BIOMASS CHEMICAL LOOPING COMBUSTION:
ADVANCED COMBUSTION TECHNOLOGY FOR LOW COST CO_2 STORAGE AND NO_X FREE BIOENERGY GENERATION.

BIO-CLC impact in the context of 40% GHG emission reduction within 2030.

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ABSTRACT: In October 2014 the EU Council formally agreed on a 40% GHG emission reduction target for 2030. This national binding target would force EU Member State to develop specific strategies and new policy measures. It is general consensus that energy and transport sectors are major contributors to the global CO_2 emissions registered in EU and worldwide, to this end, much more should be done to support biobased power generation at large scale, also forcing the introduction of CO_2 capture and storage and for GHG emission reduction, by introducing new technologies and improve national incentive schemes. One of the most interesting practices is represented by carbon capture, storage (CCS) and reutilisation (CCU) technologies; unfortunately, due to the high cost of CO_2 separation and the lack of incentives available, CCS is not yet economically viable for conventional mid-large scale power plants. At the same time, CO_2 capture represents the key for the future sustainable development of bio-energy sector. Scope of this paper is to present the huge potentials of chemical looping combustion (CLC), a disruptive sustainable combustion technology, which has been investigated in the last 10 years mainly for fossil fuels, which is demonstrating to be very promising for bioenergy generation. Chemical Looping Combustion is an innovative combustion technology where the fuel does not get in contact with combustion air. The necessary oxygen for the oxidation reaction is transported from the air reactor two the fuel reactor via a solid oxygen carrier, consisting mainly in a wide range of metal oxides, avoiding the energy demanding gas-gas separation step inherently. Furthermore, this technology allows energy generation with no-NOx formation and producing almost pure CO2 and steam, facilitating the Carbon capture and thus largely improving the overall sustainability of the combustion process. The application of Biomass as fuel is not yet developed, but thanks to the specific properties of biomass feedstock, the Biomass chemical looping combustion presents valuable aspects both in terms of environmental sustainability and techno-economic feasibility. EUBIA, in cooperation with industries and universities, is working to bring this technology to industrial scale, with the aim to move European bioenergy sector towards a cleaner future development.

1 INTRODUCTION

Despite the large efforts dedicated to "cold" energy generation technologies, like photovoltaic and wind energy, it is well known that most of the world energy demand will be reached by mid-large scale combustion plants, where solid and gaseous fuels are processed.

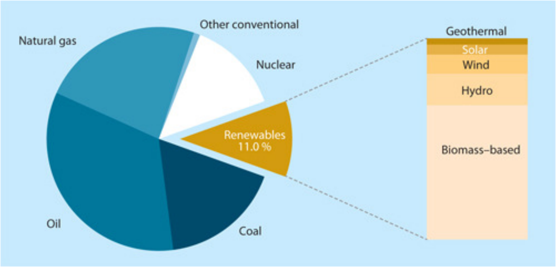

Figure. 1 Global Energy consumption by Fuel in 2011

The global trend is still to reduce the global consumption of fossil fuels, with a special focus on avoiding the use of coal and oil as fuels for energy generation. Among the large scale renewable energy sources, biomass largely dominates the market in terms of potential availability. However, the sustainability of biomass as fuel for energy is hardly discussed at EU and global level: the environmental impact of bioenergy plants depends on several issues, including the land use change, the availability of the resources and the whole carbon balance achievable with the combustion of woody biomass. One possible solution to reduce emissions of CO_2 from solid renewable and fossil fuel combustion is so called Carbon Capture and reutilization. Basically, CO_2 could be captured at point sources such as power plants and re-used for different application. Examples of potential storage sites are deep saline aquifers and depleted oil-natural gas fields. However, most of the technologies for capturing CO_2 include large scale gas separation and thus involve considerable costs and also a distinct energy penalty. Chemical looping combustion (CLC) with inherent separation of CO_2 could possibly provide cheaper and more efficient CO_2 capture compared to the alternatives. An even more important aspect of CCS may be that it can be used in the combustion of biofuels. Bio-CCS or BECCS, means that atmospheric CO_2 is captured using biomass which is burned or converted in an energy process where CO_2 is captured and stored. It means that you have "negative emissions" of CO_2. However, CCS (and CCU) application to present conventional combustion technologies is very expensive in terms of installation and process energy costs. In addition, this practice doesn't limit the emission of NOx and other polluting products. Chemical Looping Combustion is the only technology allowing to process solid fuels producing almost pure CO_2 with low cost separation and storage, reduced (almost zero) NOx and a lower impact in terms of PMs emission. These advantages must be added to a list of additional aspects which make the technology very promising for biomass application. This paper aims to show why CLC technology could represent the future of Bioenergy generation at large scale.

