# Scoping technology options for India's oil security: Part II – Coal to liquids and bio-diesel

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*India's diesel consumption is several times that of petrol. In this article, we examine two options for meeting India's diesel demand: coal to liquids and bio-diesel. Coal gasification, followed by Fischer–Tropsch (FT) synthesis offers an opportunity for large-scale production of diesel as proven by South Africa, and now being attempted by China and Qatar. India could consider this option given its large coal reserves. Four such plants consuming 60–76 million tonnes (mt) coal per annum can generate 12 mt of FT liquid, which is 20% of the expected diesel demand in 2011–12. This would require an investment of about Rs 54,000–90,000 crores. FT synthesis is a proven technology, coal prices are relatively stable and land requirements are modest. However, coal supply and transportation could be a concern and the process increases India's $CO_2$ emissions by about 80 mt. Oil-bearing plants such as jatropha, palm and sunflower can be cultivated on wastelands to produce bio-diesel. This option has several advantages: it can be integrated with the rural economy, almost $CO_2$ neutral and a large employment generation potential. However, it is a mammoth undertaking requiring an investment of about Rs 45,000–58,000 crores. We also briefly discuss the potential of energy conservation using gasoline-hybrid cars, which can potentially increase fuel efficiency up to 200 miles per gallon.*

**Keywords:** Bio-diesel, coal, jatropha cultivation, hybrid cars.

IN a recent paper, we discussed technologies and options to produce ethanol for substituting petrol[1]. However, India's diesel demand in the foreseeable future is many times larger than its petrol requirements. Development of technologies that can substitute diesel is therefore of considerable interest. In this article, we discuss two such options: coal liquefaction to produce diesel and bio-diesel from oil-bearing plants such as jatropha. We shall also discuss, though briefly, technology options for reducing hydrocarbon fuel consumption in automobiles with innovations such as hybrid cars.

## Liquefaction of coal

Coal liquefaction to produce chemicals is an established technology dating back over 70 years. One such technology, Fischer–Tropsch (FT) synthesis, was invented by German scientists F. Fischer and H. Tropsch at Kaiser Wilhelm Institute for Coal Research. Initial experiments began in 1925 leading up to an annual 600,000 tonnes industrial capacity[2] in 1945. Though the process was not economical at that time, these plants were vital for Germany's conduct of World War II. The apartheid regime of South Africa was also forced to take this step in the 1960s, when there was an embargo for oil exports to that country. SASOL (South African Steenkolen en Olie) built the first plant in the 1950s and then took up two more projects[3] in the 1980s. Now, SASOL supplies roughly 40% of South Africa's diesel requirements. The same technology is used to convert natural gas to liquid fuels and is available for license from a number of oil companies.

### *Conversion technology*

Gasification of coal is the initial process in its liquefaction. This involves partial combustion of coal with sub-stoichiometric oxygen to yield syngas (a mixture of CO, $H_2$, $CO_2$, $H_2O$ and trace amounts of HCl, $H_2S$, $NH_3$ and impurities). If air is used for gasification, then syngas contains substantial amounts of inert $N_2$ as well. Over the last few decades, several types of gasifiers were developed by Shell, Destec (E-Gas), Texaco and KRW[4–7]. Most gasifiers typically achieve efficiencies of 65–85% (LHV; Lower Heating Value). Typical heating value of oxygen-blown gasifier output is 15–20 MJ/$Nm^3$, which is roughly 30% of fossil fuels such as natural gas and gasoline. In the Integrated Gasification Combined Cycle (IGCC), the combustion of syngas occurs in a gas turbine and the exhaust

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combustion gases are used in a bottoming steam cycle. Such combined cycle power plants can achieve efficiencies of 35–40% (LHV). Not only is this higher than traditional sub-critical pulverized coal combustion plants, it also has lower $SO_2$ and $NO_x$ emissions. This technology is also amenable for $CO_2$ capture. Two such power plants, each of 250 MW capacity, are in operation in the US. Tampa Electric Company's plant uses Texaco's pressurized entrained flow gasifier[8], and the Wabash River project in Indiana uses E-Gas pressurized gasifier[9].

Once coal is converted to syngas, it can be used to generate electricity as described above or produce liquid fuels such as diesel, gasoline or methanol, or even hydrogen. A few researchers have even suggested producing natural gas from syngas given that coal prices are stable, while natural gas prices are volatile[10].

