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STEAM-REFORMING OF FOSSIL FUELS AND WASTES TO PRODUCE ENERGY AND CHEMICALS WITHOUT GREENHOUSE GASES

ABSTRACT

Worldwide concern has demanded a re-examination of our energy- and chemical-producing plants that use fossil fuel sources and release large quantities of greenhouse gases. Plant retrofits with steam-reformer/gasifiers will increase plant efficiencies, improve economics and avoid releasing the troublesome greenhouse gases, such as carbon dioxide. In this paper, we describe and illustrate the several new steam-reforming/gasification plants that are processing waste streams and fossil fuels. These plants range in size from 1 ton/day to 1000 tons/day. They are commercial and economically successful. These new concepts can be used to both upgrade fossil plants for improved economics while eliminating the release of greenhouse gases. By aggressively retrofitting our old coal plants a 15% CO_2 reduction can be met by 2010.

BACKGROUND – THE CHALLENGE

During a recent visit to the White House Office of Science and Technology Policy (OSTP), we were given a preview of the direction the Executive Branch of our Government wants to take this country with respect to energy policy [1,2]. They have a strong desire to move our energy policy toward renewable/sustainable energy sources, and they want to do it without polluting the environment. As a consequence, OSTP are very interested in the steam-reforming, solar energy, and fuel cell technologies for the future. The purpose of this paper is to give a brief overview of how these new technologies fit together and at the same time offer the synergistic opportunity of the elimination of greenhouse gas emissions from fossil plants. We illustrate an example where communities can take the lead in this area to help advance these national goals.

Many communities produce some of their energy for their needs by operating old, polluting and less-than-efficient coal power plants. And even more challenging, to the standard de-sulfurization and stack bag-house particulate controls, there is pressure to add costly acid gas controls, and now there is talk about greenhouse gas controls coming. This is indeed a hopeless and overwhelming picture for our aged fossil plants.

The burning of fossil fuels in boilers to raise high temperature, high pressure steam that have been used to power turbo-electric generators produces a problem source of carbon dioxide and other greenhouse gases. This fossil fuel combustion, especially of coal, needs a technological fix to avoid the emission of carbon dioxide and other greenhouse gases with their attendant undesirable release to the earth's atmosphere. Much of the world depends on coal for power. There have been significant efforts to develop clean coal technologies to greatly reduce the release of acid gases, such as sulfur oxides and nitrogen oxides. But to date none of these clean coal programs aim to eliminate carbon dioxide and other greenhouse gases.

Today there is worldwide concern that the atmospheric buildup of carbon dioxide and other greenhouse gases will start to have serious environmental consequences for the earth's tropospheric temperature, global rainfall distribution, water balance, severe weather storms, etc.

The latest results on the sun's cyclic output [3,4] have shown that a brightening sun would cause only 0.4°C projected over the next 100 years; whereas greenhouse gas sources of global heating [5] cause increases of 2°C over a projected 100 years. So the sun's brightening is onlt a very small part. Although there is still debate about whether global effects are being observed, the scientific and political majority are agreeing that if there is any chance, however remote, that these global effects are showing up, then we must act. Technological solutions are being demanded throughout the world.

There are also widespread efforts to increase the efficiency of power plants by utilizing advanced thermodynamic combined cycles, more efficient turbo-generators, improved condensers and cooling towers, etc. A small portion of this effort involves the use of fossil fuel gasification processes which are higher efficiency because they avoid combustion and large combustion product emissions. Finally, there is an effort by Westinghouse (Corporate literature, "SureCell®" 1996) and others [6] to combine the use of advanced high temperature turbo-generators and fuel cells to accomplish conversion to electricity around 70% instead of today's conventional power plants of about 40%.

The worldwide research establishment, encouraged by government funding from various agencies, continues to be focussed on identifying commercially attractive gas separation technologies to remove carbon dioxide from stack gases and also attractive chemistry that will utilize this carbon dioxide as a raw material to manufacture useful products. This has, indeed, been a very large challenge with poor successes as summarized by the review papers [7,8]. Trying to scrub the CO_2 from stack gases and trying to chemically react the recovered CO_2 clearly is not the right path of research because of the technical difficulty and the process expense of reacting a carbon dioxide feedstock.

The new concepts presented here (for which a patent has been filed), avoid the difficult path of attempting to strip and capture the carbon dioxide from stack gases and without attempting to carryout separate chemistry of carbon dioxide to attempt to produce useful products. The new approach uses commercially available gasification technology combined with fuel cells to generate electricity at high efficiency while being able to recover the greenhouse gases for the production of useful chemical products. In this way, a combustible feed gas can be fully oxidized without being comingled with the final oxidation products.

