AN ASSESSMENT OF BIOMASS GASIFICATION AND LIQUEFACTION (PYROLYSIS) IN VIEW OF ECONOMIC EFFICIENCY AND SUSTAINABILITY

Roland V. Siemons
Clean Fuels b.v.
P.O.Box 217, 7500 AE ENSCHEDE, The Netherlands
Telephone: +31 (0)53 4892909; Fax: +31 (0)53 4344257
E-mail: Siemons@cleanfuels.nl

ABSTRACT: Considerable research efforts are put into the development of technologies for high-efficiency biomass conversion into electricity. A major one is gasification integrated with a combined cycle (GCC). This paper compares GCC with an alternative which until today receives less attention: biomass liquefaction for conversion of the bio-oil in a combined cycle. Taking into account economic efficiency and sustainability, the potential of the technologies is determined and R&D targets are set. The assessment is based on cost and conversion-efficiency data taken from a broad range of literature published during 1993-2000.
Keywords: gasification, pyrolysis, economic aspects

1 THE RESEARCH ISSUE

It is a novel economic fact that, in terms of greenhouse gas emission reduction units (ERUs), sustainability has become a tradeable good. Whereas today ERUs are valued at about 8 €/t CO_2 equivalents, projected 2010 ERU values are in the order of 30-90 €/t CO_2 eq. ([13]).[1] Assuming that fossil fuels, with their typical specific greenhouse gas (GHG) emissions, will remain the predominant fuels in the electricity sector, and that conversion efficiencies will only slightly improve, the long-term projected ERU values are equivalent to 0.02-0.06 €/kWh_e. In comparison with electricity production cost (about 0.03-0.04 €/kWh_e), this is substantial. Therefore, when assessing technology options for biomass fuelled electricity plants, the ERU value must be taken into account, and during the next 25 years or so, the economic feasibility of biomass options will depend on five major factors:

- Capital requirement (K)
- Biomass fuel price (B)
- Energy conversion efficiency (η)
- Electricity price (E)
- ERU price (ERU)

Today, considerable research efforts are put into the development of several innovative technologies for high-efficiency biomass conversion into electricity. Two of these are gasification integrated with a combined cycle (GCC), and liquefaction for conversion of the bio-oil in a combined cycle (LCC). However, technologies for the large-scale conversion of biomass into electricity already exist. For example, biomass can be co-fired with coal, or biomass can be used to fuel a dedicated combustion-and-steam power plant (dedicated CS). The innovative technology developments initiated are intended to enable society to produce electricity and reduce GHG emissions more efficiently than with currently available technologies. A common view is that further development of the new technology concepts and learning-by-doing are needed in order to reduce capital costs, as the capital needed to construct innovative biomass fuelled power plants is still too large. The comparison with existing technology and the social economic objective form the basis for addressing the central question of this paper:

Given market expectation for the electricity price (E) and the ERU, and given targets already established for the energy conversion efficiency (η) of biomass fuelled power plant concepts, can targets be identified for the capital cost (K)?

[1]In this paper all prices are in 1998 €.

2 METHODOLOGY

One condition for an economically feasible biomass fuelled electricity generation project, is that costs and benefits are in balance, according to the following equation:

$$c_1 \times \frac{B}{\eta} + \frac{A(K)}{Q} + c_2 \leq E + ERU, \qquad (1)$$

where A(K) is the annuity of capital K. Q is the annual quantity of electricity produced, and c_1 and c_2 are parameters that are independent of annualised capital, annual production, unit biomass fuel cost and energy conversion efficiency. The parameter c_1 reflects the arithmetical conversion between electricity quantities, unit biomass fuel costs, and energy conversion efficiency. Suppose that biomass fuel prices are expressed in terms of €/t, then, since E has the dimension of €/kWh_e, and η has the dimension of kWh_e/kWh_{th}, parameter c_1 has the dimension t/kWh_{th}, which is an inverted calorific value. The other costs reflected by parameter c_2 may concern labour and maintenance costs, expressed per unit of electricity. The annuity A(K) is determined by the discount rates, DR, prevailing in the electricity sector, and the economic lifetime (project duration t) of the investment into the projected biomass fuelled power plant, i.e. as follows:

$$A = \frac{DR}{1 - (1 + DR)^{-t}}, \qquad (2)$$

so that A(K)=A.K. As a result, we find that for an economically feasible project the following expression applies:

$$c_1 \times \frac{B}{\eta} + A \times \frac{K}{Q} + c_2 \leq E + ERU. \qquad (3)$$

Equation 3 is the expression of an absolute economic criterion, i.e. that for an economically feasible project the IRR should be larger than the discount rate DR. In the space of biomass fuel costs (B), on the one hand, and sales prices (E + ERU), on the other hand, the following expression defines an iso-IRR line for a single technological concept:

$$E + ERU = c_1 \times \frac{B}{\eta} + A \times \frac{K}{Q} + c_2. \qquad (4)$$

The iso-IRR line is the set of (B, E + ERU) for which IRR=DR.

