ELECTRICITY GENERATION FROM RICE HUSK IN INDIAN RICE MILLS: POTENTIAL AND FINANCIAL VIABILITY

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Abstract—Rice husk generated as a by-product of rice processing is an important energy resource. The availability of this resource in India has been assessed and the technologies for exploitation of its energy potential in rice processing industry discussed. Nomographs have been developed for estimation of the husk required to meet the energy demand of parboiling, drying and milling operations. The unit cost of electricity using rice husk gasifier-based power generation systems has been calculated and its financial feasibility assessed in comparison with utility-supplied and diesel-generated electricity. With the cost and efficiency data assumed here, the unit cost of electricity produced by rice husk gasifier–dual fuel engine–generator system varies between Rs 2/kWh and Rs 7/kWh. (Note: 35 Rs approximates to

Keywords—*Husk availability; rice husk gasifiers; financial feasibility; unit cost of electricity; rice mill; paddy parboiling.*

1. INTRODUCTION

Rice is a major cereal in India accounting for about 40% of foodgrain production and over 30% of its cropped area.[1] India's share in world rice production is 21%.[2] Rice is the edible form of paddy (also known as rough rice) and in the process of conversion from paddy, rice husk and rice bran are generated as by-products. While rice bran is used for oil extraction and in feed formulations, the husk is generally used as a fuel, for generating heat for the parboiling of paddy or other applications, often at efficiencies below 10%. Surplus husk has many applications, mainly in tobacco curing operations and brick kilns, but include production of furfural, cement, boards etc. Use of husk in industries other than rice processing involves handling and transportation of this low bulk density (112–144 kg/m^3) by-product. On-site use of husk in the rice processing industry, which needs energy in both thermal and mechanical forms, avoids the necessity of transportation. Technologies for conversion of husk into electricity and thermal energy at relatively higher efficiencies are now available.[3,4] The present work is an attempt at assessing the financial feasibility of using rice husk as an energy source to meet on-site electrical and/or thermal energy requirements of a rice processing industry. Since there are several technological problems yet to be resolved before the rice husk gasifier–dual fuel engine–generator systems could be considered an appropriate technological alternative to grid electricity or diesel generator sets in India, the primary objective of the present work is to present a systematic methodology for financial feasibility evaluation of such systems. In fact the values of the various input parameters (like costs/efficiencies etc. of the energy conversion equipment) used may be considered as indicative only. With more authentic input data availability in near future, the methodology presented in this work could be used to arrive at specific realistic conclusions.

2. RESOURCE AVAILABILITY

The availability of husk depends on the paddy production, its proportion processed into rice and the fraction of husk in paddy. Total energy potential would depend upon its calorific value as well as the quantity available.

Annual paddy production in the country can be estimated from the area under the crop and its average productivity. These two parameters depend on several independent and interrelated

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factors such as the varieties of paddy sown, proportion of irrigated area, fertilizer use, prevailing weather, timeliness of crop production operations, agronomic practices followed, price of paddy etc. Assessment of all such factors on a countrywide basis with reasonable certainty is a very difficult task. Further, the factors such as timeliness of operations and overall management, which are quite important, cannot be quantified with the desired accuracy. As an alternative, the available data[1] indicating the trend of paddy production (P) in India over the period 1971–72 to 1991–92 was used to obtain the following least-squares regression fit for its time (t) variation:

$$P = 58.5 + 1.495t + 0.23t^{1.5}, \qquad (1)$$

where P is in million tonnes and t in years ($= 0$ for the reference year 1971–72)

Paddy produced is processed into rice for human consumption, except for a small fraction ($\sim$ 10%) retained for meeting seed and some other requirements.[5] The quantity of husk generated as a by-product of rice processing depends on the husk-to-paddy ratio (HPR), which has been reported for different varieties (and in different countries) in the range 0.14–0.27.[6] Although there are variations due to different varieties, pre-milling processes and the method of removal of husk,[7] typical proximate and ultimate analysis of rice husk is given in Table 1.[3,8] Rice husk has certain properties, mainly because of high silica content in its ash fraction and silica–cellulose structural arrangement.[6] It has an inherent resistance to burning and its abrasive characteristics cause wear and tear of mechanical components coming in contact with husk.[7] The calorific value (CV) of rice husk has been reported by various research workers to be in the range 12.1–15.2 MJ/kg.[6]

Table 1. Typical proximate and ultimate analysis of rice husk

S. No.	Component	Proportion, %
Proximate analysis		
1	Fixed carbon	19.9
2	Volatile matter	60.6
3	Ash	19.5
Ultimate analysis		
1	Carbon	38.1
2	Hydrogen	4.7
3	Oxygen	29.3
4	Nitrogen	1.5
5	Sulphur	0.1
6	Moisture	8.9
7	Ash	17.4

Source: Refs 3 and 8.