NEW CONCEPTS – A FUTURE DIRECTION

Our concept is to upgrade this typical old coal plant to a first-of-its-kind coal plant of the future, where coal can be fully utilized as an important energy and chemical resource without any emissions of carbon dioxide (CO_2) and without the typical problems of NOx, sulfur, and other particulate emissions [9,10].

It would be a cutting-edge, future-looking project that could gain the support and pride of both local communities and environmental groups alike. It would be a model for future coal plants and would help coal be considered one of the environmentally acceptable fuels for the future. The project also has the potential to stimulate the new technologies by potentially bringing several new opportunities (like fuel cells and steam-reforming) into the community. This could mean additional jobs as well as additional business opportunities. It will also be a source of local pride as the community becomes recognized as a leader in sustainable energy production without pollution.

The plant's conceptual design includes the use of several advanced technologies, most of which have been proven individually, but which have never been integrated into a single system. A wide range of coal streams (or even co-mixed with industrial/municipal waste streams) would be steam-reformed to manufacture synthesis gas (syngas) consisting of hydrogen, carbon monoxide, carbon dioxide, and steam to feed a fuel cell/turbo-electric generator system. The steam-reforming concepts are based on early work of the author conducted at Hercules, CA which resulted in the founding of Advanced Energy Conversion Division of Mittelhauser Corporation [11], and more recent commercial production at Westinghouses's Oak Ridge, TN plant. NASA and the Jet Propulsion Laboratories have advanced fuel cell technologies over many years, and there are currently many manufacturers working with many different types of fuel cells. But recent developments in Solid Oxide Fuel Cells (SOFCs) that can use syngas look particularly promising for this project, as will be discussed later in this paper.

In addition, if the energy production economics are attractive, solar photovoltaic panels could also be installed at a large scale to generate enough electricity to drive water electrolysis units that will generate hydrogen to fill large storage tanks and to supply the oxygen for the coal steam-reforming. The hydrogen from the storage tanks could augment plant syngas to supply a steady source to the fuel cells during plant outages or downcycles. The tank supply of hydrogen would be sufficient to load-follow, if the economics favor this.

Using these new concepts, energy production also has several options that involve producing power that is on-peak only, power that is produced by the fuel-cells that is base load, and a combination tailored to optimally fit the local utilities load-following need.

The production of chemicals from methanol to higher molecular weight middle distillates (i.e. kerosine) is necessary in order to utilize the carbon source so as to eliminate any carbon dioxide emission. So we see that the fossil plant of the future can be an integrated and combined simple chemical plant and power plant. Methanol/fuel cell vehicles are another sustainable futuristic possibility.

The electric energy output of the plant will be about the same as the present old coal plant, since the fuel cell/turbine combined cycle system will produce electricity at the very high efficiency around 70% compared to the old coal plant's efficiency of around 34% — more than double, but syngas is diverted for the production of methanol or other chemical products. In this manner, about half of the plant's additional energy output can be used to manufacture chemicals from 500 to 2000 tons/day and still supply electric power from 100 to 1200 MWe.

Water operations involve three areas: (1) water produced by the fuel cells by reacting H_2 and O_2 to produce water that is relatively pure, (2) water condensed out of the steam-reforming vent stack feeds the steam superheater, and (3) fresh water that is deionized and potassium electrolyte does make-up water is needed for the electrolysis cells that make the H_2 and O_2. There is an opportunity to use wastewater that is recovered from municipal sewage that can be used for slurrying the coal and make-up to the steam-reformer.

There would be only a 5 to 10% percent of solid residue formed from a 10 times mass reduction typical of steam-reforming coal.

Fuel Cell/Turbo-Generator Electricity Generation

There has been great progress in fuel cell technology [12-14]. This fossil fuel-steam-reforming plant concept will require that the fuel cell type accept carbon monoxide and other light hydrocarbons in addition to the normal hydrogen. This requirement almost guarantees that the only two types to be considered are Solid Oxide Fuel Cells (SOFCs produced by Westinghouse and Technology Management Inc.) or Molten Carbonate Fuel Cells (Energy Research Corp.). For the smallest size plant (say 300 tpd of coal feed), we estimate that about 14 6.93 MWe AC fuel cells can be powered at maximum by the 468 tpd or 650 lbs/min syngas generated from a coal feed stream, assuming an 85% fuel utilization and an electrochemical 74% fuel cell/turbo-generator efficiency. This is 9.73 kW/scfm of H_2, which is much higher than the strictly electrochemical phosphoric acid fuel cell at 4 kW/scfm of H_2. Integrating the solid oxide fuel cell with the turbo-generator and in some cases combustion turbines improves efficiency greatly [13,14].