2 ENVIRONMENTAL SUSTAINABILITY OF BIOENERGY SECTOR

There is a general consensus in Europe that a biobased sector development is strongly related to the sustainability challenge. A very important aspect must be mentioned, even if not discussed in this paper: the indirect land use change. The environmental sustainability of biomass feedstock, considering food-non food land use competition, has a huge impact on the whole bioenergy value chain. This aspect is taken in account when considering the whole carbon balance of the plant and the environmental impact in general. Therefore, the present trend for sustainable bioenergy generation in EU is represented by the valorization of biomass residues and wastes. However, the introduction of a new "no-emission" technology would extend the market to all types of biomass. Despite the uncertainty of the market and the restrictions related to the installation permission, the market forecast expected for bioenergy in Europe shows a strong positive growth. This huge demand of bioenergy should be provided by taking in consideration all the environmental sustainability issues reported in the paragraph below. This ambitious target opens a large market area dedicated to advanced low emission technologies

2.1 Bioenergy demand perspectives in EU

With 130 MTOE of energy produced from biomass expected in 2020 and a fast growth expected until 2050, the future market is expected to be promising for new investment. The development trend of Emerging biobased sectors can be reported as follows:

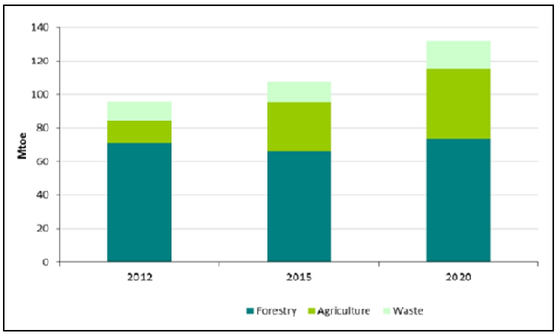

Figure. 2 Bioenergy production by source in Europe 2012-2020

As mentioned above, currently the target seems difficult to reach, especially for bioenergy production, because biomass combustion process is often considered "not clean as other renewable energies" and the large scale biomass plant installation is in standby. The sustainability of bioenergy production strongly depends on the life cycle of the plant, where the whole sustainability assessment is calculated considering not only the process and reaction emissions, but also the supply chain, from biomass growth (cultivation practices, ILUC, etc) to power plant delivery. Forestry biomass combustion plants present a valuable reduction of global CO_2 emission, however, due to the long time needed for growth, the CO_2 absorption is lower compared to the emissions produced and these plants can't reach a negative carbon balance. In addition, biomass combustion is responsible of relevant $PM_{2,5}$ and PM_{10} emissions.

On the basis of the expected bioenergy market growth, and to the parallel European incoming energy policy, it is clear that a more sustainable biomass combustion process would bring great benefits to the whole sector.

2.2 Biomass Combustion Sustainability And Indirect Land Use Change (ILUC)

The sustainability of the whole value chain strongly depends on Indirect Land Use change, affecting the sustainability of the process in terms of land utilization for dedicated biomass production, and CO2absorption rate, which depends on the type of biomass used. In any case, it must be underlined that bioenergy generation present better carbon balance compared to all fossil fuel combustion processes.