The molar ratio of $H_2$ to CO in syngas generated in many commercial gasifiers is about 0.8–0.9. This needs to be increased to about 2 for FT synthesis to proceed. This is achieved by Water Gas Shift (WGS) reaction that shifts CO to $H_2$. The reaction can be controlled to achieve a desired $CO/H_2$ ratio.

$$CO + H_2O \rightarrow CO_2 + H_2.$$

FT synthesis involves catalytic reaction of CO and $H_2$ to give a mixture of straight chain aliphatic hydrocarbons[11–13].

$$CO + 2H_2 \rightarrow -CH_2- + H_2O.$$

Polymerization like chain growth results in a range of products comprising light hydrocarbons ($C_1$–$C_4$), naphtha ($C_5$–$C_{10}$), diesel ($C_{11}$–$C_{20}$) and wax ($>C_{20}$). Distribution of products depends on the catalyst and the operating conditions, and is modelled by the Andersen–Schulz–Flory equation[11]:

$$\log\frac{W_n}{n} = n\log(a) + \log\frac{(1-a)^2}{a}.$$

Here, $W_n$ is the mass fraction of a product consisting of $n$ carbon atoms and $a$ (selectivity) is the chain growth probability factor.

We have modelled a coal-to-liquid plant with coal consumption rate of 450 tonnes per hour (TPH; Figure 1). This is comparable to the coal consumption of a 1000 MW power plant. A part of the process simulation (gasifier and gas clean-up) was performed using Integrated Environment Control Model[14]. Low-ash coal is mixed with water to form a slurry, which is then fed to an oxygen-blown Texaco gasifier. The syngas is cleaned and shifted to undergo FT synthesis to yield a range of hydrocarbon products. The $CO_2$ produced in WGS reaction could be vented or, in an advanced power plant, sequestered to prevent the release of greenhouse gases.

In this campaign, instead of 1000 MW electricity the plant generates roughly 90 TPH of naphtha and diesel. Assuming 6000 annual hours of operation, the plant consumes 2.7 million tonnes (mt) coal and generates 0.55 mt FT liquids (Table 1). Twenty-five such plants can annually produce about 12 mt of FT liquid fuels. This is roughly 20% of India's expected diesel demand in 2011 12; a handful of such plants is adequate to produce this output. This is also equivalent to planting 11 million hectares (m ha) of land with jatropha as proposed by the Planning Commission[15].

China is building two plants with SASOL, each with a capacity of 80,000 barrels per day. Each plant would consume 15–19 mt of coal and produce about 3 mt of FT liquids per annum[3,16]. Four such plants could meet 20% of India's diesel demand by 2011–12. Given India's abundant coal reserves, this option is worth exploring for large-scale diesel production. However, there are a few issues that need to be addressed.

## Coal supply and quality

Indian coal production and transportation capacities are already overstretched and unable to meet the growing

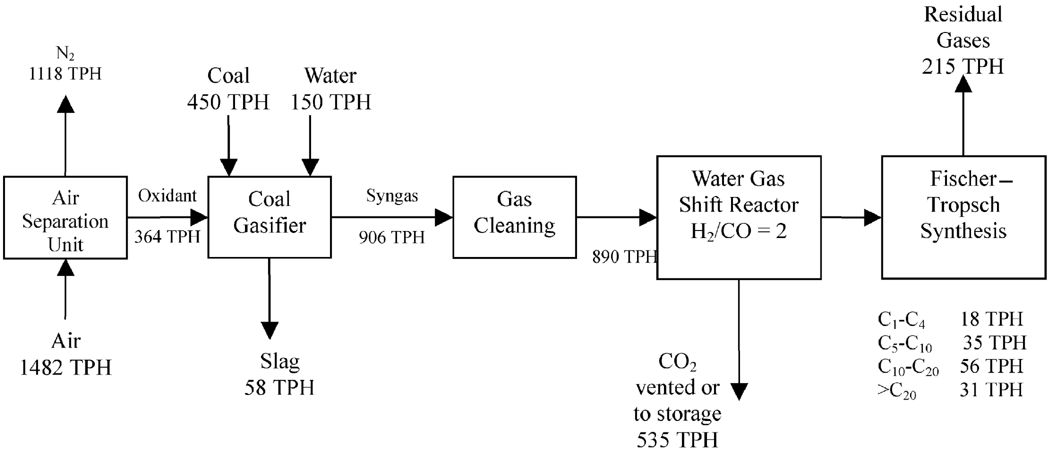

**Figure 1.** Coal-to-liquid plant using Fischer–Tropsch synthesis. This is based on a Texaco gasifier using illinois # 6 coal at 450 TPH.

