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Can coal-derived DME reduce the dependence on solid cooking fuels in India?

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ABSTRACT

The Indian government is currently promoting and subsidising the replacement of solid cooking fuels with cleaner-burning liquefied petroleum gas (LPG). India is however a growing importer of LPG, the cost of which strongly linked to the prevailing oil price, which makes this program vulnerable to oil price shocks. Dimethyl ether (DME) is a synthetic fuel which may be blended with LPG and, if produced from domestic Indian feedstocks, one way of potentially reducing this vulnerability. A techno-economic analysis of the use of low grade Indian coal for this purpose is described in this paper, and the coal rich state of Jharkhand, where more than 18% of households used coal as a cooking fuel in 2011, was chosen as a study area. Here it was found that, due to higher cooking energy efficiency, the production and use of the DME (together with an associated electricity export) could result in 35% less coal being consumed when compared with a scenario where coal is used for cooking and to generate an equivalent amount of electricity. This analysis further shows that producing DME through this means would likely require oil prices in excess of $72 per barrel to be cost competitive with imported LPG.

Introduction

Globally, there are approximately 1.4 billion people without access to electricity, and 2.7 billion people who rely on solid fuel (wood, crop residue, dung and coal) for cooking (Johansson et al., 2012). The use of these traditional cooking fuels creates a number of significant problems which includes deforestation and an estimated 4 million attributed deaths annually due to the negative health effects associated with indoor air pollution (Rockall, 2008; Johansson et al., 2012). In addition, the labour and time intensive collection of traditional fuels often occurs at the cost of more productive activities and contributes to gender inequality (Guruswamy, 2011). Improving energy access as a means of addressing these problems in developing countries has been high on the agenda of the international community for some time. Most recently, this resulted in the announcement of the United Nations Sustainability for All (UNSE4All) initiative, with key objectives of achieving global electricity access, and a primary reliance on non-solid fuels for cooking by 2030 (UNSE4All, 2012). In this context, various governments, including China, India, Guatemala, Indonesia, Kenya, Pakistan, Sri Lanka, Albania, Brazil, Mexico and Peru, have instituted programs aimed at replacing solid fuels with liquefied petroleum gas (LPG) (D'Sa and Murthy, 2004; Fall et al., 2008; Kojima, 2011; Khandker et al., 2012; Andadari et al., 2014). These countries currently represent more than 45% of the world's total population.

In 2011, more than 67% (or 165.8 million) of Indian households still relied on the use of solid fuels for cooking, compared with approximately 74% (or 142.6 million) in 2001. Approximately 28.5% of the country's population had transitioned to the use of LPG (and piped natural gas (PNG)), and only 0.2% of the population used electricity for this purpose (India-Census, 2012). The vast majority of India's LPG consumption is supplied through imports (either as final product LPG or as imported crude oil) (MoPNG, 2015) and some studies (TERI, 2012) suggest that the demand for petroleum products is expected to increase more than four-fold between 2011 and 2031, and that by 2031 India would be 90% dependent on oil imports, compared with 74% in 2011.

The price of LPG is strongly linked to the prevailing crude oil price, and the cost is high when compared with traditional fuel alternatives (Kojima, 2011). As a result, the Indian government subsidises the provision of LPG to make it affordable to a greater part of the population and protect them against oil price volatility. The LPG price is regulated by the Government through its controlling share in public oil marketing companies (OMCs) and subsidised through a mechanism by which the OMC's are reimbursed for the difference between the cost price and regulated price (IISD/GSI, 2014). This cost difference is referred to as an LPG under-recovery, the extent of which is depicted in Fig. 1, together with the Saudi Aramco LPG price and the Indian Basket crude oil price.

The impact of oil price volatility on the LPG price and under-recovery is clear to see. At high oil prices, the cost may be significant and in 2012/2013 the total LPG-related subsidy was approximately 2.7% of the total

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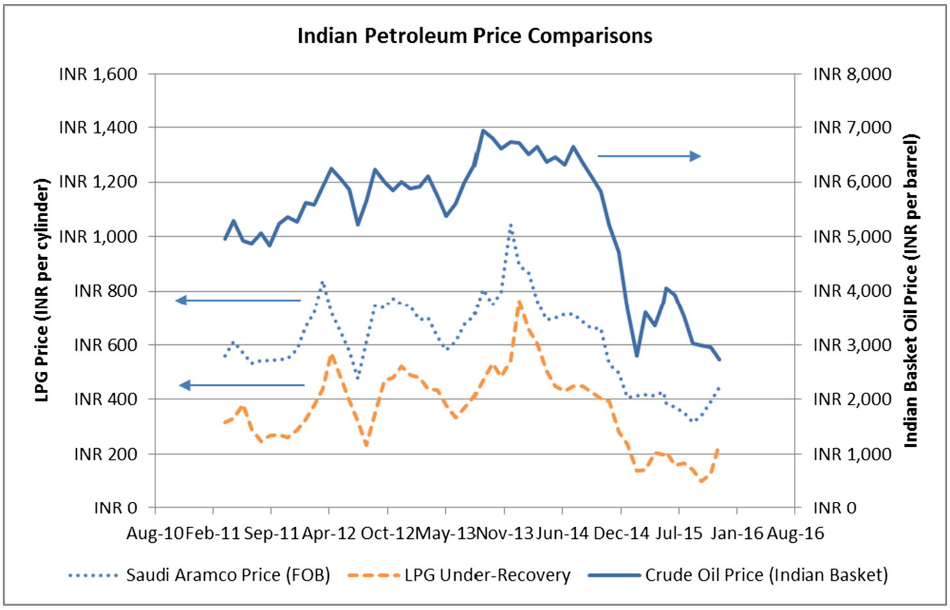

Fig. 1. Indian petroleum price comparisons. The Saudi Aramco price conversion (from US$ per tonne into INR per cylinder) is based on prices published by Gas Energy Australia (http://gasenergyaustralia.asn.au/reports-and-submissions/saudi-aramco-lpg-prices), a LPG blend containing 40% propane and 60% butane, a 14.2 kg of LPG per cylinder and the monthly average INR to US$ exchange rates published by www.xe.com.