2.1. *Variations in husk availability*

2.1.1. *Geographical distribution*. Paddy is cultivated in almost all the states of India. However, Andhra Pradesh, West Bengal, Uttar Pradesh and Punjab are the leading states in that order and account for nearly 50% of production. Statewise availability of husk was assessed on the basis of paddy production and its fraction processed into rice.

2.1.2. *Seasonal distribution*. Paddy is cultivated mainly in the kharif season (July–October), which accounts for 92–94% of annual gross cropped area under paddy and 86–90% of gross annual production. The average productivity of paddy during the rabi season (November–April) is over 1.5 times that of kharif, probably because most of the area during the rabi season is irrigated. Processing of paddy, in general, for conversion into rice is also a seasonal activity (November–April) in most parts of the country. However, in areas where two crops are taken, it continues almost round the year.

2.1.3. *Rice mill*. At the level of an individual rice mill, the annual availability of husk and its energy potential depend on the capacity of the rice mill, annual hours of operation, HPR of paddy and CV of the husk generated. For a typical one tonne per hour (t/h) rice mill operating 2400 h a year the available energy potential works out to be 6.4 TJ for an HPR of 0.2 and assuming a CV of 13.4 MJ/kg for the husk.

3. ENERGY DEMAND FOR RICE PROCESSING

Rice processing mainly includes paddy parboiling (if undertaken), its drying and milling. Paddy milled without parboiling produces raw rice (also called white rice). Otherwise, the product is called parboiled rice. Parboiling and drying operations largely require thermal energy whereas milling requires motive power which is generally provided through electric motor drives. Some electricity may also be used in material handling operations during parboiling and drying. For milling, mainly three types of systems, huller, sheller and modern rice units, are used. Electrical energy intensities vary for raw and parboiled rice in these three milling systems. Similarly thermal energy demand for parboiling varies according to the parboiling method practised. Both electrical and thermal energy demands of rice processing have been analysed elsewhere[9,10] and are summarised in Table 2.

4. THERMOCHEMICAL CONVERSION OF RICE HUSK INTO ENERGY

The available literature on use of rice husk as an energy source relates to its thermochemical conversion. Combustion in furnaces as a boiler fuel or for generating heat is the traditional and well-established technology for husk utilisation but the overall heat utilisation efficiencies have been low (5–15%).[11] Though there are several technical problems yet to be resolved, gasification of rice husk to generate producer gas is another technology which has potential for use in India.[12,13] Producer gas can be used to generate motive power/electricity through the use of internal combustion engines and generators. It can also be used to generate thermal energy for use in process industries. Pyrolysis-cum-steam gasification of rice husk for generating electricity and value-added products such as amorphous silica, sodium silicate and activated carbon has also been reported. Briquetting of rice husk has also succeeded as an economic enterprise in a specific situation in India.[14]

While the overall heat utilisation efficiencies of traditional furnaces/boilers were 5–15%, improved design of furnace boiler and furnace-dryer systems with efficiencies in the range of 33–54% are reportedly being used in the country.[15] Some of these systems can meet the entire thermal energy requirements of rice processing. However, the mechanical energy requirements have to be met from sources other than husk. By gasification of rice husk, efficiencies of the order of 15%[3] have been achieved in practice for generation of electricity and of the order of 55% for thermal applications[16] in India. It is worth mentioning that there is considerable variation in the efficiency figures quoted in the literature for gasifier–dual fuel engine–generator systems using rice husk as a feedstock.[3,17] It is, however, expected that efficiencies of over 40% for electricity generation through biomass gasification on a large scale (say over 20 MWe) may be achieved in the near future.[4] Cogeneration of electricity and process heat using rice husk is probably the best option for the rice processing industry, but it is yet to be demonstrated for rice mills of lower capacities (up to 4 t/h), which dominate the Indian rice processing industry. For a rice mill of 120 t/h installed capacity, cogeneration is already being practised in India for meeting electricity and thermal energy requirements of rice milling, solvent extraction of rice bran oil and production of furfural as well as sale of surplus electricity to the grid.[3,12,18]