**Table 1.** Overall annual performance of a baseline FT plant (6000 h of operation)

| | |
|---|---|
| Coal consumption per annum (mt) | 2.7 |
| FT liquids per annum (mt) | |
| Light hydrocarbons ($C_1$–$C_4$) | 0.11 |
| Naphtha ($C_5$–$C_{10}$) | 0.21 |
| Diesel ($C_{11}$–$C_{20}$) | 0.34 |
| Waxes (> $C_{20}$) | 0.19 |
| $CO_2$ emissions per annum (mt) | 3.2 |

power-sector demand[17–19]. Therefore, it is not clear how the additional coal required for liquefaction could be supplied. Four large plants (as described above) would increase India's present annual coal consumption from 260 to 330 mt. It is possible that with more nuclear power reactors having large capacities coming on stream, the demand for coal could be reduced to some extent[19]. It is also possible that a few new coal mines be reserved exclusively for coal liquefaction. Coal imports might also be a useful option, as in this case it avoids imports of petroleum products, and is less expensive. Another issue is that Indian coal is high in ash, sometimes up to 40%. The gasifier would have to be suitably designed to handle the large amount of ash generated.

### *Environmental impact*

Ash is not merely a technological challenge, but also an environmental one. In addition, about 3.2 mt of $CO_2$ (Table 1) is emitted for producing 0.55 mt of diesel and naphtha. This does not include $CO_2$ that would be emitted when the fuel is burnt in the automotive engines. It is therefore a matter of concern that if India opts for large-scale coal liquefaction[20], annual $CO_2$ emissions would increase by at least 80 mt from the present 660 mt. In the absence of cost-effective carbon sequestration technologies, this has undesirable environmental consequences.

### *Investments*

Present and future costs of FT synthesis are not well documented. A few studies estimate the cost of production to be around US$ 35/barrel[12] and thus predict that FT synthesis could become an attractive strategy if crude prices remain above US$ 40/barrel. However, these cost analyses have to be verified. Cost data are not easily available as cost and other details of this technology are closely guarded and are not available for detailed scrutiny. China's plants, also being built in collaboration with SASOL, would likely cost US$ 5–7 billion each[21], though some reports peg the cost at US$ 3 billion[16]. Qatar, which is rich in natural gas, recently inaugurated its low-temperature FT gas-to-liquids plant, named Oryx, in collaboration with SASOL Chevron. The US$ 950 million plant, with an initial capacity of 35,000 barrels/day, is expected to have an ultimate capacity of over 100,000 barrels/day, and at conservatively forecast oil prices, should deliver a 30% return[22]. Preliminary calculations by us suggest the production cost of diesel from coal to be around US$ 32–45/barrel, and detailed calculations are in progress.

## Bio-diesel

The production of ethanol described in our earlier article relied on sugar (when possible with cellulose), but the conversion process is energy-intensive requiring distillation to separate ethanol from water. In contrast, if oil is extracted from an oil-bearing fruit, such as jatropha or *Pongamia pinnata*, conversion to bio-diesel is simpler based on catalytic trans-esterification of the oil. The process also generates modest quantities of glycerine and oil cake.

The bio-diesel properties are similar to those of fossil diesel. Its cetane number is 48–60, comparable to diesel. The sulphur content is less than 15 ppm. Experiments with bio-diesel have resulted in lower emissions of CO and particulate matter, but reportedly higher $NO_x$ emissions[15]. Bio-diesel has higher viscosity, and it has to be warmed before injection to avoid gum deposition, especially in colder climates. This is not a major issue in many parts of India. Engines can operate totally on bio-diesel (B100), or with varying blends of bio-diesel and conventional diesel. In either case, engine performance is reported to be satisfactory. A number of European diesel vehicles are certified to operate over a wide range of blends and the emissions are reported to be lower[15,23,24].