budget, and almost twice the (non-plan) amount spent on social services (which included education, health, broadcasting, etc.) (IISD/GSI, 2014).[1]

The uptake of LPG as a cleaner cooking fuel is also dependent on the reliability of supply (Kojima, 2011) and any operational disruption resulting in LPG shortages has a much more immediate effect on households. One of the consequences of these disruptions may also be a return to the use of solid fuels, as evidenced by recent events in Nepal where a blockade on petroleum (and other imports) resulted in a sudden jump in the demand for firewood and an increase in deforestation.[2]

One strategy of reducing the impact of LPG price volatility and supply disruption may include the substitution of imported LPG with a non-crude-oil derived equivalent, produced through the use of domestically available alternative feedstock. Dimethyl ether (DME) has properties similar to LPG and may be produced from a variety of different feedstock types including natural gas, coal, biomass, municipal solid waste (MSW) and CO_2 (Larson and Yang, 2004; IRENA, 2013). It is therefore particularly attractive in this regard. DME is suitable for a wide variety of different applications, which includes use as an aerosol propellant, diesel fuel substitute, gas turbine fuel and a number of studies have shown that the use of LPG/DME fuel blends containing up to 20% are completely compatible with existing LPG cooking devices, without modification (Fleisch et al., 2012).

In 2000, the total global production of DME was estimated at 150,000 t per year (Larson and Yang, 2004) but increased more than 30-fold by 2012, with the consumption of DME amounting to approximately 4.8 million tonne per year (CMAI, 2012).

This growth was largely driven by increased consumption in Northeast Asia, and specifically China, and the production underpinned by the use of coal (primarily) and natural gas (CMAI, 2012). Approximately 90% of the produced DME was blended with LPG, with the remainder used for refrigeration or as a propellant (Fleisch et al., 2012).

Unlike China, there are currently no known commercial DME production facilities operational in India where its use is very limited. India had however, as early as 1998, been identified as a prospective market for DME by a joint venture comprising Amoco, the India Oil Company (IOC) and the Gas Authority of India (GAIL). The joint venture was interested importing DME produced in countries with large gas resources (such as Qatar) and using it to generate power, replace diesel with a cleaner burning alternative and blend it with LPG for cooking fuel use. Amoco merged with British Petroleum (BP) in late 1998 however, after which the resulting company (BP Plc) terminated the project to pursue more favourable gas related ventures (Fleisch et al., 2012).

There has been a resurgence in the interest in DME in recent times and the Indian and Australian Governments are currently engaged in a joint research program aimed at informing the development of small scale plants which may produce DME from remote and stranded natural gas.[3] This research is focused at improving the conversion efficiency of the DME production process to make the use of these gas resources, currently challenged by high capital costs and low economies of scale, economically viable. Broadly speaking, the objective of this initiative is similar to that of an emerging industry which is focused on monetisation of natural gas resources (stranded due to remoteness and/or lack of scale) through small scale gas-to-liquid (or so-called miniGTL) plants (Fleisch, 2014). Once proven to be commercially viable, these plants may not only unlock the value in small scale gas reserves but also improve the chances of producing DME from feedstocks such as biomass and MSW, the cost of which is similarly challenged by economies of scale. This is an exciting development and considered to be an area worthy of future investigation.

A study (Larson and Tingjin, 2003) of the use of DME as a clean cooking fuel determined that LPG equivalent cost[4] of producing DME from coal in the Yanzhou City area (Shandong Province) was comparable with the prevailing LPG wholesale price. An extension to this work (Larson and Yang, 2004) concluded that for China's coal rich provinces, which are mostly located inland and a great distance from sea-borne import terminals, the production of coal-derived DME became cost competitive with imported LPG at oil prices between $20 to $26 per

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[1] See http://indiabudget.nic.in/budget2012-2013/glance.asp (accessed 7 May 2016).

[2] See http://www.bbc.com/news/science-environment-34468821 (accessed 7 May 2016).

[3] The joint research program is being conducted through joint collaboration by the CSIRO, Indian Institute of Petroleum (CSIR-IIP), Indian Institute of Technology (IIT-Roorkee), Bharat Petroleum Corporation Limited (BPCL), The Center of Advanced Materials and Industrial Chemistry (CAMIC) at RMIT, and The University of Melbourne (http://australianresources.com.au/988/australia-india-collaborate-clean-fuel-production — accessed 7 May 2016).

[4] The LPG equivalent cost is equal to the actual cost of producing DME multiplied by the ratio of the heating value of LPG (46.6 MJ per kg) to DME (28.9 MJ per kg).