There is a possibility that the 14 SOFC fuel cells in such a small fossil plant could be sufficient to achieve an economy of scale, which will to drop the unit price and stimulate their use in other markets which could further expand the fuel cell business. And, of course, the largest plants of 3,000 tpd coal feed could use 140 fuel cells, that certainly would stimulate the market and encourage expansion of the fuel cell manufacturing facilities in order to meet this demand.

Even for the smallest fossil plant, there is an option for the future, in addition to the 100 MWe of fuel cells powered by the coal-generated syngas, there could be more fuel cells (about 5) at the site being supplied with hydrogen gas from a large storage tank that is maintained near capacity with solar-photovoltaic-generated electrolytic hydrogen gas to cover outages and downcycles. Another purpose is to allow the plant to load-follow to a much greater degree than the present coal plant, which has a limited turn-down capability. The additional 5 fuel cells (35 MW AC electric) could be fueled by solar-produced stored hydrogen will require about 250 MW DC of solar panels typically operating about 5 hours per day in sunny weather. Thus, there must be about 8 times the power available from the solar panels on clear days to produce hydrogen that can be used 24-hours per day by the fuel cells.

This number of solar panels will justify building a panel assembly plant in the Billings area that will employ the local skilled labor force and utilize cheap local raw materials. ASE Americas, Inc. is pioneering the development of the technology for such a plant. It is based on one of its products, the 300 watt module, currently the largest and most powerful photovoltaic module on world markets. For this project, the number of modules would be 830,000 – large enough to drop the energy price to levels comparable to those at peak power demand in many parts of the U.S.A., e.g. in the range of 15 to 30¢/Wp. This would catalyze and stimulate new solar markets.

Process Block Diagram Options

Assembling the three critical technologies outlined above into an integrated block diagram for the small coal steam-reforming plant reveals what the internal flows and the critical output flows can be. This assumes that the coal feed coming into the plant has excess water, otherwise wastewater could be used to augment this water feed, so that none of the water production (i.e. industrial water or bottled water) needs to be used for the plant and is available for sale in the community.

BASE CASE – OPTION I:
The base case to be considered is the coal steam-reforming plant producing a combination of electricity, methanol, and carbon disulfide shown in FIGURE 1.

The methanol plant produces about 150,000 gal/day or about 2720 55-gallon drums per day that can be used by the local refineries for gasoline octane extender or as feed to a MTBE plant for higher octane extender. It can also be used for methanol/fuel cell vehicles.

