.

2.3. Synergistic effects on system performance

It is necessary to conduct an investment assessment of SCWG reactors and ORC systems, operational stability, reliability and lifecycle maintenance respectively, additionally, potential coproduct from methanogenesis process and secondary utilization of waste heat process also can improve economic feasibility function for whole SCWG-CCS system [7]. Life Cycle Assessment (LCA) indicates compared conventional methods like incineration, anaerobic digestion and dry gasification etc. the whole integrated system is better on reduce emission greenhouse gases area, each 1 kg of dry sludge processed, the 3.8-8.2 kg of CO2 emissions can be reduced [7,8]. Coupled these technologies have significant effect on treat high moisture content sludge situation. The hydrogen coproduct produced from SCWG also can convert electricity power to supply energy power for Ulva aeration system, the waste heat energy recycled by ORC system can supply drive power for CO2 gasification unit, so that can achieve positive moving towards collaborative cooperation between systems. From the perspective of economy and cost, the economic competitiveness of whole system will be affected due to utilize nature gas which low-cost electricity power. The system self-sufficiency rate will be raised by heat pump cycle generated electricity power rise, therefore, the dependence on additional purchased electricity will be reduced which can bring benefit function of enhance economic performance. The economic incentive of carbon capture and storage technology also will be enhanced by the impact of the carbon tax policy. When carbon tax over a certain level, the Net Present Value (NPV) of the system will be significantly improved. For the amount of large and capital-intensive projects, it is essential that the proper coordination of cash flow is crucial for the financial feasibility of the project. Hence, the target achieves NPV maximization get the approval and believe of the deciders. The review reveals each 1% reduction in subsidies, NPV will reduce 1.05M dollars, the cost of treat 1 ton sludge will be reduced 0.31 dollars. The profitability of the system will be impacted by the reduction in sludge subsidies. Oppositely, when sludge subsidies rise 33.33% the NPV of the factory will improve reach at 5.8M dollars, the cost of treat 1 ton sludge will be reduced at 17.25 dollars [9]. The financial condition of factory will be significantly improved by such subsidies rises which means there have significant positive relation between the higher level of subsidies and project profitability.

3. Carbon dioxide transportation and sequestration

Collected liquid CO_2 transport to the Ulva farm the method typically use specialized oil tankers transport within short to medium distances or choosing submarine pipeline within big scale, in order to maintaining stable condition the situation should control air pressure keep 65bar and the temperature should maintain 20℃. Then liquid CO_2 evaporated convert gaseousness dissolve into Ulva farm, the effect of dissolve can be improved by microbubble aeration which the diameter of the bubbles is less than 50um that enhance transpiration efficiency of photosynthesis in Ulva. Collected Ulva biomass react pyrolysis within temperature range from 300-500℃, then output stable biochar which can persist for a hundred years, effectively captured and locked the captured CO_2 finally. The whole process finish CO_2 convert from industrial sludge to stable marine biomass biochar.

3.1. Liquid CO2 transport

In fact, there are already have many examples about transport CO_2 by oil tankers in global. These oil tankers suitable transport short distances. Ensure transportation efficiency and safety by controlling heat input, simulating start, stop condition, insulation measures and other related methods collaboratively [10]. This container transport method can build connect between gas capture under the sea, SCWG and Ulva farms, become materials bridge of redistributing carbon. The control of thermal disturbances and the start/stop frequencies need to be coordinated, however, to avoiding pressure change due to the liquid CO_2 phase change. For most large transport, submarine pipeline gives solution to oil tankers. Computational fluid dynamics (CFD) simulations with Soave-Redlich-Kwong (SRK) equation of state confirm that coordinated control thermal input, start/stop protocols and insulation measure can high effectively transport liquid CO_2 by submarine pipeline. The review also reveals the best safety situation about liquid CO_2 input which within 65bar and 20℃ after steady and state dynamic simulation. On this simulation, the maximum conveying flow rate of pipeline can be improved at 148,000kg per hour, if over this rate the stability of predict operation will decrease. The properties of CO_2 in the submarine pipeline also supply a kind of safety and efficiency solution for gas transport and storage. Moreover, the research result has been verified that analysis example by start/stop and unusual operating conditions, it can supply valuable predict conclusion about improve efficiency of CO_2 in the submarine pipeline transportation [10]. Hydrogen coproduct can supply energy replenishment for Ulva aeration systems.