The table below shows the average Carbon balance of different power plant using biomass, coal and natural gas with and without CCS.

Table I. Total CO_2 eq. emissions of different power plant using biomass, coal and natural gas with and without CCS (including whole value chain)

Power Generation System	CO_2 emission no-CCS	CO_2 emission with CCS
Direct Coal	847 g CO_2eq. /kWh	247 g CO_2 eq./kWh
Direct Coal NGCC	499 g CO_2eq. /kWh	245 g CO_2 eq./kWh
Dedicated woody biomass	49 g CO_2 eq./kWh	-667 g CO_2 eq./kWh
Biomass residues	-410 g CO_2 eq./kWh	-1368 g CO_2 eq./kWh

It is clear that the benefits given by CCS practices have a sensible impact on the sustainability of all types of plants reported above. In particular, the negative balance reported by dedicated woody biomass combustion can give an idea of the potential contribution of biomass CCS (and CLC) to the EU GHG emission reduction target.

However, as mentioned above, the Carbon Capture and storage is not yet economically viable, and NOx emission reduction seems to be hard to avoid in conventional solid biomass combustion plants.

It is for this reason that Chemical Looping Combustion technology, used for bioenergy generation could represent a disruptive technology able to valorize the high volatility of biomass fuel and to improve the sustainability of bioenergy plants up to a negative CO2 balance.

3 THE CHEMICAL LOOPING COMBUSTION PROCESS (CLC)

3.1 CLC Process Chemistry

Chemical-looping combustion (CLC) originally proposed by Lewis et al. in 1951, is an innovative combustion technology where the fuel does not get in contact with combustion air (unmixed combustion). A CLC reactor system consists of two separate reactors: air reactor and fuel reactor. The necessary oxygen for the oxidation reaction is transported from the air reactor two the fuel reactor via a solid oxygen carrier, avoiding the energy demanding gas-gas separation step inherently.

Fuel reactor - Reduction: Fuel is introduced in a reactor (fuel reactor) where it reacts with an oxygen carrier (MeO_x)

$$(2n+m)Me_xO_y + C_nH_{2m} \rightarrow (2n+m)Me_xO_{y-1} + mH_2O + nCO_2 \qquad (1)$$

Air Reactor - Oxidation: the reduced metal oxide, Me_xO_{y-1}, circulates to a second reactor (air reactor).

$$Me_xO_{y-1} + ½O_2 \rightarrow Me_xO_y \qquad (2)$$

Thus, the exhaust gas stream of the fuel reactor contains only (almost pure) CO_2 and H_2O while the exhaust gas stream of the air reactor contains N_2 and excess O_2.

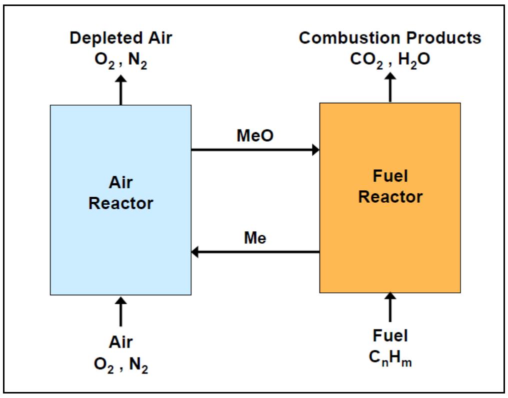

Figure. 3 Scheme of CLC REDOX Reaction

The chemical-looping combustor consists of two reactors, an oxidation reactor and a reduction reactor. The fuel and air go through different reactors. Eqs. (1) and (2) illustrate a basic concept of a chemical-looping combustion (CLC) system.