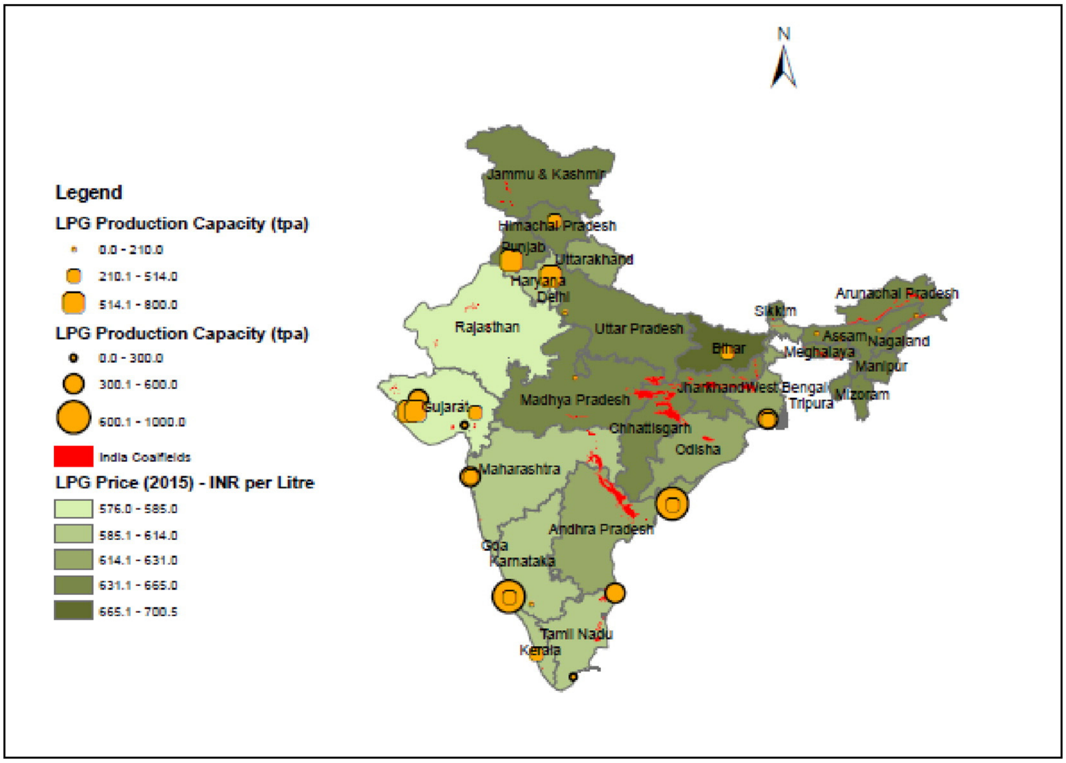

Fig. 2. Retail LPG prices in August 2015.[1,2] [1]Retail LPG prices were obtained from statistics provided by the Ministry of Petroleum and Natural Gas (MoPNG) (http://ppac.org.in/). [2]LPG production and import capacities were obtained from the 2015 annual statistics report published by the Indian Ministry of Petroleum and Natural Gas (MoPNG).

barrel (compared with an oil price of $24 per barrel at the time). Another outcome was that the co-production of DME and electricity in a coal to fuels facility could result in a 25% reduction in the amount of primary coal needed to meet an equivalent demand of cooking energy plus electricity.[5] Lastly, in contrast to standard coal-fired power production, a coal to DME facility will produce a sizeable high purity CO_2 stream (in one case containing 28.8% of the carbon present in the feed coal (Celik et al., 2004)), which may be sequestered if and when carbon storage technology becomes available.

Like China, India has modest amounts of natural gas but very large quantities of domestic coal.[6] Given the rapid growth of the coal-to-DME industry in China, it is therefore posited that the production of DME using local Indian coal may be done at large scaler scale and within a relatively short timeframe. Other feedstocks such as biomass and MSW have not seen such extensive deployment elsewhere and hence we have chosen to focus on the coal to DME opportunity where the experience in China verifies the potential for rapid deployment. Other feedstocks will be examined in future studies.

In this case, it may therefore be one strategy worth considering in the context of reducing energy poverty through the replacement of solid cooking fuels, whilst catalysing local economic growth, and reducing the dependence on imported LPG. The economic viability of such a strategy will however depend on India-specific factors (including coal quality, feedstock costs, capital costs, electricity prices, the cost and logistics associated with LPG transport). In this paper we conduct an India-specific techno-economic analysis which considers these different elements and is seen as an extension of the analysis done for China (Larson and Tingjin, 2003; Celik et al., 2004; Larson and Yang, 2004).

Study area

The relative location of India's coal resources (more than 95% of which is located in the states of Jharkhand, Odisha, Chhattisgarh, West Bengal, Madhya Pradesh and Andhra Pradesh)[7] and facilities currently importing or producing LPG are shown in Figs. 2 and 3. Also depicted is the relative retail price associated with different regions, as well as proportion of households which had transitioned to the use of LPG.

It is noteworthy that some of the coal bearing states (particularly Jharkhand) are among those where the retail cost of LPG is the highest and where the number of households using LPG is among the lowest. Table 1 contains a summary of primary cooking fuels used in households in these states in 2011 and shows that, except for Andhra Pradesh, the use of solids fuels was higher than average for India. The use of coal as a cooking fuel was particularly high in West Bengal and Jharkhand.

Approximately 26% of India's coal is located in Jharkhand. Here, approximately 86.9% of households still relied on the use of solid cooking fuels, and 18.1% used coal for this purpose. The data further shows that more than 31% of all Indian households that used coal, lignite and charcoal for cooking were located in Jharkhand.

If one assumes an average LPG equivalent cooking energy requirement of 22 kg per person per year in India (Goldemberg et al., 2004), and that cooking with LPG is 60% efficient compared with 20% when cooking directly with coal (Larson and Yang, 2004), then this translates into an equivalent coal consumption of approximately 1.2 million tonnes per year.[8] The environmental and health hazards associated

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[5] The net reduction in the amount of coal used was due to the fact that the efficiency of using a LPG stove (60%) is significantly higher than the assumed efficiency of cooking with coal directly (20%), which more than compensated for the energy loss associated with converting the coal into DME.

[6] According to the International Energy Agency China was ranked 1st in the world in terms of coal production and 6th in terms of natural gas production in 2014, compared with India which was ranked 3rd in the world in terms of coal production and 19th in terms of natural gas production in 2013 (www.eia.gov).

[7] See http://coal.nic.in/content/coal-reserves (accessed 7 May 2016).

[8] Assumes a lower heating value for coal of 15.6 MJ per kg, typical of the North Karanpura resource and a population of 33 million in 2011 (as per 2011 India census data).