The comparison of GCC and LCC technologies with the existing CS technology introduces an additional, comparative, criterion: the IRR of GCC or LCC power plant projects should be larger than the IRR of CS power plant projects. Typically, the GCC and LCC concepts are characterised by high energy conversion efficiencies (and high capital cost), in contrast with the existing low efficiency/low cost CS concept. The two types of character are indicated with H and L respectively. An equi-IRR line, comparing H and L technologies, can be defined by the following expression (elaborated in [19]):

$$E + ERU = c_1 \times \frac{\left(\frac{K_H}{\eta_L} - \frac{K_L}{\eta_H}\right)}{(K_H - K_L)} \times B + \frac{(K_H.c_{2L} - K_L.c_{2H})}{(K_H - K_L)}. \tag{5}$$

Given the two technologies H and L, characterised by the respective technology specific parameters K, η and c_2, this equation defines the set of market prices (B, E+ERU) for which IRR_H equals IRR_L. In the space of 1) biomass fuel prices, 2) electricity prices and ERU prices, the Equations 4 an 5 determine market niches where the GCC or LCC technologies ('H technologies') can be successfully implemented. This is shown in Figure 1. Technology selection according to this schedule is based on two major principles: economic efficiency and sustainability.

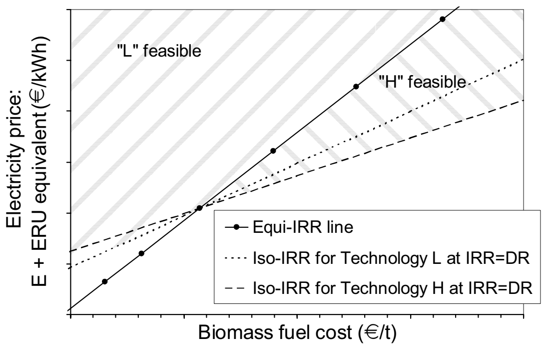

Figure 1: Feasibility niches for two competing technologies.

For the EU, reduction of capital cost for the GCC and LCC technologies may serve three possible economic objectives:[2]

- Increased investor profits (high IRRs)
- Reduced ERU costs
- Increased affordable biomass fuel costs.

The first objective, though respectable, is not further investigated here, as it is a private objective which is not in the primary interest of society. The latter two are societal objectives. However, to expect that ERU values will be reduced as a result of developments in biomass fuelled energy technology, is unrealistic in view of the projected ERU market size and projected impacts of biomass based energy in the EU. The objective of reducing ERU costs is therefore not investigated here either. The increase of affordable biomass fuel costs, finally, is relevant, because it enables a widespread application of biomass fuelled electricity generation technologies, and thus effectively implies the feasibility of a more sustainable electricity sector. The search for investment targets is therefore confined to the last issue: an increase in the affordable biomass fuel price. The principle is that capital cost reduction results in an enlargement of the market niche where a technology can be implemented in an economically feasible manner, such that affordable biomass costs increase (see Figure 2). This is caused by a shift of the iso-IRR line towards higher fuel prices.

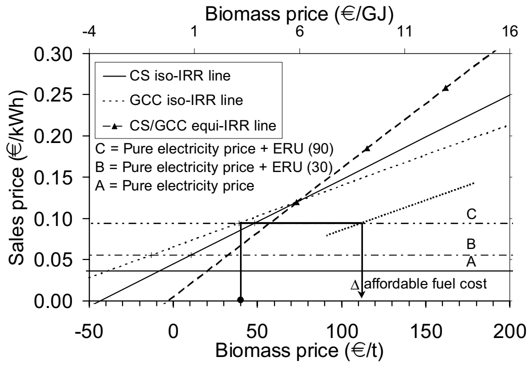

Figure 2: Effects of reduced capital cost at constant energy conversion efficiency. This graph compares 30 MW GCC with CS technology.