For example, a fuel such as CH_4, CO or CnH_2n+2 reacts with metal oxide, NiO, CuO or Fe_2O_3 in the reduction reactor according to Eq. (1), releasing water vapor and carbon dioxide from its top and metal particles from its bottom. The solid products, reduced metal particles, are transported to the Air reactor and oxidate according to Eq. (2), producing high-temperature flue gas and metal oxide particles. Metal oxide particles at high temperature are again introduced to the reduction reactor. The very hot metal particles are able to supply the heat required for the reduction reaction, efficiently providing oxigen for the combustion of fuel. Between the two reactors, metal (or metal oxide) particles perform the role of transferring oxygen and heat and, therefore, looping material between the two reactors is named as oxygen carrier particle

3.2 Fundamentals aspects of Chemical Looping Combustion process.

3.2.1. High Purity CO_2 Emission

Thanks to the absence of air in the fuel reactor, the Metal Oxide reduction reaction of Eq. (1) presents only three products:

- Reduced Metal Oxide (Metal particles),
- H_2O (steam)
- CO_2 (high purity)

Reduced metal is circulated to the air reactor, therefore, apart for a small amount of fly ashes, the final emissions exhausted by fuel reactor are only highly concentrated CO_2 and water vapour. For this reason, CO_2 produced in the reduction reaction can easily be recovered by cooling the exhaust gas and removing the condensate liquid water, without any extra energy consumption (energy penalty) for CO_2 separation.

The purity of CO_2 exhausted by the reactor is related to the velocity and the efficiency of the fuel oxidation reaction. In particular, this aspect is influenced by the quality of the oxigen carrier, the volatility of the fuel (gaseous fuels present higher oxidation efficiency). Regarding the solid fuel oxidation, the CO_2 purity aspect will be analysed later in the paper.

3.2.2. No NO_x Formation

One crucial aspect is that by using this combustion technoloyg, NO*x* formation can be thoroughly eradicated. The reason for which NOx can be considered almost avoided are mainly due to the lack of air-fuel contact snd lack of flames, and to the re-oxidation reaction relatively low temperature. In fact: Nitric oxides are formed in flames by three mechanisms:

- fuel NO*x*
- prompt NO*x*
- thermal NO*x*,

Fuel NO*x* is formed during the combustion of nitrogen-containing fossil fuels and prompt NO*x* occurs by the collision and fast reaction of hydrocarbons with molecular nitrogen in fuel-rich flames. However, in a chemical-looping combustor, oxidation of reduced metal takes place without fuel and flame. Therefore, there are no fuel NO*x* and prompt NO*x*. Moreover, the thermal NO*x* mechanism is important in high-temperature flames; for instance, Pershing and Wendt [1977] showed that thermal NO*x* becomes significant at temperatures above 1,650K (1,377 *C). Because oxidation in a chemical-looping combustor occurs at considerably lower temperature (around 900-1050°C) without flame, there is almost no thermal NO*x* formation [Podolski et al., 1995; Jin et al., 1998].

3.2.3. Thermal Efficiency

The thermal efficiency of a chemical-looping combustion system is very high. In addition, if the calculation is provided including the CO_2 separation and storage process, CLC becomes largely the most efficient technology for electricity generation. Wolf et al. [2001] reported that an LNG fueled chemical-looping combustor achieves a thermal efficiency between 52-53% and is 5 percent point more efficient than an NGCC system with state-of-the art technology for CO_2 capture.

4 CHEMICAL LOOPING COMBUSTION USING DIFFERENT FUELS

Chemical looping combustion technology presents different potential applications, a wide range of efficiencies and related technical design strategies depending on several factors: oxygen carriers, type of fuels used (solid, gaseous), reactors logistic. Below an overview on the most relevant aspects:

4.1. Oxygen Carriers

Oxygen carriers applied for chemical looping process should provide excessive oxygen carrying capacity, high reaction rate, great mechanical strength, and long-term recyclability (Hossain and de Lasa, 2008). It must be consider that the quality of oxygen carrier influences the efficiency of the process. In particular, a low volatility material requires higher quality oxigen carriers.Examples of metal oxide usable are Ni-, Fe-, Cu-, Mn- and Co-based metal oxides, typically employed as oxygen carrier for chemical looping process (Mattisson *et al.*, 2003). $CaSO_4$ was also used for transferring oxygen for methane combustion in fluidized bed reactors (Song *et al.*, 2009). However, sintering and attrition of these oxygen carriers during chemical looping operation are considered to be the main concerns to reduce their reactivity and recyclability. Oxygen carriers currently represent the highest cost limiting the competiveness of Chemical Looping Combustion.