Because of the above-mentioned properties, bio-diesel has caught the imagination of scientists and policy makers[15,25]. The Planning Commission set up a committee to examine various issues pertaining to large-scale production of bio-diesel. The committee's report[15] argued that large-scale jatropha cultivation on about 11.2 m ha of land could substitute for fossil diesel to the extent of 20% by 2011–12. Some workers have suggested that given an estimated 60 m ha of wastelands, there is sufficient scope to grow jatropha on at least 30 m ha. In this article, we examine some of the techno-economic and policy issues to assess a realistic potential of bio-diesel from jatropha.

### *Choice of oil-bearing tree*

Several oil-bearing trees can be cultivated for producing bio-diesel and they give varying oil yields. The optimal values are: palm oil (5 t/ha), jatropha (1.6 t/ha), sunflower (0.8 t/ha) and *Pongamia* (0.8 t/ha)[26]. The optimal choice of tree depends on the local geo-climatic conditions, soil, economics of cultivation and familiarity of local people. We have considered jatropha as an illustration for this analysis since it can easily grow on wastelands, requires low maintenance and investments. However, clearly it is not a universally applicable choice.

### Land requirement

India's total recorded area is 305 m ha, out of which 142.82 m ha is under cultivation and 68.90 m ha is recorded as forest (Table 2)[27].

Jatropha could be planted on cultivable wastelands, fallows, forests and on sown area. One of the oft-quoted advantages of jatropha is that it can grow as a wild crop along railway tracks and on hedges of cultivated lands. However, long-term sustainability and yield of such casual plantations is suspect. Besides, haphazard and dispersed sowings will increase the supply-chain costs. Such plantings are not expected to contribute significantly to bio-diesel production.

Crop switching by farmers is not an unknown phenomenon and depends on the relative economics. Malaysia, faced with the large availability of synthetic rubber transferred millions of acres from rubber to palm-oil plantations. Considering that rubber was not in the food chain, this transfer was solely dependent on economics. However, in India as large acreages are for the cultivation of foodgrains and sugarcane, and thus constitute a vital part of the food chain, crop switching becomes a major issue. When the Government is considering import of foodgrains to arrest prices, switching to jatropha on a large scale is fraught with danger. Even perceived wastelands become precious commodities and energy needs may have to get a lower priority than food. Arable lands may not therefore be available for planting jatropha.

It therefore appears that large-scale jatropha cultivation will have to be taken up on wastelands and its availability is a subject of contention. There are varying estimates on their availability ranging from 38 to 187 m ha, and the ground realities are often different from statistical records[28]. Data from remote-sensing techniques estimate the wastelands at 55 m ha[29]. To add to the confusion, many categories of wastelands are also unfit for cultivation. Wastelands that could potentially be used for cultivation come down to 32.27 m ha (Table 3).

Considering there are competing claims for using this land given pressures of population, urbanization and even production of essential foodgrains, it may not be advisable or feasible to plant jatropha on this entire area. A target of 11 m ha appears realistic. Apart from producing about 12 mt of diesel, there is a potential for employment generation up to 30 million in farming, seeds collection, oil extraction and other associated activities.

This is a mammoth undertaking as jatropha then will rank third in cropped area after paddy and wheat. There will have to be appropriate institutional arrangements to support crop growing, harvesting, fruit collection and transportation to processing plants. Indiscriminate expansion without providing adequate support in the above areas can be counter-productive.

**Table 2.** Land use statistics in India (in m ha)[27]

| | |
|---|---|
| Forest area | 68.90 |
| Area covered by towns, cities | 22.45 |
| Barren uncultivable land | 19.09 |
| Permanent pastures | 11.04 |
| Miscellaneous tree crops | 3.57 |
| Cultivable wastelands | 13.94 |
| Current fallows | 13.33 |
| Other fallows | 9.89 |
| Net sown area | 142.82 |
| Total | 305.03 |

### Economics of jatropha cultivation

Bio-diesel production involves several primary activities: jatropha cultivation, oil extraction and trans-esterification. The cost of jatropha cultivation is estimated to be about Rs 25,000–40,000/ha[15]. Normally 2000–3000 plants are grown/ha at a cost of Rs 4/plant. Jatropha plants start yielding after the third year and the annual yield varies between 0.75 and 2 kg/tree depending on the soil type and growing conditions. The seeds are sold to the extraction plant at a baseline price of Rs 5/kg.