3 PARAMETER VALUES

In Figure 3, data on energy conversion efficiencies are shown. Sources for the CS concept are: [23], [2], [21], and [6], and [19]. For biomass-fuelled GCC projections: [23]], [2], [4], [6], [10], and [9]; and for biomass-fuelled GCC plant projects: [5], [12], [14], [17]. For the LCC concept: [19]. Figures 4 and 5 summarise cost estimates for several concepts. Sources for the CS concept: [23], [2], [21] and [6], and [19]. For biomass-fuelled GCC: [5], [12], [1], [17]. Cost data on coal-fuelled GCC power plant are quoted from [7] and [11]. Cost for natural gas-fuelled combined cycles (NG-CC) originate from [18]. In constructing Figure 4 it was assumed that the same system boundaries apply as those for the CS technology indicated above. For LCC: [3], [15], [16], [22], [8], [20], and estimates by BTG. All data were converted to 1998 € by means of the Chemical Engineering Plant Cost Index. Combined, the efficiency and cost data yield a cost-quality characteristic over a range of plant capacities for projected typical plant types of each individual technology. Note that the costs given for the GCC concept reflect the first generation of this type of power plant, and that these costs are expected to be lowered as a result of further development and learning.

The future market situation in which the innovative GCC and LCC concepts are expected to be functional is characterised by the costs of biomass fuels, prices of electricity and ERUs. Projected values are summarised in Table 1.

Table 1: Market parameters.

Pure electricity price	0.036 €/kWh$_e$
ERU value	30 - 90 €/t CO_2-eq.
= (approximately)	0.0194 - 0.0581 €/kWh$_e$
Unit biomass fuel cost	0 - 200 €/t biomass
= (approximately)	0 - 16 €/GJ$_{th}$
Discount rate	10% /yr

For justifications of the parameter assumptions, and for further parameter values, the reader is referred to [19].

4 RESULTS

A range of plant capacities (10-270 MW$_e$) was evaluated. As an example, the feasibility of the 30 MW$_e$

[2]Note that under economic conditions prevailing in developing countries - not obliged to reduce GHG emissions under the Kyoto Protocol, and often endowed with relatively large quantities of biomass - reduced electricity production cost, rather than reduced ERU cost, would be a potential objective of developing innovative biomass electricity generation concepts.

GCC case, in comparison with CS technology, is shown in Figure 2. Clearly, the CS technology is economically feasible up to biomass prices of nearly 50 €/t under the 90 € ERU scenario. However, the GCC concept is not economically feasible under any realistic ERU scenario if the capital cost of the technology are not reduced.

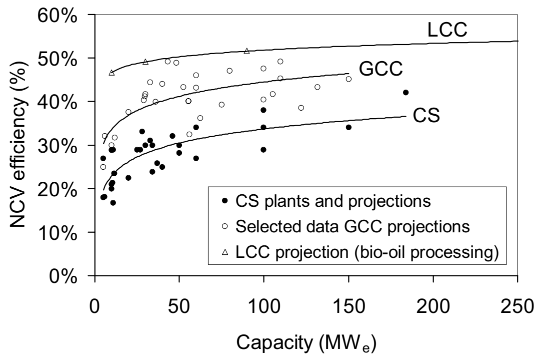

Figure 3: Summary of efficiency estimates for three biomass conversion concepts: CS, GCC and LCC.

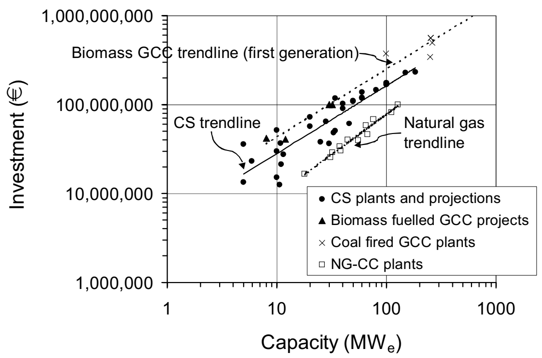

Figure 4: Summary of investment estimates for two biomass conversion concepts (CS, GCC), coal fired GCC power plants, and the natural gas fuelled combined cycle.

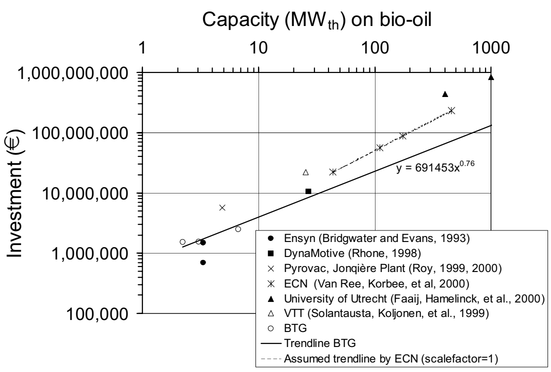

Figure 5: Cost estimates for biomass liquefaction plants (pyrolysis technology).