3.2. Ulva biochar conversion and sequestration

As an aquatic plant need photosynthesis reaction, Ulva main absorb dissolved CO_2 or gaseous CO_2 from water. Therefore, Ulva cannot directly absorb liquid CO_2 captured from SCWG, because the liquid CO_2 have to convert to the gaseous CO_2 by controlling temperature and decreasing pressure, then be put and dissolve into the Ulva water farm to supply Ulva photosynthesis reaction. Around 300-500℃ temperature situation react pyrolysis on the collected Ulva biomass, then product stable biochar which the carbon atoms turn into a persistent aromatic structure. Microbubble aeration as an alternative dissolution enhancement method by producing bubbles and overcoming interfacial limitations of direct liquid CO_2 injection to avoiding high consumption energy control of temperature and pressure [11]. Compared to the conventional gasification method using control of temperature and pressure can reduce consumption energy.

3.3. Environmental impact analysis

From the perspectives of resource recycling and ecological cycling, biochar can as a soil amendment enhancing moisture and retention capacity of fertilizer, absorbing hazardous material, reducing pollution in farmland and underwater. Ulva biochar rich contain minerals which can put into agricultural fertilization. The special properties of high PH suitable treat acid soil, but cause salinization and salinity issues which can solve by biochar cleaning pretreatment. The pretreatment still important for removing salt, heavy metals and microplastics, the biochar's cellular structure can solidify heavy metals and prevent these heavy metals moving into farmlands and underwater. In addition, Ulva rapid reproduction can promote early collection and resource transformation. It is not only help for carbon storage but also effectively reducing marine eutrophication. For Ulva rich contain moisture, around 200-210°C hydrothermal carbonization (HTC) can directly convert biochar derived from HTC from wet sludge, consumption energy of drying decreasing 60% [11]. Market value of the biochar as soil amendment can improve project benefit, there are also have two main problems exist: the one is sea desalination and microplastic removal can rise cost of pretreatment, the other one is the accumulation of sodium may limit the expansibility of agriculture which need special cleaning process to deal with it. In terms of policies, the carbon credit mechanism and pollution control subsidies will significantly enhance the economic feasibility of the projects.

3.4. Techno-economic feasibility

The limitation of existence includes due to Ulva growth cycle and environmental sensitivity leads to the wave rate of biochar efficiency over 30%, need planting strategies with climate adaptability to assist with policy subsidies. In terms of energy requirement, compared to the conventional pyrolytic technology, this method can reduce drying process but still need high pressure hot water to treating. In terms of cost of pretreatment, needs to removing salt, heavy metals, microplastics and hazardous material. At the biochar market, in terms of soil amendment and pollution control agent, their can bring great benefits for project. Developing planting strategies with climate adaptability and policy subsidies can mitigate meteorological risks which is very important to maintaining stability in the future. In conclusion, based carbon storage of Ulva biochar is a method. The main advantages include achieve reusability of biomass and the coordinated control of pollution. Nevertheless, this way may face potential limitation which dependent on the influence of environmental factors that affect the growth cycle of Ulva and the stability of the systems impressionable. The production capacities proportion matching between CO_2 emission from WWTPs and biochar production from Ulva farms is a key factor in evaluating the feasibility of project.

4. Conclusions and outlook

4.1. Conclusions

This review built a closed cycle carbon management system which coupling SCWG, ORC and Ulva biochar storage technologies. SCWG method avoid energy loss within conventional drying process choosing directly treating wet sludge, the exothermic character make recycle waste heat by ORC become possible, which reach carbon capture self-sufficiency. Collected liquid CO_2 transport at 65 bar and 20 ℃ high pressure situation through containerized systems or submarine pipelines, then efficiently dissolution into the Ulva aquaculture pools the concentration is 40% by microbubble aeration. Whereafter, put Ulva into the pyrolysis reaction process within 300-500°C temperature can produce high stability biochar, the whole processes successfully finish change from industrial emissions to hard degrade storage. The technological and economic analysis reveals compared incineration and anaerobic digestion, the whole integrated system is better on reduce emission greenhouse gases area, each 1 kg of dry sludge processed, the 3.8-8.2 kg of CO2 emissions can be reduced. Meanwhile, policy mechanism about subsidy for sludge when the carbon tax exceeds 40 dollars each ton, the NPV of the projects will increase to 5.8M dollars. It is necessary to promoting this massive application.

4.2. Outlook

Although this review comprehensive coupling SCWG sludge handing, ORC recycle waste heat and Ulva biochar storage technologies establish an industrial carbon cycle system, the accurate mechanism of energy exchange has not yet been quantitatively defined between the SCWG-ORC units and Ulva biochar storage system. It is essential to build a mathematical model to systematically tracing the path of the energy transfer. These models have to quantified the process of converting the waste heat from SCWG into the electrical energy through the use of the ORC technology firstly, then in order to achieve the optimal cultivation of amounts of algae which need to simulating the generated electrical energy to adjust the thermal condition in the aquaculture pools. Such models can accurately adjust energy flow between different systems, significant improving deployment adaptability of the coastal industrial zone. In addition, it is essential to maintain cooperative ecosystem by clearly incentive mechanism seamlessly integrated with the carbon market.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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