4.2. Gaseous and Solid Fuels

Apart from the power rate, the scope, and other conventional design aspects, one of the most relevant aspects to consider is the fuel used. In fact, CLC can be working both for solid and for gaseous fuels. **Oxidation of gaseous fuels injected in fuel reactor takes place quickly and more efficiently, producing an almost pure CO_2 (96-98%) in comparison with solid feedstock.**

However, despite the easier design condition of gaseous fuel chemical looping combustion systems, the highest benefits of this technology are related to the utilisation of solid fossil fuels, responsible of higher CO_2, NO_x, and other pollutants like PM_{10}, $PM_{2,5}$, etc..

It is for this reason that for more than 10 years the chemical combustion has been tested with the aim to reduce the emissions of fossil solid fuels like coal, lignite, anthracite. The application of biomass fuel, investigated below, represents the new, promising application of this technology.

4.3. Solid Fuel: Different Chemical Looping Combustion Strategies

The direct use of solid fuels in the CLC concept for energy generation is highly relevant because solid fuels are considerably more abundant and less expensive than natural gas. CLC with solid fuels involves the fuel being physically mixed with the oxygen carrier in the fuel reactor.

For solid fuel combustion in the fuel reactor, a two step mechanism is proposed, including gasification and combustion, as illustrated in Fig. 4

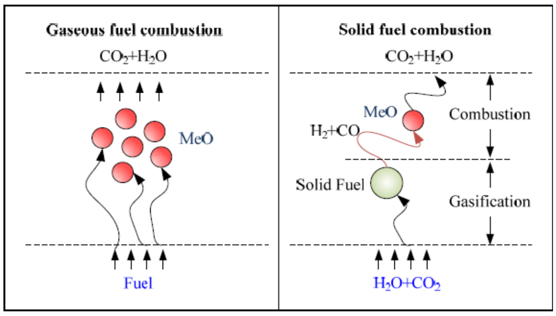

Figure. 4 Reaction Schemes of CLC of Gaseous and solid fuels

4.3.1. Separated gasification of solid fuel.

Combining solid fuel gasification with a CLC process represent probably the easiest practice to process solid fuels in chemical looping combustion. In this case a separated gasifier is installed (preferably close to the plant) in order to efficiently process solid fuel and inject the produced gas into the fuel reactor. The produced gas, mainly composed by CH4, H2, CO, CO2, is oxidized by Metal Oxide reaction exactly in the same manner of Natural gas. This solution reduces the design risks but increases the installation and operational costs.

4.3.2. In-situ gasification of solid fuel.

Gasification of solid fuel is a partial oxidation process that fixed carbon in the solid fuel is partially oxidized by gasification reactants, such as O_2, H_2O and CO_2 to form CO and/or H_2 as gaseous fuels all happening in the Fuel reactor.

The fixed carbon of solid fuels is gasified to mainly CO and H_2 (as H_2O employed to be the gasification reactant) by gasification reactants in the fuel reactor. The CO and H_2 from gasification process is immediately combusted by oxygen carriers in the same manner of gaseous combustion to yield H_2O and CO_2. Oxygen carrier is reduced in the fuel reactor to provide oxygen for gaseous fuel combustion. In the in-situ Gasification Chemical Looping Combustion concept (iG-CLC) solid fuel is fed directly to the fuel reactor.