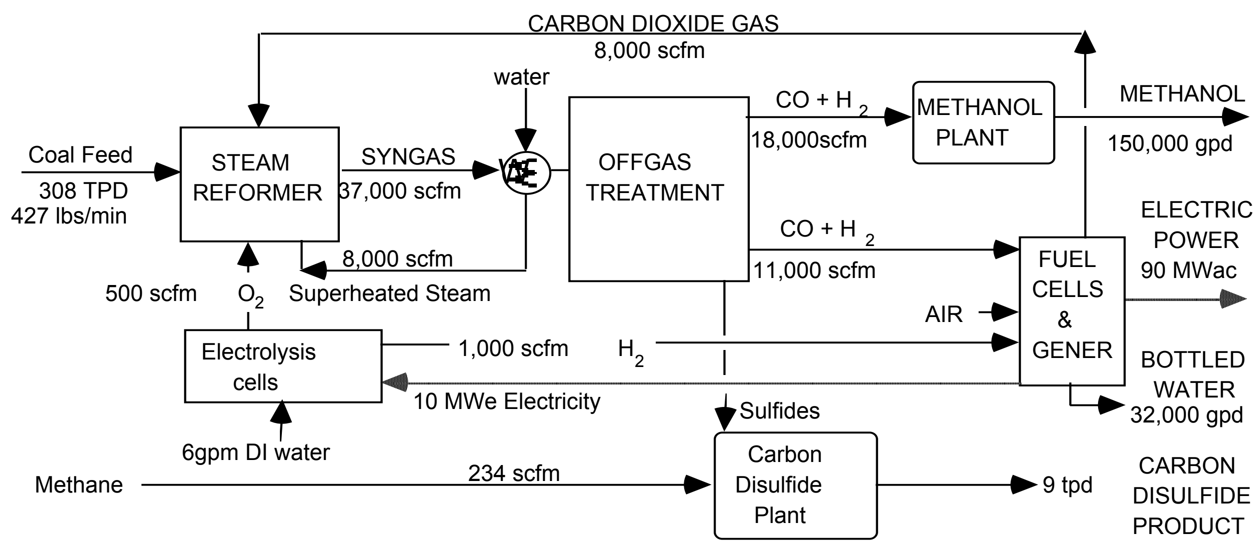

FIGURE 1: WASTE STEAM-REFORMING TO POWER & BOTTLED WATER

The carbon disulfide is a high value commodity product, for which there is a large market. This plant is made more efficient by the use of minor sidestreams and waste heat from the larger plant complex. The "Bottled Water" product shown as output from the fuel cells using the electrolytic hydrogen is expected to be of the highest quality; in fact, it might be referred to as "chemical pure" or "chemically certified." It may even be possible to add a small bottling plant here that would produce the final bottled water product.

The arrangement of the electrolyzers receiving power from the fuel cell output provides the ability for the plant to load follow while keeping the coal feed and the steam-reformer operating at near constant throughput. The amount of plant electrical output can be diverted in varying amounts to operate the electrolyzers so that excess hydrogen and oxygen can be produced and stored. During peak power demands, a modest increase in fuel cell output power can be generated from this extra hydrogen fed to the fuel cells.

Cost Analysis of Coal to Methanol and Electricity

The capital expenditure for the steam-reforming to methanol and electricity can only be very roughly estimated at this time, but this first cut simple payback analysis is important to show that the project can be profitable and be an exemplar of the coal utilization technology of the future.

The coal preparation, steam-reforming system, and gas processing might cost $34 million, the conventional methanol plant at $38 million, gas treatment at $2.7 million, the 34 Westinghouse SOFC SureCell® fuel cells at $126 million, the 80 Teledyne-Brown HP-200 electrolyzers at $52 million, the carbon disulfide plant at $7.9 million, the bottling plant at $4.5 million, tanks at $5 million, balance of plant at $25 million and 25% contingency at $50 million. This totals $345.1 million.

The methanol product at 150,000 gpd at 65¢/gal could provide an annual income of $28.47 millon operating 90% of the year. We believe that the electricity can be sold at a 16% premium using "Green Pricing." If the average price of electricity from the coal plant now is around 4.5¢/kWh, the "Green" market should bring 5.33¢/kWh or annually $31.1 million based on Sacramento Municipal Utility District (SMUD) experience of being able to realize a 16% premium for "Green" electricity. Carbon disulfide production around 9 tpd at $12/liter ACS Grade 99.9% would annually bring $26.28 million. If we assume that the bottled water product at 35¢/gallon is marked up 30% and the plastic bottle is 5¢ per labeled bottle, the daily income might be $8960/day or $3.27 million annually. The total income stream is estimated at $93.71 million/year.

Thus, if the plant capital cost is $345.1 million plus $55 million for salvaging the unused portions of the old coal plant and the installation and start-up of the new plant, the simple payback period would be 4.27 years. We project that the operating costs of the new plant would be less than the old plant owing to a high level of automation, and a very positive record of stand-alone operation of the SOFC fuel cells and the electrolyzers.

As a comparison, if the coal-fired boiler and turbine systems of the coal plant were replaced at the same 90 MWe, producing 4.5¢/kWh electricity and paying for sulfur disposal, the capital cost at the estimated projection of $2500/kW for a rebuilt plant (about half of a new greenfield plant) would be around $225 million with a payback of 7 years. Thus, a new multi-product cogeneration plant with no greenhouse gas emissions and drawing "Green" pricing is a much better investment today.

Another chemical product option in addition to methanol, could be isobutylene or even the middle distillates, such as kerosine [15,16]. In this way, this new coal plant could co-produce methanol and middle distillates in the right portions to serve as feeds to nearby MTBE plants at the larger refineries. This combination may be even more attractive than methanol alone. There are a full variety of combinations that might be optimal for the local community's economic marketplace.

Thus, by aggressively retrofitting only 285 of our old 1000 MWe coal plants, a 15% CO_2 reduction of 200 millions tons of CO_2 can be met by 2010 – the goal of the European Nations.

So $36 billion/yr over 12 years would stimulate the economy and correct the tarnished U.S. environmental image worldwide, starting at the Kyoto Conference.

