BioLPG for clean cooking in Sub-Saharan Africa: present and future feasibility of technologies, feedstocks, enabling conditions and financing

Supplementary Information

1. Methodology and assumptions for the TEA capital and operating cost estimates

Both Cool LPG and IH^2 are new processes. Use of each process for selective production of LPG from municipal solid waste feedstock and agro-residues is projected using accepted estimation models and data. However, further investments in detailed bioLPG pilot plant design, followed by construction and operation, are necessary to progress to data that can support well-founded, wide-scale commercialization. It should also not be forgotten that bioLPG project economic projections presented here also require availability of site-specific feedstock cost projections.

Costs of equipment and/or plant sections were based on known equipment costs and duties and scaled using factors specific to the equipment or process, in the form of Equation X:

$$C_1 = C_0 \left(\frac{D_1}{D_0}\right)^n \qquad \text{Equation X.}$$

Where C refers to the equipment cost and D refers to the equipment duty, which is a quantity representative of the installed cost (e.g. rate of steam output for boilers, etc.). n represents the scaling factor. In the case of IH^2, the capital costs were based on a previous report specifically focused on IH^2, whereas Cool LPG capital costs were based on information from a variety of sources [1–5].

The IH^2 TEA was based on an extensive report on IH^2 economics [6], which was conducted for liquid fuels production from a wood chip/corn stover feed. For the current work, the various product yields were adjusted based on an overall mass and energy balance for municipal solid waste (MSW) feed, assuming that the selectivity of the IH^2 plant could be tailored towards maximizing the LPG yield (rather than the yield of gasoline) without significant changes in capital costs. A calorific value of 12.5 MJ kg^{-1} was taken for MSW, assumed to be sorted waste with incompatible materials (glass, metal) removed, and the mass yields of LPG and gasoline from MSW were assumed to be 15 % and 14 %, respectively. This calorific value, as well as material balances, determined the MSW feedstock quantity estimate for IH^2. The IH^2 capital costs were scaled using a scaling factor of n = 0.6 [6].

For Cool LPG, the process was based on proprietary models built in the HYSYS software, based on information obtained in the literature and at the Gas Technology Institute. The overall mass yield of LPG from biogas was taken as 33 %, with no external energy input required either for heat or electricity. Equipment in separate plant sections was costed individually, as described below.

Anaerobic Digestion capital costs

The Anaerobic Digestion (AD) capital costs were based on published studies [1] and scaled according to the rate of biogas production. AD plant costs were scaled linearly with the biogas throughput (n = 1). The rate of biogas production from MSW was assumed to be 65 m^3 of methane per tonne of MSW, based on biogas productivity of MSW sampled from Kigali City, Rwanda [1]. The combination of the LPG mass yield from biogas and the biogas productivity determined the feedstock requirements for AD+Cool LPG.

Cool LPG capital costs
For the Cool LPG capital costs, bare material costs were calculated and then scaled to the total capital requirement based on linear factors for converting total purchased equipment cost into total capital requirement for similar processes [5]. Overall, the total capital requirement was 3.73 times the bare materials cost. Steam reformer costs were based on three references and scaled using n = 0.67 [2,7,8].

Cool LPG vessel, column and heat exchanger costs were obtained from APEA and, where necessary, scaled with an exponent of 0.6. Compressor costs were obtained from vendor quotes. CHP plant costs were based on two references [1,9].
Plant construction was assumed to take two years in each case, with 40% of the project investment in year 1 and the rest in year 2. Plant lifetime was assumed to be 25 years in all cases. For levelized cost of LPG analysis, an 8% discount rate was used.

Fixed operating costs for both IH^2 and Cool LPG
The following assumptions were made to calculate the annual fixed operating costs for both IH^2 and Cool LPG. Indirect labour: 30% of the direct labour costs; insurance: 0.5% of the total project cost; local taxes and fees: 0.5% of the total project cost; O&M cost: 1.5% of the total project cost. Direct labour costs were calculated assuming an average annual salary of $60,000. The IH^2 plant was assumed to require 18-22 direct employees [6] whereas the Cool LPG plant was assumed to require 8-12 direct employees, depending on plant capacity.

The following start-up costs were charged on the first operating year of each project. Modifications to the plant: 2% of the total project cost; Inefficient start-up operation: 25% of the annual feedstock and fuel costs; personnel training costs: 3 additional months of operating and maintenance labour costs; waste management: 1 additional month of chemical, catalyst, and waste disposal cost and maintenance materials costs; owners' costs and fees: 7% of the total project cost.

All plants were assumed to have a 90% annual capacity factor, however using a 75% capacity factor for the first year to allow for additional downtime during start-up.

Variable operating costs, excluding feedstock costs, were calculated assuming the following commodity prices. 180 USD MWh^{-1} electricity; $0.85 per tonne of water; an annual catalyst cost of $2.50 per tonne of LPG (based on methanol plant catalyst costs [10]. The gasoline selling price for IH^2 was taken to be $800 per tonne.

Feedstock costing
Feedstock costs are a category of operating costs but are analysed separately. Following the determination of general feedstock types suited to the technical options, and selection of the countries with supportive environments, research focused on identifying specific locations that could offer sufficient feedstock to serve a plant and costing the feedstock for that.

Details on assumptions used for each feedstock cost element in the candidate projects are discussed in Section 4.1 in the paper. The cost of feedstock delivered in appropriate form to the process gate is calculated in the following way:

$$\begin{aligned}&Feedstock\ cost\ per\ tonne\\&\quad = Raw\ feedstock\ cost + Transport\ cost + \ Sorting\ costs\\&\quad + Preprocessing\ cost\end{aligned}$$

The site and market-specific feedstock costs are an externality to the paper financial modelling and are proxied by the range of tipping fees presented in Table 6 of the main paper.

2. Country level assessments of LPG sector investment build-up needed to deliver LPG cooking capacity to countries across West and East Africa

Table S1 below presents the underlying data from national LPG sector studies and plans for four countries across West, East and Central SSA [11–14].

Table S1. Country-level data on Industry CapEx and Consumer CapEx required to create physical LPG capability in Sub-Saharan Africa (US$)

Country	New Users Through 2030 (mm)	Industry Capex* (US$ mm)	Per New User	Consumer cooking Kit Cost [#]	Household Size	Per New User	Industry CapEx Rank	Consumer CapEx Rank
Cameroon	12	$332	$27.6	$46	5.2	$8.8	Low	Low
Ghana	14	$405	$29.0	$59	4.0	$14.8	Intermediate	Intermediate
Kenya	17	$129[**]	$7.6	$60	4.0	$15.0	N/A[**]	High
Rwanda	6.5	$247	$37.8	$51	3.5	$14.6	High	Intermediate

Sources: [11–14].

[*] Industry CapEx includes all LPG equipment (including LPG cylinders) and facilities, except for maritime import terminals, ocean transport, and consumer kits.
[#] The consumer kit includes an LPG double-burner stove, a hose to connect the stove to the LPG cylinder, and a pressure regulator that allows precise control over the LPG flame.
[**] Kenya Industry CapEx includes only LPG cylinders, because Kenya already has pre-built all other needed LPG infrastructure to serve its projected consumption needs to at least 2030. Kenya's Industry CapEx value is therefore excluded from the ranges used in Table 7 of the main paper.

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