While technologies to meet the entire thermal energy demand of rice processing from rice husk generated in the rice mill have already been reported to be in use,[15,16] the rice mills still depend on the utilities and/or captive power generation using diesel generator sets for meeting electrical energy demand. With the rising demand for fossil fuels, it may be desirable to look for alternative options for electricity generation. Moreover, with efficiency improvements, it may be possible to meet the total energy demand, both thermal and electrical energy, through rice husk generated in the rice mill itself. With these considerations in view, the financial viability of electricity generation using rice husk gasification–dual fuel engine–generator route has been investigated in the following section.

Table 2. Energy demand of rice processing operations

S. No.	Operation	System/Method	Energy Demand, MJ/t Raw	Energy Demand, MJ/t Parboiled
1	Milling[a]	Huller	144	164
		Sheller	108	123
		Modern mill	79.2	90
2	Parboiling[b]	Single steaming		241
		Double steaming		391
		Open drum		391
		Hot soaking and steaming		425
		Pressure parboiling		271
3	Drying[b]			827

[a] Demand is for mechanical energy indicated in terms of electricity i.e. MJ/tonne of paddy.

[b] Demand indicated is useful thermal energy demand in terms of MJ/tonne of paddy; In addition, mechanical energy @ 28.8 and 86.4 MJ/t may be required for material handling during parboiling and drying operations respectively.

Source: Refs 9 and 10.

5. FINANCIAL ANALYSIS

An attempt has been made to estimate the unit cost of electricity (UCE) obtained from rice husk using gasification–dual fuel engine–generator route (in Rs/kWh). For this purpose, the amounts of husk and diesel required to produce one unit of electricity are determined. These would primarily depend upon the efficiency of the diesel engine in independent and dual-fuel mode as well as the efficiencies of the gasifier and the generator. Once these amounts are known, standard procedures of engineering economics may be used to determine the UCE for a given set of input parameters (details of the financial analysis are given in the Appendix).

In order to study the impact of any variation in the choice of numerical values of the input variables, a sensitivity analysis was also undertaken. Sensitivity of UCE with respect to discount rate, useful life of gasifier, diesel replacement factor and the efficiency of gasifier was considered specifically.

6. RESULTS AND DISCUSSION

At the very outset it may be pointed out that there is a general lack of data relating to rice processing operations[6] in India. There are wide variations in the reported values of energy intensities of rice milling operations.[10, 19] Though data on the performance of rice husk gasification systems in many countries is available,[20] very limited data is available regarding the performance characteristics of rice husk-based gasifier generator systems in India. Therefore, the results presented below may be considered merely as indicators of emerging trends.

6.1. *Paddy production and husk availability*

Time variation of paddy production based on the regression fit obtained earlier (eqn (1)) is depicted in Fig. 1. Assuming that 90% of paddy produced is processed into rice, the husk availability has been computed at three levels of HPR (0.15, 0.20 and 0.25). It is found that for the year 1996, the energy potential of husk generated (22.4×10^6 t) would be about 300 PJ (HPR = 0.2 and CV = 13.4 MJ/kg). Statewise availability of husk at different HPR is presented in Table 3 and seasonal distribution of available energy potential from husk in Table 4.

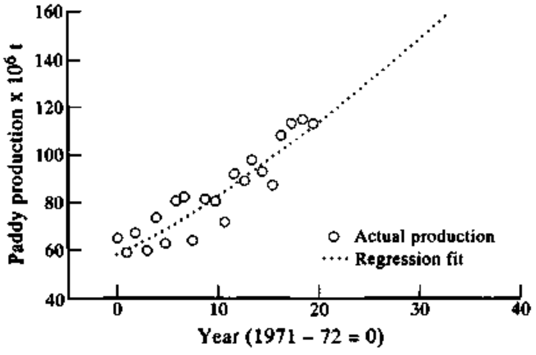


Fig. 1. Time variation of paddy production in India.