The increase of affordable biomass fuel cost, as a function of capital cost reductions for the GCC technology, are shown in Figure 6. Techno-economic literature generally projects GCC systems of around 100 MW_e at capital cost levels of about 50% relative to the originally assumed value of this paper, [19].

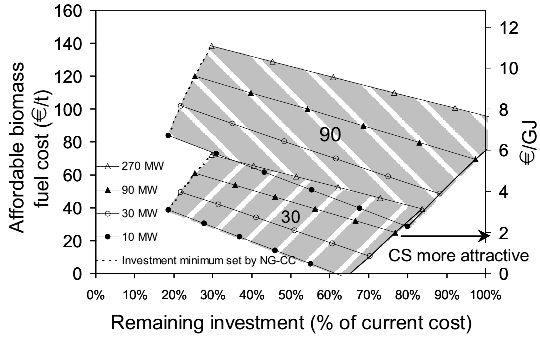

Figure 6: Affordable biomass fuel cost for GCC technology with reduced investments. Lower cluster: assumed ERU value = 30 €. Upper cluster: assumed ERU value = 90 €.

Major conclusions as regards GCC technology are:

- Generally anticipated cost reductions for GCC technology are not sufficient to achieve levels of affordable biomass fuel costs desirable for EU market conditions.
- What is more, the GCC concept cannot be developed to the extent that it enables the production of electricity and ERUs at economically efficient costs using biomass fuels at the maximum desired cost levels (up to 200 €/t) relevant for EU-like economies.

The LCC concept can be implemented in a manner quite different from the GCC concept. Liquefaction plants can be located in countries (such as developing countries, and countries in C&E Europe) able to produce biomass feedstocks at much lower costs than the majority of EU member states. A reasonable estimate for biomass cost is 1 €/t, [19]. From the place of bio-oil manufacture, bio-oil can be shipped to power plants in the EU where the bio-oil is converted into electricity by means of gas turbines in combined cycle with steam. Figure 7 shows the potential of the LCC concept.

The potential of the multiple-site LCC technology would be enhanced if it could become economically feasible for a wide range of bio-oil manufacturing capacities. The broadening of this range towards smaller capacities is especially desired, since these enable the use of low value biomass feedstocks available from a variety of small-scale agro-industrial and forestry operations. The economic feasibility at small scales is especially critical if a low-value ERU scenario develops, since the smallest capacity at which the liquefaction technology appears economically feasible, in that scenario, is no smaller than 120 MW_{th} (Figure 7). One would desire feasible scales which are at least one order of magnitude smaller. Capital cost reductions as a result of learning is the key to this issue. Reducing the capital requirements to levels of 80% and 60% of the assumed values gives the results also shown in Figure 7. Such capital cost reductions rapidly decrease the minimum capacities at which the technology becomes economically feasible. The sensitivity to capital cost reduction is due to the weak economies of scale with bio-oil manufacturing costs at larger capacities (flatness of the curve). Since this is not the case with capacities smaller than about 30 MW_{th}, continued capital cost reduction will not reduce the minimum economically feasible size below approximately 20-30 MW_{th}.

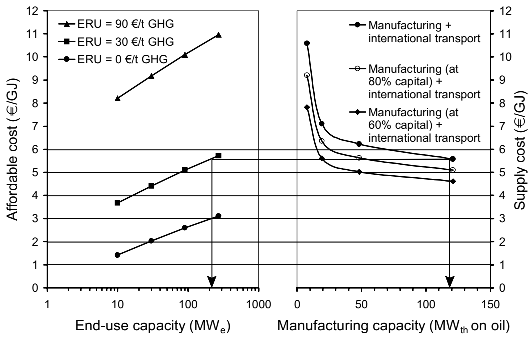

Figure 7, Maximum affordable prices for delivered bio-oil in comparison with estimated manufacturing and supply costs. Effects of capital cost variation.

Under the assumption that future ERU values will be towards the lower end of the range of 30-90 €/t GHG, R&D targets are assessed as follows:

- Liquefaction technology should be made technically feasible for capacities of 20-30 MW_{th} and above.
- Above these capacities, capacity-specific investment costs need to be below the value of $690{,}000 \times C^{0.76}/C$ €/MW_{th} (with the capacity C expressed in MW_{th}).

These conclusions are contingent upon an assumed cost of international bio-oil transportation of about 3 €/GJ. One further economic assumption, influencing this conclusion, is the cost of adapting electricity plants to use bio-oil. Both assumptions require further justification.

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