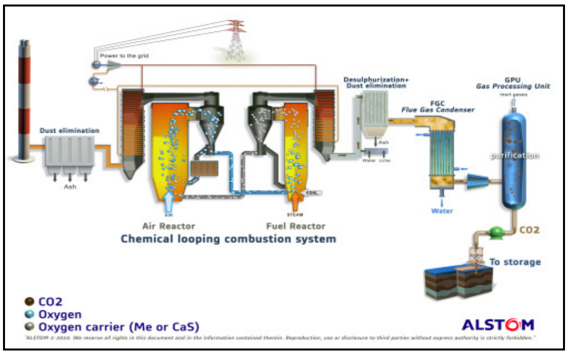

Figure. 5. Scheme of ALSTOM Power reactor for Coal direct CLC

The in-situ gasification of solid fuel happens here, as well as subsequent oxidation of generated gases by reaction with the oxygen carrier. To avoid CO_2 losses due to char entry to the air reactor, a carbon stripper is often implemented to the system. This process has been published and demonstrated in units of 10 to 100 kWth with coal.

4.3.2. The CLC - CLOU Process

The main limitation found in solid fuel conversion in in-situ gasification chemical looping combustion process (iG-CLC) for coal processing is the slow gasification process, as well as the incomplete combustion of gases evolved in the fuel reactor. To overcome the low reactivity of the char gasification step in the iG-CLC, an alternative process, Chemical Looping with Oxygen Uncoupling (CLOU), was proposed: produce CO_2 from solid carbonaceous fuels by using the gaseous oxygen produced by the decomposition of CuO. The CLOU process is based on the strategy of using oxygen carrier materials which release gaseous oxygen and thereby allows the solid fuel to burn with the gas phase oxygen. These materials can be also regenerated at high temperatures. The slow gasification step for the direct solid fuel experienced in iG-CLC is avoided in the CLOU process, unfortunately, oxygen carriers inventory is much lower than the ones required in the iG-CLC system with solid fuels, which is in the range of 1000-2000 kg/MWth for Fe-based oxygen carriers. Thus, a special requisite applies to the oxygen carrier to be used in the CLOU process in comparison with oxygen carriers for normal CLC, where the fuel reacts directly with the solid oxygen carrier without any release of gas phase oxygen. **Only those metal oxides that have a suitable equilibrium partial pressure of oxygen at temperatures of interest for combustion (800-1200ºC) can be used as oxygen carrier materials in the CLOU process.**

4 APPLICATION OF BIOMASS AS FUEL FOR CHEMICAL LOOPING COMBUSTION

The chemical looping combustion of coal and fossil solid fuels investigated during the last years provided good results, but the limitations related to the efficiency of the coal in-situ gasification and the higher installation costs are still limiting the development of this new technology. **However, thanks to the higher organic content and a different physical structure, biomass utilization could represent a new profitable market solution.**

4.1 Chemical Looping Combustion of solid biomass (in-Situ Gasification).

Because of its combustion characteristics, using biomass seems to be an appropriate intermediate step in the development of direct coal CLC. At operating temperatures of the Fuel reactor (900 °C) biomass has a very high volatile content (up to 85 % of the dry organic matter). Furthermore, regarding char conversion and transportation from fuel to the air reactor: considering the experiences obtained in the last years, biomass feedstock char shows very high reactivity compared to char obtained from coal and, additionally, biomass is carbon neutral, thus the final carbon balance would be Negative! In fact, since biomass does not contain fossil carbon, biomass-CLC with subsequent CO_2 storage can be a tool for selective removal of carbon from the atmosphere. As mentioned above, there are two different approaches using biomass as fuel for CLC: the first one combines two technologies already demonstrated: biomass steam gasification at atmospheric pressure and CLC using the product gas as fuel. The second is the already mentioned InSitu Gasification. Due to the difficulties of handling four fluidized bed reactors in small complex, and the higher investment required, this paper on biomass CLC will focus on the inSitu gasification, in order to use the biomass directly as fuel for the CLC process.