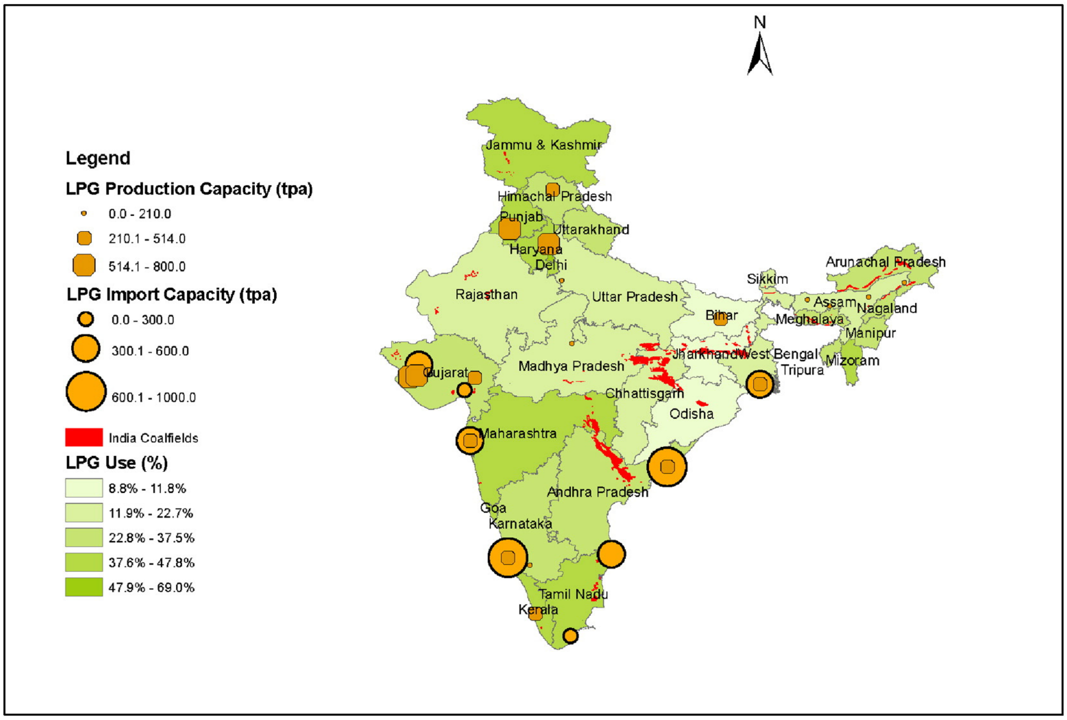

Fig. 3. Relative proportion of households using LPG (NSSO, 2012).

with using coal-converted DME as a clean cooking fuel in China were found to be less than using coal as the cooking fuel (Larson and Tingjin, 2003). For these reasons, this study will consider the construction of a coal-to-DME facility in Jharkhand as a basis.

Low grade coal to DME process simulation

DME may be produced from solid feedstock (including municipal solid waste, biomass or coal) via two typical process routes. The first process route (Fig. 4) involves gasifying the feed to produce a synthesis gas (syngas), adjusting the syngas H_2 to CO ratio to roughly 2:1 through a water-gas shift (WGS) reactor, removing CO_2 and sulphur components from the syngas, converting the resulting sweet syngas into methanol as an intermediate product, and then dehydrating the methanol to yield DME (and water). The vast majority of global DME is produced via methanol as an intermediate product and large scale commercial methanol to DME plants typically have design capacities of 100,000 t per year or larger (STSTC, 2015).

The methanol synthesis reaction ($CO + H_2 \leftrightharpoons CH_3OH$) may be accomplished to almost the extent predicted by chemical equilibrium (Larson and Tingjin, 2003), and processes aimed at maximising methanol production require that methanol be removed from the reactor product, leaving an unconverted syngas stream, most of which is recycled back to the reactor inlet. In this configuration a small stream is purged (and used for power generation) to avoid the build-up of inerts (e.g. CH_4 or N_2) in the system. This configuration is referred to as the recycle configuration (RC) in a number of prior publications (Larson and Tingjin, 2003; Larson et al., 2006; Liu and Larson, 2014a, 2014b), and an alternative configuration, in which none of the unconverted syngas is recycled, is referred to as the once-through (OT) configuration.

For a similar feedstock quantity, the OT configuration produces more power and less fuel and previous studies (Larson and Yang, 2004) indicated that this was the most economical approach to producing DME under the prevailing circumstances in China. The outcome of a comparison between the RC and OT configuration is however highly dependent on a number of local factors and, when the revenue generated through the sale of electricity is counted as a credit, the prevailing electricity price.

The second process route (called the single-step process) uses the same unit operations to produce a sweet syngas, but in this case the

Table 1
Primary fuels used for cooking in India (as determined by the 2011 India Census[1] 2011).

Geographic area	Total number of households	Type of fuel used for cooking					
		Coal, lignite, charcoal	Other solid fuels[a]	Kerosene	LPG/PNG	Electricity	Other[b]
India	246,740,228	1.4%	65.8%	2.9%	28.5%	0.1%	1.2%
Andhra Pradesh	21,024,534	0.3%	58.8%	3.8%	35.8%	0.1%	1.2%
West Bengal	20,067,299	7.9%	68.6%	2.1%	18.0%	0.1%	3.3%
Madhya Pradesh	14,967,597	0.2%	79.7%	1.3%	18.2%	0.0%	0.6%
Odisha	9,661,085	1.6%	84.6%	1.1%	9.8%	0.4%	2.4%
Jharkhand	6,181,607	18.1%	68.8%	0.2%	11.7%	0.3%	0.9%
Chhattisgarh	5,622,850	2.3%	85.4%	0.5%	11.2%	0.1%	0.5%

Notes:
[a] Other solid fuels include fire-wood, crop residue and cowdung cake.
[b] Any other also includes biogas as well as no fuels used for cooking.
[1] Cooking fuel statistics were obtained from http://www.censusindia.gov.in/2011census/Hlo-series/HH10.html (accessed 20 May 2016).

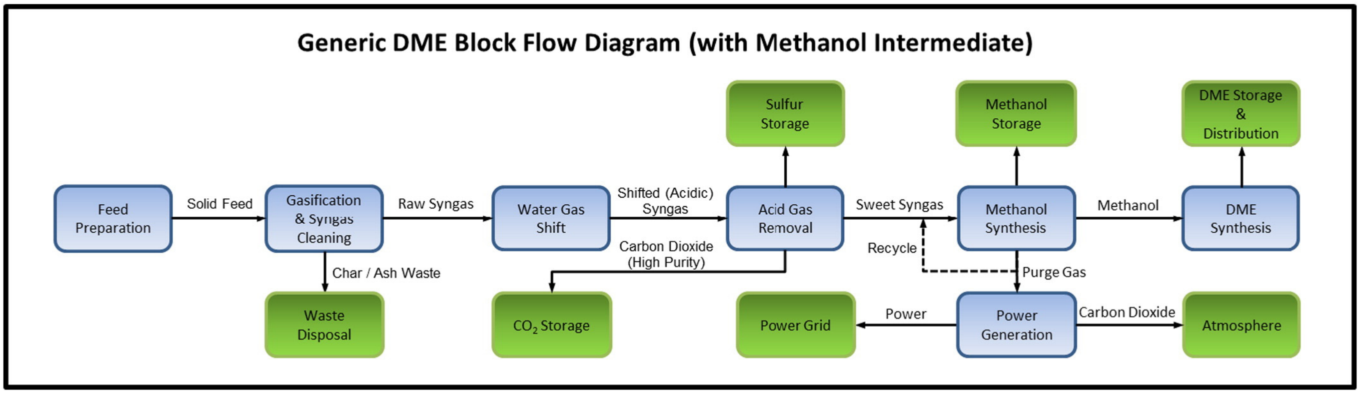

Fig. 4. Solid feedstock to DME block flow diagram.