Jatropha seeds will have to be collected and transported to a central processing plant. A recent study[30] has shown that biomass transportation costs place an upper limit on the scale of a central processing plant. In case of biomass-based electricity, biomass transported from villages in a 15–20 km radius can sustain a power plant of about 2 MW. This appears to be an economically optimum distance[30]. Beyond this, the transportation costs and associated uncertainties render the plant unviable. Similar calculation would be helpful for bio-diesel transportation as well.

We examine the economics of such a plantation based on the above assumptions (Table 4). The return on investment of the plantation (IRR; internal rate of return) is highly sensitive to the seed yield/tree. For a seed purchase price of Rs 5/kg, the yield should be at least 1.5 kg/tree for the project to produce reasonable returns on investment to the cultivators (Figure 2). Thus the plantation has to be well managed, and a corollary is that jatropha plantations on hedges and along the railway tracks will most probably have low yield and may not be sustainable.

The IRR is also sensitive to the seed purchase price (Figure 2). It is nominally assumed to be Rs 5/kg. How-

**Table 3.** Wasteland availability for cultivation (in m ha)[28,29]

| | |
|---|---|
| Gullies and/or ravenous | 1.02 |
| Lands with scrub | 15.05 |
| Lands without scrub | 3.73 |
| Shifting cultivation – abandoned | 1.22 |
| Saline/alkaline (slight) | 0.41 |
| Degraded forest – scrub | 10.84 |
| Total | 32.27 |

ever, even a slight reduction in price makes the plantation unviable. This is also corroborated by field experience of farmers[31]. Therefore, cultivators have to be assured of a stable minimum price, which may have to include some subsidies when necessary. Our analysis suggests that only with an average yield of 1.5 kg/tree and a purchase price of at least Rs 5/kg is jatropha cultivation economically viable.

### *Economics of bio-diesel*

Bio-diesel production process involves seed collection and transportation, oil extraction and trans-esterification. Oil content in seeds is usually 30–35% and most modern oil expellers can achieve 90–95% oil extraction efficiency. Bio-diesel production process also generates two by-products, oil cake and glycerol, that have economic value.

Capital cost and operational cost data available for bio-diesel plants are still tentative (Table 5)[32,33], since plants of varying capacities are still being established. Operational experience with the technology will lead to robust cost information.

Based on the above assumptions, bio-diesel price (excluding sales tax and excise) is about Rs 20/l corresponding to seed price of Rs 5/kg, and Rs 35/l for seed price of Rs 10/kg. This underlines the importance of stable seed price. The present glycerol market price is about Rs 40/kg[15]. However, large-scale bio-diesel production will lead to a glut of glycerol and consequently diminish its value. If the economic value of glycerol is disregarded, bio-diesel price is expected to be in the range of Rs 24–40/l for the seed prices we have considered (Figure 3).

The present market price of bio-diesel is reported[34] to be Rs 32–55/l, which is well above these theoretical calculations and also above the present retail price of ‘conventional’ diesel. This could be because of lack of maturity in technology and varying oil content in the seeds. The bio-diesel purchase policy of the Government specified that the oil marketing companies purchase bio-diesel at Rs 25/l (including taxes and duties)[35] from 1 January 2006. Given the uncertainty in bio-diesel cost, it is not clear whether this price is attractive to bio-diesel producers.

## Bio-diesel vs FT synthesis

It is of interest to compare relative techno-economics of bio-diesel and FT synthesis for producing 12 mt of diesel (Table 6). For bio-diesel, we consider ‘one unit’ as a cultivated area of 50,000 ha supplying jatropha seeds to a bio-refinery of capacity 80,000 t/annum as specified by the Planning Commission. About 150 such units would then be required to generate 12 mt of bio-diesel. For FT synthesis, we consider a 3 mt plant as a unit. This is the scale of plants now under construction in China[16] and we have assumed that for the purpose of our analysis four such units would be required.