Table 3. Estimated state-wise availability of rice husk (million tonnes)

S. No.	State	Husk-to-paddy ratio (HPR)		
		0.15	0.20	0.25
1	Andhra Pradesh	2.0	2.6	3.3
2	Assam	0.7	0.9	1.1
3	Bihar	1.3	1.8	2.2
4	Gujarat	0.2	0.2	0.3
5	Haryana	0.4	0.5	0.6
6	Karnataka	0.5	0.7	0.8
7	Kerala	0.2	0.3	0.4
8	Madhya Pradesh	1.2	1.5	1.9
9	Maharashtra	0.5	0.6	0.8
10	Orissa	1.1	1.4	1.8
11	Punjab	1.3	1.8	2.2
12	Rajasthan	0.03	0.04	0.05
13	Tamil Nadu	1.2	1.6	2.0
14	Uttar Pradesh	2.1	2.8	3.5
15	West Bengal	2.1	2.8	3.5
	All India	14.6	19.5	24.4

N.B. Paddy production data for the year 1990–91[1] has been used.

6.2. *Utilisation of husk as an energy source for rice processing*

In rice processing energy is primarily required for parboiling, drying and milling operations. The demand varies with capacity of the rice mill, type of rice (raw or parboiled), method of parboiling used etc. Similarly the energy supply potential of husk depends on the capacity of the rice mill, husk collection efficiency, HPR, CV of husk and the efficiency of energy conversion/utilisation devices used. Taking all these factors into consideration, nomographs have been

Table 4. Seasonal variation of estimated available energy potential of rice husk

S. No.	Husk to paddy ratio	Calorific value of husk, MJ/kg	Available energy potential, TJ	
			Kharif harvest	Rabi harvest
1	0.15	12.6	124 951	15 016
2		13.4	133 281	16 017
3		14.2	141 611	17 018
4	0.20	12.6	166 601	20 021
5		13.4	177 708	21 356
6		14.2	188 815	22 691
7	0.25	12.6	208 251	25 027
8		13.4	222 135	26 695
9		14.2	236 018	28 363

N.B. (i) Paddy production data for the year 1990–91[1] has been used.

(ii) Kharif harvest time generally is Oct–Nov, while for Rabi it is Mar–Apr.