Table 2
North Karanpura coal properties (Lau, 2015).

Property		Value
Ultimate analysis	C (daf %)	74.5%
	O (daf %)	18.3%
	H (daf %)	4.9%
	N (daf %)	1.5%
	S (daf %)	0.7%
	Cl + F (daf %)	0.1%
Ash (wt%) – ROM		37.4%
Moisture (wt%) – ROM		6.6%
Lower heating value (LHV) - MJ/kg		15.6

H_2 to CO ratio of the syngas is adjusted to roughly 1:1 and converted directly into DME, thereby avoiding the intermediate production of methanol. Although demonstrated at small scale, there are no commercial plants using this process route operational today. Further development of single-step DME production is currently being pursued by Linde (Germany)[9] and Kogas (Korea).[10] A number of prior studies have assumed the production of DME through direct synthesis (Larson and Tingjin, 2003; Celik et al., 2004; Larson et al., 2006).

Using mature technologies, proven at commercial scale, to the maximum extent possible is a key design philosophy in this study which therefore assumes the production of DME via methanol. All of the technologies downstream of the gasifier fall into this category. There is however no large scale commercial coal gasification plants operational in India presently.

Coal quality is a key to selecting an appropriate gasification technology, which in turn determines the design and operating requirements for the feed preparation circuit. In this context, India's thermal coal resources have been characterised as being highly reactive, containing high levels ash[11] and having high ash fusion temperatures (IEA, 2002). Coal from the North Karanpura resource in Jharkhand (composition shown in Table 2) has high ash deformation (oxidising and reducing) temperatures (>1482 °C) and also fits this description (Lau, 2015).

Entrained flow gasifiers are used in approximately 94% of the coal to chemicals (and liquid fuels) plants currently operational,[12] but generally require coal with ash contents less than 20% to 25% (Synthesis Energy Systems, 2012), and low ash melting points, and are therefore generally not suitable for use with typical Indian coal (Chikkatur, 2008). The use of fluidised bed gasifiers is however suitable for this purpose (Abraham, 2013; Reddy, 2014).

The largest scale fluidised bed gasifier currently in service is based on the so-called U-Gas technology and operates at a pressure of 10 bar. Initially developed by the Gasification Technology Institute (GTI), this technology has been commercialised by Synthesis Energy Systems (SES) in two coal-to-methanol plants in China using coal with ash contents ranging between 30% and 45% (Khan and Lau, 2012; Synthesis Energy Systems, 2012). It has been reported that recent technology

Table 3
Coal to DME plant simulation results.

Case		Recycle	Once through
Feed metrics[a]	Coal feed rate (tonne per day)	3803	3803
	Combined feed energy content (MW LHV)	685	685
	Oxygen feed (tonne per day)	1478	1478
Main product metrics[a]	Ash/char rate (tonne per day)	1536	1536
	Intermediate methanol rate (tonne per day)	1338	551
	DME rate (tonne per day)	963	397
	DME energy content (MW)	316	130
	Rate of high purity CO_2 produced (tonne per day)	2847	2847
	Rate of CO_2 in flue gas streams (tonne per day)	643	1744
	Total CO_2 produced (tonne per day)	3490	4591
Electrical power consumed[b]	ASU (plus O_2 compression)	20.6	20.6
	Gasification	4.7	4.7
	Syngas compression	16.3	16.3
	AGRU and CO_2 compression	11.7	11.7
	Recycle gas compression	2.8	0.0
	Methanol synthesis	1.1	0.4
	DME synthesis	0.4	0.2
	Ancillary plant	2.6	3.2
	Power consumed internally (MW)	60.2	57.1
Electrical power produced and exported	Gas turbine	45.8	127.1
	Syngas expander	0.7	2.7
	Steam turbine	51.0	82.0
	Total power produced	97.5	211.8
	Net power exported (MW)	37.3	154.7
Efficiency metrics	Electric efficiency (%)[c]	5.4%	22.6%
	Fuel efficiency (%)[d]	46.2%	19.0%
	Total efficiency (%)	51.6%	41.6%
Carbon footprint metrics	Plant CO_2 captured (tonne per year per MW exported energy)[e]	2496	3098
	Plant CO_2 not captured (tonne per year per MW exported energy)	564	1898

Notes:
[a] Derived through Aspen simulation.
[b] The determination of power production and consumption is based assumptions listed in Table S4 in the supplemental information accompanying this paper.
[c] Electric efficiency is the ratio of net electricity divided by the energy content in the feed.
[d] Fuel efficiency is the ratio of the energy content of the produced DME divided by the energy content in the feed.
[e] Total exported energy is sum of the energy contained in DME and the energy contained in electricity (MWe).

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[9] See http://annualreport2012.linde.com/reports/linde/annual/2012/gb/English/204020/linde_basf_br-_2-teams-_-1-idea-_-new-energy.html (accessed 7 May 2016).
[10] See http://www.businesswire.com/news/home/20110209005232/en/Korea-Gas-Build-300000-Tons-Year-Dimethyl (accessed 7 May 2016).
[11] More than 80% of India's coal resources contain between 30% and 50% ash.
[12] See http://www.gasification.org/what-is-gasification/world-database/ (accessed August 2015).

Table 4
Resource utilisation associated with replacing coal as a solid cooking fuel.