**Table 4.** Assumptions in cost assessment of jatropha plantations[15]

| | |
|---|---|
| Initial capital investments | Rs 25,000–40,000/ha |
| Jatropha plants/ha | 2000–3000 |
| Planting cost | Rs 4/plant |
| Yield | 0.75–2 kg/tree |
| Seed price | Rs 5/kg |
| Discount rate | 6% |
| Duration | 10 years |

**Table 5.** Cost data and assumptions for bio-diesel extraction and trans-esterification plant[15,32,33]

| | |
|---|---|
| Capital cost of oil extraction and trans-esterification plant | Rs 9000–10,000/tonne bio-diesel |
| O&M costs | Rs 3500/tonne bio-diesel |
| Oil content in seeds | 25–35% |
| Seed price | Rs 4–10/kg |
| Cake price | Rs 1/kg |
| Glycerol price | Rs 0–40/kg |

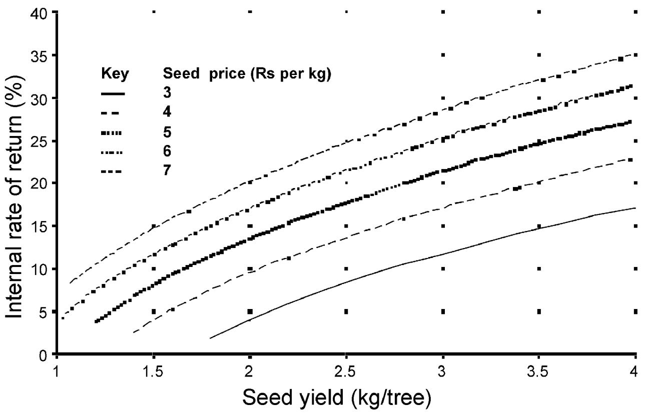

**Figure 2.** Economics of jatropha cultivation as a function of annual jatropha yield (kg/tree) and jatropha seed price (Rs/kg; 2500 trees/ha).

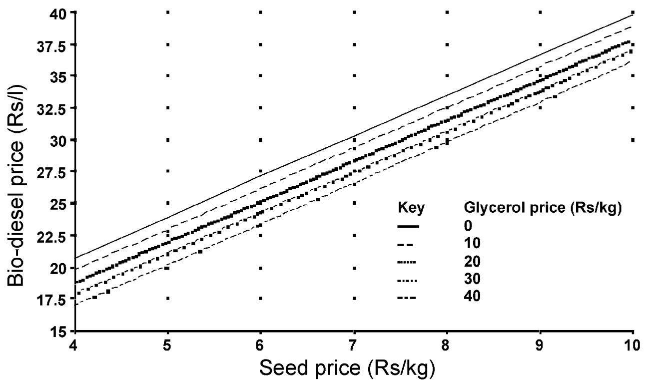

**Figure 3.** Bio-diesel production cost as a function of seed and glycerol price.

**Table 6.** Comparison of bio-diesel from jatropha with FT synthesis for producing fuel of 12 mt/yr

| | Bio-diesel from jatropha | FT synthesis |
|---|---|---|
| Definition of a unit | 50,000 ha of jatropha cultivation feeding a processing plant of capacity 80,000 t bio-diesel/annum | Plant producing 3 mt/annum of FT liquids using 15 mt coal |
| Number of such units | ~150 | 4 |
| Resource required | 11 m ha land cultivated with jatropha or other oil-bearing plants | 60 mt coal/annum |
| Initial capital investments | Rs 45,000–58,000 crores | Rs 54,000–90,000 crores |
| $CO_2$ emissions | Low (bio-fuels are not zero-emission) | 80 mt/annum |
| Constraints | Land availability and economics. Difficult to produce more than 12 mt of bio-diesel | Coal supply and quality. May have to import coal |

Bio-diesel plantation requires 11 m ha of land and the total investments are expected to be Rs 45,000–58,000 crores. FT synthesis requires an annual coal consumption of 60 mt with an expected investment of Rs 54,000–90,000 crores. There is considerable uncertainty in the cost estimates of both bio-diesel and FT synthesis. However, even so, the initial capital investments of bio-diesel and FT synthesis are in the same order of magnitude. However, at the right location the feedstock cost of coal per unit output can be lower than for bio-diesel.

The main advantages of bio-diesel are that it is almost carbon-neutral and could potentially create about 30 million unskilled to skilled jobs, mainly in rural areas. However, given constraints in the availability of land for cultivation, it may be difficult to produce more than about 12 mt of bio-diesel.