The fuel reactor section consists of three distinct zones for devolatilization, char gasification and oxidation of the gaseous products. Below the theoretical three parts for solid fuel oxidation reaction taking place in Fuel Reaction with solid fuel injection:

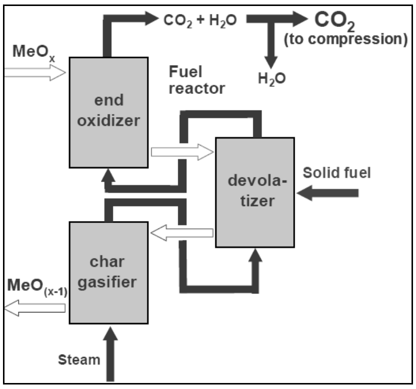

Figure. 6. Scheme of theoretical reactions taking place in Fuel reactor

Actually, the design is included in a single reactor where the three main reaction take place:

1. Devolatilization of Biomass organic fraction
2. Gasification of Char
3. Oxidation of produced gas with MeO

4.2 Behavior Of Biomass Fuel In CLC Reactor.

The content of biomass such as wood, rice husk, and bagasse are mainly volatile compounds, such as CO, CO2, CH4, H2 and CnHm whereas coal and petroleum coke are majorly fixed carbon (Shen *et al*., 2009a, b). The literatures indicate that the volatile compounds are decomposed at high temperatures in the fuel reactor, and the biomass combustion by chemical looping process is supposed to achieve higher CO_2 yield with less solid inventory than coal combustion. This aspect is crucial to reduce the cost of Oxigen carrier, as the volatility of the biomass increases the gasification reaction rate and the efficiency of the reaction compared to coal. The combustion of hybrid poplar with Fe-based oxygen carriers in a moving bed reactor was simulated by ASPEN PLUS, the operating temperature in the fuel reactor should be above 900°C to achieve fully biomass conversion and nearly 100% of CO2 yield (Li *et al.*, 2010b). Pine sawdust contained 14.8% of fixed carbon and 75.8% of volatile compounds was combusted by chemical looping process with Fe-based oxygen carriers in a 10 kWth fluidized bed reactors, and achieved 95% of CO_2 yield at 920°C (Shen *et al.*, 2009a).

The recent tests done demonstrate that biomass direct combustion in chemical looping reactor presents higher efficiency compared to the utilisation of coal.

Some tests have been provided also with CLOUS process, this process is helpful for achieving high gas conversion, and especially when using solid fuels, where slow steam gasification of char can be avoided, showing high performance with solid fuels. Under CLOU operation, biomass combustion was complete to CO_2 and H_2O without the presence of any unburnt material, including tars. Moreover, high carbon capture efficiencies were achieved using very low oxygen carrier inventories and without a carbon separation unit.

5 BENEFITS OF BIOMASS UTILIZATION AS FUEL FOR CHEMICAL LOOPING COMBUSTION

The utilisation of Biomass as fuel in Chemical looping combustion is under investigation due to the wide range of expected technical and economic benefits. The characteristics of biomass present further benefits like reduced cost for oxygen carriers and improved purity of CO_2; also problems encountered with coal like char deposition on metal oxide particles are reduced thanks to the higher velocity of the reaction and the lower content of fixed carbon in the fuel.

What reported in the paragraphs above can be summarized from the paragraphs above is reported in the table II:

Table II. Benefits of Biomass CLC in comparison with Coal

BENEFITS COMPARED TO CHEMICAL LOOPING COMBUSTION OF COAL	
Lower cost oxygen carriers	Typical of the volatile content of biomass in contrast to coal is the low fraction of CH_4 and other saturated hydrocarbons, high fractions of oxygen containing compounds, more easily to be oxidized, low-cost oxygen carriers are suitable for biomass application (i.e. Ilmenite).
Higher reaction efficiency	The high organic fraction (high volatility) of biomass compared to coal permits a more efficient gasification reaction, improving the fuel oxidation and resulting in a higher reaction velocity, with a consequent higher CO_2 purity
Better CO_2 balance	The CO_2 balance is improved as Biomass is a renewable feedstock with a high rate of CO_2 absorption during its life. The application of biomass to CLC represents the most sustainable combustion process achievable

The benefits of biomass application compared to other fossil solid fuels in CLC process are clear and under demonstration in several research activities in Europe and USA. In addition, the comparison with coal seems to be more and more favourable for biomass as the application of woody feedstock seems a more competitive solution for chemical looping combustion application.