Cases		Recycle[a]		Once through[a]	
Primary cooking fuel		Coal[c]	DME[b]	Coal[c]	DME[b]
Total electricity required (MWe)		37	37	155	155
Total cooking energy required (MW)		190	190	78	78
Cooking appliance efficiency (%)		20.0%	60.0%	20.0%	60.0%
Fuel supplier	Electricity produced (MWe)	0	37	0	155
	Fuel produced (MW)	949	316	391	130
	Coal feed rate (MW)	949	685	391	685
External power plant	Coal to electricity conversion efficiency (%)[d]	37.0%	37.0%	37.0%	37.0%
	Electricity produced (MWe)	37	0	155	0
	Coal feed rate (MW)	101	0	418	0
Total coal feed rate (MW)		1050	685	809	685
Total coal feed rate (MW) relative to the base case		1.00	0.65	1.00	0.85

Notes

[a] The "Coal" case assumes the use of coal as a cooking fuel and as a means of generating electricity (providing the same amount of cooking energy and electricity as the "DME" case).

[b] In the "DME" cases, the quantities of fuel and electricity produced, and coal feed rates are taken from Table 3. The total cooking energy required is calculated by multiplying the fuel produced by the cooking appliance efficiency (60%) and the total electricity required is equal to the electricity produced by the DME facility.

[c] The cooking coal feed rate for the "Coal" cases is calculated by dividing the total cooking energy required by the cooking appliance efficiency (20%). Similarly, the coal feed rate required by an external power plant is calculated by dividing the total electricity required by the power plant efficiency (37%).

[d] This efficiency is an approximate estimate for using an IGCC configuration which captures an equivalent proportion of CO_2 as the OT and RC cases.

advancements have resulted in carbon conversions of up to 98% and cold gas efficiencies of up to 80% (Khan and Lau, 2012).

Although not currently operational in India, trials conducted by GTI have confirmed that this technology is suitable for the gasification of high ash Indian coal (Reddy, 2014). Another potential candidate is the so-called High Temperature Winkler (HTW) gasification technology, promoted by Thyssen Krupp Uhde, who have estimated that carbon conversions of 93% and cold gas efficiencies greater than 75% were expected in the gasification of high ash Indian coal (Abraham, 2013).

Aspen Plus was used to simulate a process plant operating in both the OT and RC configurations, and summary process flow diagrams for these may be found in the supplemental information accompanying this paper. Based on the estimated quantity of coal currently used for cooking in Jharkhand, the plant size was limited to the conversion of 1.2 million tonnes per year. The plant design included facilities to clean-up and compress high purity CO_2 produced in the process (thereby making it sequestration ready), and the power required to do so is accounted for in the calculation of overall process efficiency.

The coal properties of the North Karanpura coal are, aside from ash quantity and moisture, similar to the properties of Beluga coal (Alaska), which formed the basis of a coal-to-methanol plant feasibility study (Cook Inlet Region Inc. et al., 1981) completed in 1981. This work (with a stated cost estimate accuracy of ±20%) assumed the use of a HTW fluidised bed gasifier (operating at 10 bar and 1150 °C) and was therefore used to validate the Aspen gasification model, and to design the feed preparation and gasification plant used in this study.

A large part of the remainder of the plant, including the WGS, Acid Gas Removal (AGR) and methanol synthesis sections was based on a configuration proposed by Larson and Tingjin (2003). As such, it assumed the use of the Selexol™[13] process as an AGR technology and the use of the Claus™[14] and SCOT™[15] technologies to recover elemental sulphur. The methanol-to-DME conversion plant was not modelled explicitly and the estimated yield and utility consumption for the DME synthesis plant was based on figures from a technology provider (STSTC, 2015).

Plant performance and resource utilisation efficiency

A high level summary of the overall plant mass and energy balance (Table 3) shows that an overall process efficiency of approximately 52% is expected for the RC case and 42% for the OT case.

Both cases produce a significant amount of exportable power. It can be seen that the use of internal power is dominated by the Air Separation Unit (ASU), and syngas and CO_2 compressors, which is common to both circuits. In absolute terms, the RC configuration produces around 960 t per day of DME and 38 MW of exportable electricity. In contrast, the OT configuration produces around 400 t per day of DME and 155 MW of exportable electricity. If one assumes an annual plant availability of 85%, and a per-capita cooking energy requirement equivalent to 22 kg per year of LPG, then the RC configuration is able to supply the needs

Table 5
Production cost estimates.

Production cost estimates		Recycle	Once through
Capital cost[a] (Million US$ — 2016)	Feed preparation	75	75
	Gasification	120	120
	ASU (incl. O_2 and N_2 compression)	58	63
	Syngas compression	12	12
	Sour water gas shift	5	5
	Acid gas removal	50	50
	Sulphur recovery	10	10
	CO_2 drying/compression	16	16
	Methanol synthesis	78	23
	DME synthesis	86	38
	Power generation	92	163
	Total overnight cost (TOC) — US	601	574
	Total overnight cost (TOC) — India	613	586
	Interest during construction	75	72
	Total capital investment (TCI)	688	658
Annual production cost (Million US$ — 2016)	Capital cost[b]	98	94
	Feedstock cost[c]	9	9
	O&M[d]	25	23
	Electricity[e]	−13	−55
	Total annual production cost	119	72
Production cost metrics	Fuel cost ($ per tonne DME)	398	583
	LPG equivalent cost ($ per tonne LPG)[f]	642	941
	Breakeven oil price ($ per barrel)[g]	72	110

All annual costs assumes an operating capacity factor of 85% (Larson et al., 2006).

Notes

[a] The methodology and assumptions are described in section 3 of the supplemental information accompanying this paper.

[b] Assumes a capital charge rate of 14.3%, which is based on assumptions used for the calculation of the generation cost of thermal power plants in India (which included a debt to equity ratio of 70:30, 10% debt interest rate, 15% return on equity, a 25-year economic life and a depreciation of 5.28% per year) as well as a 35% tax rate (Motghare and Khan, 2014).

[c] Assumes a coal cost of $7.70 per tonne.[2] [2]Coal prices obtained from www.oreteam.com (accessed October 2015).

[d] The annual non-fuel operating cost was assumed to be 4% of the overnight installed capital cost (Larson et al., 2006).

[e] Assumes an electricity sales price of $47.60 per MWh (which is equivalent to a the average price negotiated in a long term power purchase agreement (PPA) recently negotiated in Jharkhand (Buckley, 2014).

[f] This is the DME price multiplied by the ratio of the LHVs of DME (28.9 MJ per kg) and of LPG (46.6 MJ per kg).