FT synthesis requires significantly less land than bio-diesel. Further, coal prices are relatively stable, whereas jatropha yield and price are expected to show some volatility. However, coal supply and transportation are concerns, and the present coal production of 260 mt, already under considerable strain, gets stretched by another 60 mt. This may lead to the country importing coal to meet its demand. However, FT synthesis has a major downside in that it increases India's annual $CO_2$ emissions by about 80 mt.

Considering India's power needs, it is not an either/or choice between the two technologies. It will have to adopt a mix-and-match strategy and may have to adopt both options to reduce crude imports.

## Investments

Initial investments required for either of the two technology options are large. It may not be desirable for the Government to own these projects fully. Private industry should step in to take up these initiatives and the Government's role should be limited to policy formulation, guarantees and price support where necessary. Large tracts of land can be given on long-term lease to cooperatives and industries for cultivating jatropha and other oil-bearing seeds. Oil-marketing companies and other industries should be encouraged to set up bio-diesel production facilities in close proximity to farmlands. In the short run, the Government could fix a purchase price for bio-diesel. However, with experience, the price should be market-determined and the Government could consider providing tax benefits and other incentives, without any direct budgetary allocation. The US government gives a tax credit of US 51 ¢/gallon for making corn ethanol, and such a measure could be considered in India. Similar support should be available to FT synthesis plants as well. For FT synthesis, industry may have to depend on collaboration with international partners who have built similar plants in other countries.

## Hybrid vehicles and efficiency options

In the previous sections we discussed the technologies and policies for replacing fossil-based gasoline and diesel. Along with these it is worthwhile to consider various options for improving the fuel efficiency of vehicles. Hybrid (gasoline-electric) vehicles offer interesting possibilities for improved fuel consumption, especially for passenger vehicles in urban and semi-urban environments. In a hybrid, the electric motor adds additional thrust, allowing a smaller-sized gasoline engine, and the brakes regenerate electricity to be stored in batteries. The most successful hybrid vehicle, the Toyota Prius[36], achieves a rated urban fuel efficiency of 60 miles/gallon or 25.5 km/l. All-electric vehicles never took-off because of the limited range, high costs, and lack of optimum vehicle designs. On the lifecycle perspective (well-to-wheel), gasoline electric hybrids are better than natural gas and hybrid fuel cell vehicles because of the higher well-to-tank efficiency[37,38].

Hybrids can improve the fuel efficiency up to 50 miles/gallon, and it is expected that the next generation of hybrid technology will include lithium ion batteries. This and the so-called plug-in hybrids could extend the fuel efficiency to over 100 miles/gallon (42 km/l). A plug-in hybrid can be charged overnight, taking advantage of inexpensive, off-peak electricity. Further efficiency gains of up to 200 miles/gallon (84 km/l) are possible using carbon composites for fabricating the body parts. These materials are now becoming common in fabricating aircraft fuselage and wings, and also racing cars. If we further blend ethanol with regular gasoline, as E50, the effective gasoline import requirements would be equivalent to a pure gasoline efficiency of 400 miles/gallon (168 km/l). Admittedly, not all these innovations may work in the short term. However, even a modest application of some of these technologies would help in reducing oil imports, or at least help in keeping the fuel consumption low.

## Conclusion

India has large coal reserves and hence FT synthesis is an option to produce liquid fuels such as naphtha and diesel. Four large plants of 3 mt capacity can generate about 12 mt of FT liquids, which is 20% of India's expected diesel demand in 2011–12. There are, however, concerns about coal supply, $CO_2$ emissions and the large investments such plants would need.

Jatropha plantations of 11 m ha can produce about 12 mt of bio-diesel. Given that India has about 33 m ha of cultivable wastelands, this target appears achievable, but not much more. Even this is a challenging task and will rank jatropha as the third in cropped area after wheat and paddy. Bio-diesel is almost carbon-neutral and has an impressive potential for employment generation. However, various stages in this route such as fruit harvesting, collection and transportation would all have to be carefully planned and structured for making this option commercially viable. For making bio-diesel viable, sustained high yield (1.4 kg/tree) and seed price (Rs 5/kg) are necessary.

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