5.1. A more sustainable and energy efficient technology

Despite the high number of issues to be solved, the target is to demonstrate that biomass chemical looping combustion could be more competitive than most of the conventional power plants, mainly for large scale markets. CLC of solid fuels clearly has a potential for a dramatic reduction of energy penalty and costs for CO_2 capture. Thus, the energy penalty for chemical-looping combustion would ideally be equal to the power needed for CO_2 compression of around 2.5%, with a relevant saving on energy consumption (and higher energy efficiency). Recent researches demonstrate that if the calculations include the CO_2 separation and storage process, CLC becomes largely the most efficient technology for electricity generation. Wolf et al. [2001] reported that an LNG fueled chemical-looping combustor achieves a thermal efficiency between 52-53% and is 5 percent point more efficient than an NGCC system with state-of-the art technology for CO_2 capture.

5.2. Expected economic benefits

Regarding the economics, a power plant using solid fuel CLC would have significant similarities to a CFB power plant, which is a commercial technology for plants up to 460 MWe. The air reactor would be very similar to a CFB, with some notable differences, such as the need for higher solids circulation, and a smaller gas flow. The gas flow through the fuel reactor is the flow that is not going through the air reactor, typically 20-25% of the total gas flow, plus the extra flow of gas for fluidization. Thus, the fuel reactor should be considerably smaller than the air reactor. At the same time, in comparison to a conventional CFB power plant, a CLC plant with an air reactor and a fuel reactor would involve additional costs. Nevertheless, the similarities would be significant, and the cost of the boiler system is typically 30-40% of the total cost of a power plant. So, in all, the additional costs for such an ideal CLC system would be expected to be moderate in comparison to other CO_2 capture technologies. Below a table summarizing the benefits of biomass CLC compared to conventional processes.

Table III. Benefits of Biomass CLC in comparison with conventional combustion systems

BENEFITS COMPARED TO BIOMASS CONVENTIONAL COMBUSTION	
Low Corrosion - longer life of components	Fine ash from the biomass can be expected to leave the fuel reactor in the gas stream in the form of fly-ash, thus, biomass ash not expected to reach the air reactor, where cooling surfaces are located
Higher termal efficiency	No corrosion problems of wall tubes due to alkali components in fuel ash steam, higher temperature in comparison with conventional biomass combustion
No NOx - More healthy for human safety	Almost no NOx emissions . Compared to Conventional biomass combustion systems, the NOx is almost avoided thanks to the lower reaction temperature: No Thermal NOx produced. Reduced
Pure CO_2 storage - More sustainable for the atmosphere	No CO_2 emission thanks to the easy pure CO_2 storage and reutilization: a negative CO_2 balance achievable with all types of biomass used, with a very high impact in Global warming reduction

The benefits reported in the tables II and III provide a valuable overview on the economic benefits related to green incentives, CO2 market and other aspects which could bring this technology towards a fast development in EU.

5.3. A promising competitive technology for future energy market

First of all, the CO_2 absorption brings valuable economic benefits in terms of green certificates. The Carbon credits market, developed in many EU countries, would have a very high economic impact in a Negative CO2 emission industry. The same can be stated for NOx. The free-NOx process would bring relevant incentives to the plant, as CLC is generally considered one of the most sustainable technology. In addition, the CO2 emitted and stored can be sold, if pure, to a wide range of industry sectors, for example the beverage industry and other process industries. The free-NOx process would bring relevant incentives to the plant, as CLC is generally considered one of the most sustainable technology. This high sustainability of the process would facilitate the permission procedures, the installation practices and the agreements between industry and municipalities, citizens and other public bodies in the plant installation area.

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