[g] This is the oil price at which the energy equivalent cost of the domestically produced DME becomes equal to the cost of LPG delivered to import terminals. This price is referred to as the Refinery Transfer Price (RTP) which is paid by Oil Marketing Companies (OMCs) to refineries. It is an import parity price, and determined by the prevailing weighted average Saudi Aramco contract price for propane (40%) and butane (60%) in the Arabian Gulf, the cost of ocean freight from the Arabian Gulf to ports in India and customs duty and import charges.[3] The historical (yearly average) relationship between the LPG RTP and the Indian Basket oil price (at an average shipping cost of $35 per tonne) shows a linear relationship (with a correlation coefficient of 0.986), where the $\mathit{LPG\ Price}(\$\ \mathit{per\ tonne}) = 7.8435 * \mathit{Indian\ Basket\ Oil\ Price} + 77.24$. [3]See http://ppac.org.in/content/149_1_PricesPetroleum.aspx (accessed 7 May 2016).

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[13] Selexol is a technology licenced by UOP (which is owned by Honeywell).

[14] The Claus process is a technology licenced by Linde.

[15] The Shell Claus Off-Gas Treatment (SCOT) process is licenced by Shell.

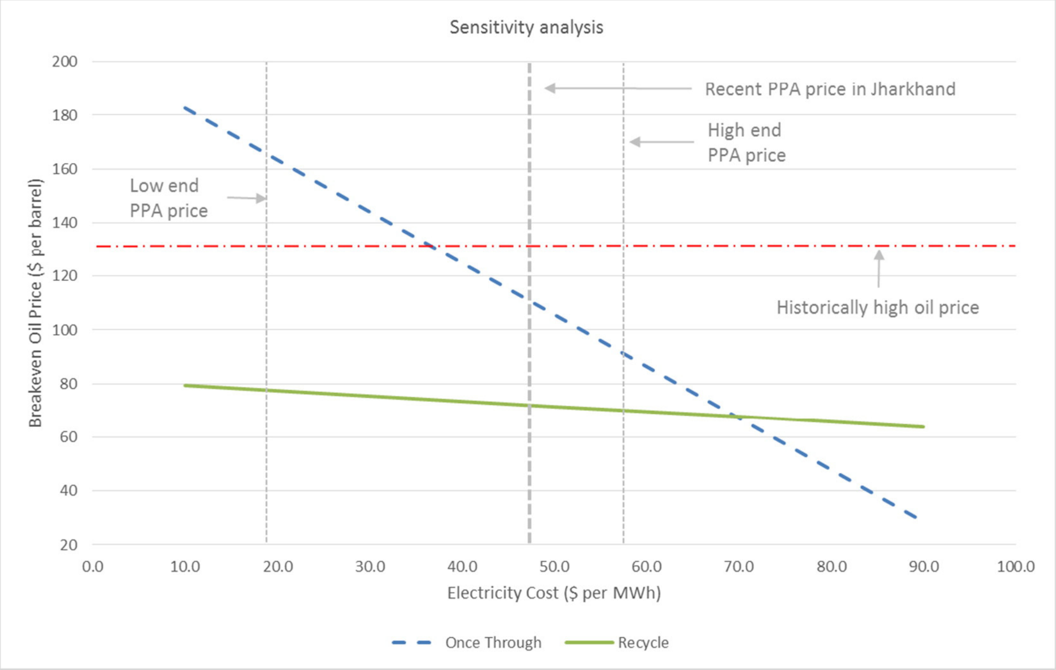

Fig. 5. Comparative break-even prices for the RC versus OT configuration. Calculations are based on an assumed exchange rate of 64.10 INR per US$.

of 9.7 million people and the OT configuration the needs of 4.0 million people, in addition to the exportable electricity.

A determination of the relative amount of coal that may be consumed if converted into DME (and co-producing electricity), as opposed to being directly as a cooking fuel and generating an equivalent amount of electricity in an external power plant, is described in Table 4. The results show that based on these assumptions, an overall reduction in coal consumption of 35% looks likely in the recycle case as opposed to a 15% reduction in the once-through case.

Economic assessment

An assessment of the cost of producing DME using North Karanpura coal through both the RC and OT configuration is shown in Table 5.

The results show that the RC and OT configurations will likely result in equivalent overall capital costs. The per-unit production cost associated with the RC configuration is however substantially lower than the equivalent cost associated with the OT configuration and is due to differences in the DME production rate and revenue obtained through

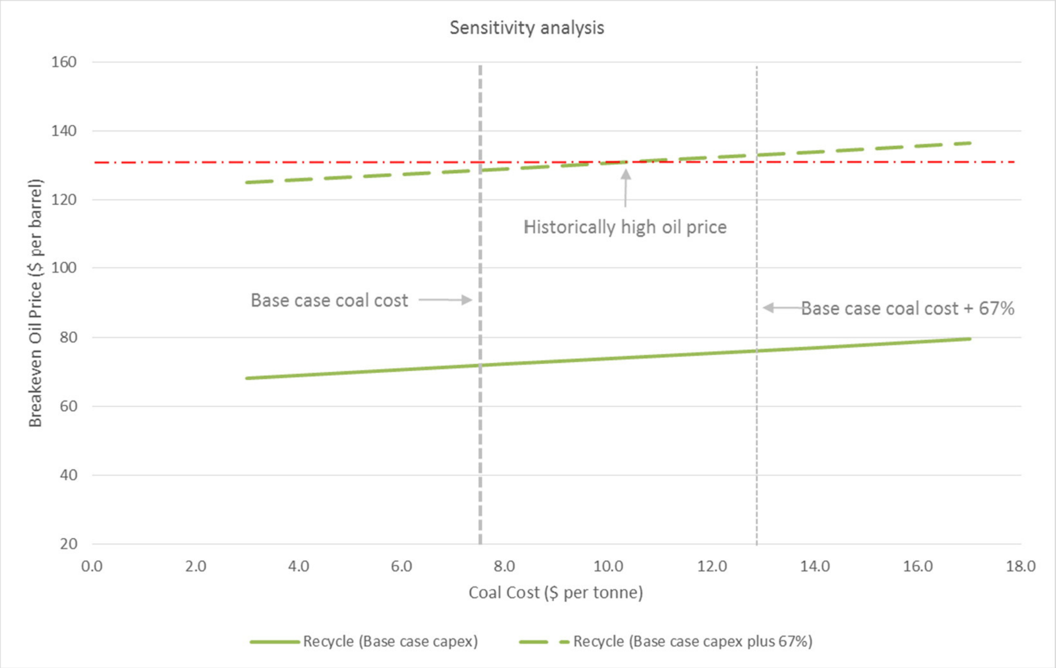

Fig. 6. Impact of a variation in capital cost and coal feedstock price. Calculations are based on an assumed exchange rate of 64.10 INR per US$.

power generation. Higher electricity prices will result in the economics of the OT system becoming more favourable and the break-even point between the RC and OT configurations is estimated at approximately \$70 per MWh (Fig. 5).