Other Options

Other options that have been explored, but are not presented here, include Solar Options for production of base-load power, production of peak-load power, and production for variable-load power to follow local power company demand. We have also explored natural gas options for peak-load or load-following scenarios. These will be presented at a later time.

Steam-Reforming of Waste to Produce Syngas

Two examples of such steam-reforming/gasification processes are Royal Dutch Shell, Amersterdam, The Netherlands, [17] and Texaco [18]. Near optimal operating conditions for petroleum coke feed involve 6% oxygen, 12% CO_2, and 15% steam within the gasifier. These conditions allow for enough oxygen for the gasifier to maintain temperatures of 500°C (1200°F) and produce syngas of 22% CO and 45% H_2. These conditions vary somewhat with the H/C ratio of the feedstock, but the syngas H_2/CO ratio goal of 2.0 can be controlled by varying slightly the relative proporations of O_2, CO_2, and H_2O.

This project also has the future possibility of co-feeding waste with the coal using the same steam-reforming process unit. When waste is processed, there are a variety of EPA regulations that must be satisfied as well as performance data on waste types and waste surrogates. This concept is viable as evidenced by the experience in operating steam-reforming systems in the destruction of waste as a commercial business by Westinghouse Electric Corp., Scientific Ecology Group at Oak Ridge, TN – now owed by GTS Duratek [19-24].

Future Waste Streams Available for Co-feeding

There are a number of attractive options of co-feeding various waste streams with the coal to this plant. One problem waste stream involves the sulfur-rich petroleum coke from the local refineries. Another involves the sulfur-ladden waste from the surrounding coal power plants. If these sulfur-ladden waste streams could be used, the carbon disulfide plant could be increased in size to the optimum 90 tpd size for which we have the complete, detailed plant design. This would provide a very economic option.

There is a substantial stream of waste lubricating oil available in most communities, the exact quantity of which is usually small compared to the other waste streams available. Thus, this entire waste lub-oil stream could be co-fed with the coal and pet-coke to fully utilize the energy and carbon values from this waste lub-oil.

Finally, in most communities there are municipal waste landfills that are of increasing environmental or land capacity concerns. In a typical community, the problem wastes that could be diverted are around 50 Mlbs/yr or 75 tpd. Although the entire total of 300 to 500 tpd is a waste source option; however, the economics of treatment of the whole municipal stream versus burying would not be favorable at this time. So in order to divert waste, there would have to be important environmental incentives other than economic. To help this argument, the worst and least desirable waste streams now going to the landfill, could be diverted first -- such as oily waste, solvent, volatile, toxic, bio-hazardous, infectious and hazardous wastes. A fraction could be considered first (say 15%) and then transitioned to increasing diversions over time as more capacity can be achieved by this waste-to-energy project with better efficiency and then more installed process equipment capacity in increments. The plant could be designed to allow for this expansion. This diverted waste is a real important issue, since even 15% of 300 tpd is a huge 300 million lbs/yr -- a number that makes the project large enough to have huge effect in the economy of scale in fuel cell and even solar PV panels business generation. And, in the future for growth, the total landfill stream could be diverted, which would yield typically 2 billion lbs/yr!

Conclusion

With this new technology breakthrough, coal can be fully utilized as an important energy and chemical resource without any emissions of carbon dioxide (CO_2) and without the typical problems of NOx, sulfur, and other particulate emissions. By aggressively retrofitting only 285 of our old 1000 MWe coal plants, a 15% CO_2 reduction of 200 million tons of CO_2 can be met by 2010 – the goal of the European Nations.

These can be cutting-edge, future-looking projects that could gain the support and pride of both local communities and environmental groups alike. Improving the country's energy infrastructure, improving the local economy and the labor market. It would be a model for future coal plants and would help coal be considered one of the environmentally attractive fuels for the future. The project also has the potential to stimulate the new technologies by potentially bringing several new opportunities (like fuel cells and steam-reforming and also solar PV) into a larger economy-of-scale competitive market. This could mean additional jobs as well as additional business opportunities. It will also be a source of local respect as the community becomes recognized as a leader in sustainable energy production without pollution.

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Legend

DI	=	Deionized
CO	=	Carbon monoxide gas

CO_2 = Carbon dioxide gas
gpm = gallons per minute
H_2 = Hydrogen gas
MW = Megawatts of thermal energy value
MWe = Megawatts of electric energy
scfm = Standard cubic feet per minute
Syngas= Synthesis gas consisting of H_2, CO, CO_2, and water
tpd = Tons per day

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