The range of recent Indian power purchase agreement electricity sales prices (Buckley, 2014) is represented by the dotted lines in Fig. 5. At each end of this range, DME produced through the RC configuration will require oil prices between \$70 and \$78 per barrel to become cost competitive with imported LPG. Similarly, the OT configuration would require oil prices between \$91 and \$166 per barrel. The current Indian Basket oil price (May 2016) is in the order of \$40 per barrel, which is significantly below the indicated break-even prices. That being said, the breakeven price range determined for the RC configuration is well below a historically high oil price of \$132 per barrel (recorded in July 2008).

Table 5 shows that the recovery of the capital investment is responsible for the greatest majority of the overall production cost, and variations in this number will therefore have a large impact on the overall economics. In this context, It has been pointed out that capital estimates determined through the scaling of costs found in open literature (such as the one in this study) may underestimate actual costs by a significant margin, and examples are cited where the actual costs of two IGCC plants in the US exceeded estimates based on publically available National Energy Technology Laboratory (NETL) data by 67% and 122% respectively (Liu et al., 2015).The green dotted line in Fig. 6 illustrates the impact of a 67% increase in the capital cost of the RC configuration and shows that in this case, historically high oil prices would almost be required for domestically produced DME to become cost competitive with imported LPG. The study results should be viewed in this light. The relationship between the breakeven oil and coal price is also depicted in Fig. 6 and shows the impact of an equivalent increase in the coal cost will be significantly less than an equivalent variation in capital expenditure.

Conclusions

The objective of this paper was to perform a techno-economic evaluation of the use of low grade Indian coal to produce DME as a means of augmenting or replacing imported LPG. There are currently no DME production facilities operational in India, and the work is aimed at contributing to an existing body of work (Larson and Tingjin, 2003; Celik et al., 2004; Larson and Yang, 2004; Chiesa et al., 2005; Kreutz et al., 2005; Liu and Larson, 2014a, 2014b), which is geographically focused in China and the USA.

The production of DME from North Karanpura coal was modelled using Aspen Plus and the subsequent analysis showed that the production of DME from North Karanpura coal in a recycle configuration was expected to result in an overall energy efficiency of approximately 52%, and require oil prices in the region of \$72 per barrel to break even with imported LPG. The modelled DME production process is also expected to generate excess electricity which may be exported. It is estimated that providing this electricity, and using the produced DME as a cooking fuel, will result in 35% less coal being consumed when compared with a scenario where coal is used as a cooking fuel and as a means of producing an equivalent amount of electricity. DME (and electricity) produced in a once-through conversion process is expected to result in an overall energy efficiency of approximately 42%, require oil prices in the region of \$110 per barrel to break even with imported LPG and, if used for cooking, result in an overall decrease in coal consumption of 15%.

In 2011, approximately 18% of households in Jharkhand used coal as a cooking fuel. The quantity needed for this purpose (assuming an energy content typical of coal from the North Karanpura resource) was approximately 1.2 million tonnes per year. Converting an equivalent amount in a DME production facility could result in the substitution of approximately 185,000 t per year of imported LPG. This production is equivalent to more than 1.7% of LPG produced in India (from both indigenous oil and gas resources and imported crude oil) in 2013/2014 and therefore a relatively large contribution from a single plant. Stated differently, and if one assumes an annual consumption of 22 kg per person per year (Goldemberg et al., 2004) and that Jharkhand's entire current population (32.9 million people) has converted to using LPG as a cooking fuel, then this plant would be able to supply approximately 29% of the state's cooking fuel requirement.

Whilst it is technically feasible to replace LPG with neat (i.e. 100%) DME, it is likely that this will require some changes in distribution infrastructure and end-use devices (seal materials, gas regulators, etc.) typically associated with the use of LPG. In order to avoid this, a more pragmatic approach would be to blend the DME with LPG up to a limit of 20% (by volume) below which no such changes are necessary. In this case, the outlined production scenario would require an overall blended fuel market penetration equivalent to approximately 70.3 million consumers and make export to adjacent states necessary. The adjacent state of West Bengal, with a current population of approximately 90 million people, and where 8.7% of the population used coal as a cooking fuel in 2011, may potentially be one target market of interest in this regard.

From a geographic perspective, India's coal resources overlap with areas where the conversion from solid cooking fuels to LPG is low, and where LPG retail prices are high. Many of India's coal resources are all located inland and far away from LPG import terminals (with a higher associated cost component for freight).

With India's LPG control mechanism in place, higher retail prices mean a larger burden on the Indian exchequer. Inland production of DME (close to the mine-mouth) may have the potential to lower this burden and augment imported LPG in support of government initiatives aimed at transitioning from the use of solid to cleaner cooking fuels. Although not quantified in this study, it is expected that the construction of coal-to-DME facilities will stimulate local investment and enhance economic growth which may in turn enable a larger part of the population to convert to LPG. This may be a motivation for the government to invest in such a venture, and determining the overall macro-economic impact in such a scenario is seen as an area for future study.

Likewise, DME may also be produced from a number of alternative feedstocks, which includes gas, non-food biomass, MSW and CO_2. The transition to a low-carbon economy over the long terms is seen as vital and, whilst coal-derived DME may become an alternative clean cooking fuel contender as oil prices increase, it is recommended that the techno-economic viability of these other feedstocks also be investigated.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.esd.2017.01.001.

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