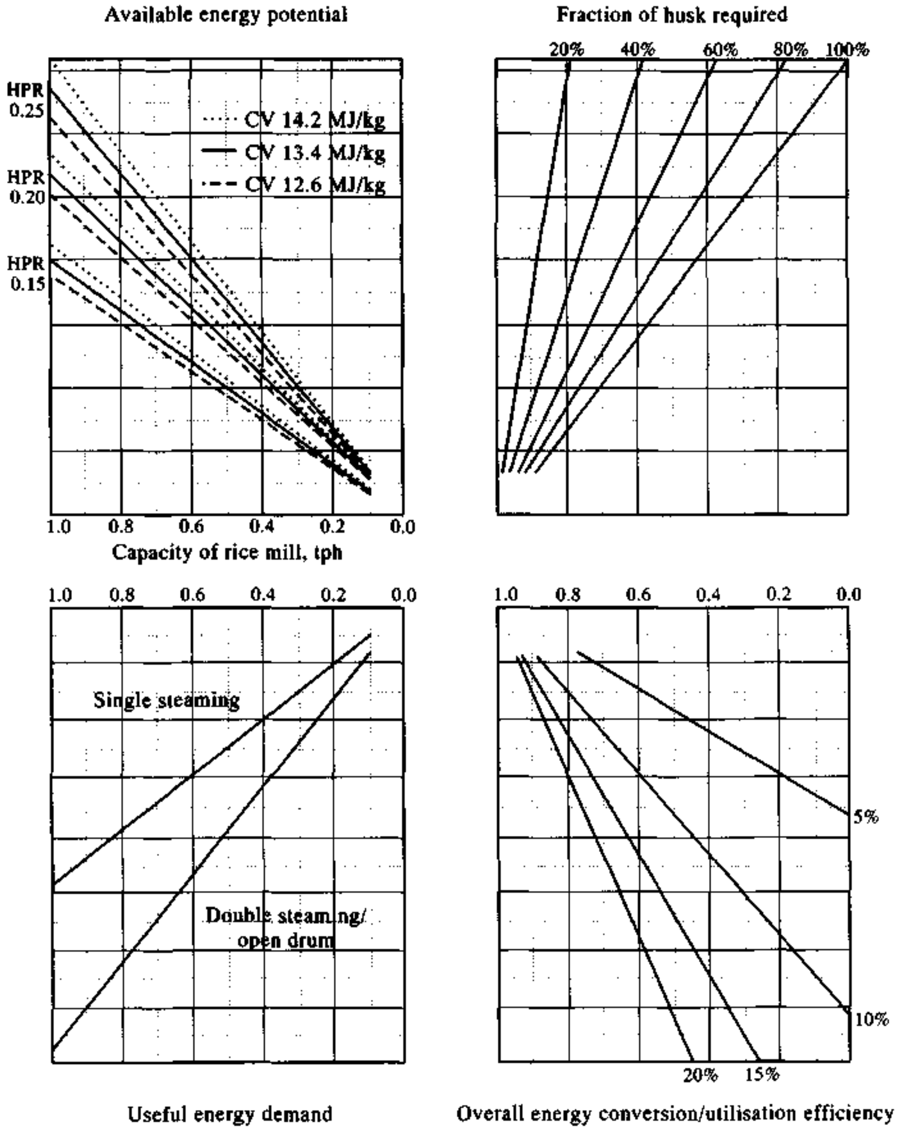


Fig. 2. Nomograph for estimation of fraction of husk required to meet thermal energy demand of parboiling operation in huller and sheller type rice mills.

developed for estimating the fraction of husk required to meet the energy demand of parboiling, drying or milling operations in a rice mill. The nomographs are presented as Figs 2 and 3 for parboiling operation and Figs 4 and 5 for mechanical energy for milling and other operations. It may be noted that Figs 2 and 4 are for low capacity rice mills (hullers and shellers) using traditional methods of parboiling/milling. On the other hand, Figs 3 and 5 correspond to modern rice mills using improved methods of parboiling/milling. In drawing the nomographs, the values of overall energy conversion/utilisation efficiencies have been used accordingly.

For estimating the fraction of husk that would be required to meet the energy demand of a particular operation by using the nomograph, one would need to know the capacity of the rice mill, HPR, CV of rice husk and overall efficiency of energy conversion/utilisation devices used. As an example, if the case of a 2 t/h rice mill is being considered for parboiling operation, then one would start from points S1 and D1 in Fig. 3. Following the upward arrow from S1 and selecting the HPR of the paddy being processed (say 0.20) and the CV of husk (say 13.4 MJ/kg), one reaches point S2 in the graph on "Available Energy Potential". Similarly, following the downward arrow from D1 and selecting the method of parboiling being practised (say hot soaking and steaming), one reaches point D2 in the graph on "Useful Energy Demand". From D2, following the horizontal arrow and selecting the overall energy conversion/utilisation efficiency of the devices used for parboiling operation (say 40%), one reaches point D3 in the graph on "Overall Energy Conversion/Utilisation Efficiency". The point of intersection of the vertical line from D3 and horizontal line from S2 would indicate the fraction of husk required (~ 40%) to meet the thermal energy demand of parboiling operation for the case under consideration. In case this point of intersection lies between two curves in the graph on "Fraction of Husk Required"; it can be estimated by interpolation.

6.3. *Availability of rice husk for electricity generation*

Table 5 presents the quantities of rice husk available in typical rice mills of huller, sheller and modern type in India. It also indicates the surplus/deficit in these quantities if husk is used for meeting electrical energy demand of raw rice milling at different overall energy conversion efficiencies.

6.4. *Unit cost of electricity*

It is expected that the cost of rice husk and the annual operating hours of the rice mill (and hence that of the husk gasifier–dual fuel engine–generator system) would crucially affect the unit cost of electricity produced by the husk gasification route. However, it is the sensitivity of the UCE to the costs of energy conversion equipment and/or fuels which is of considerable importance to permit a realistic feasibility evaluation of the emerging technology with the

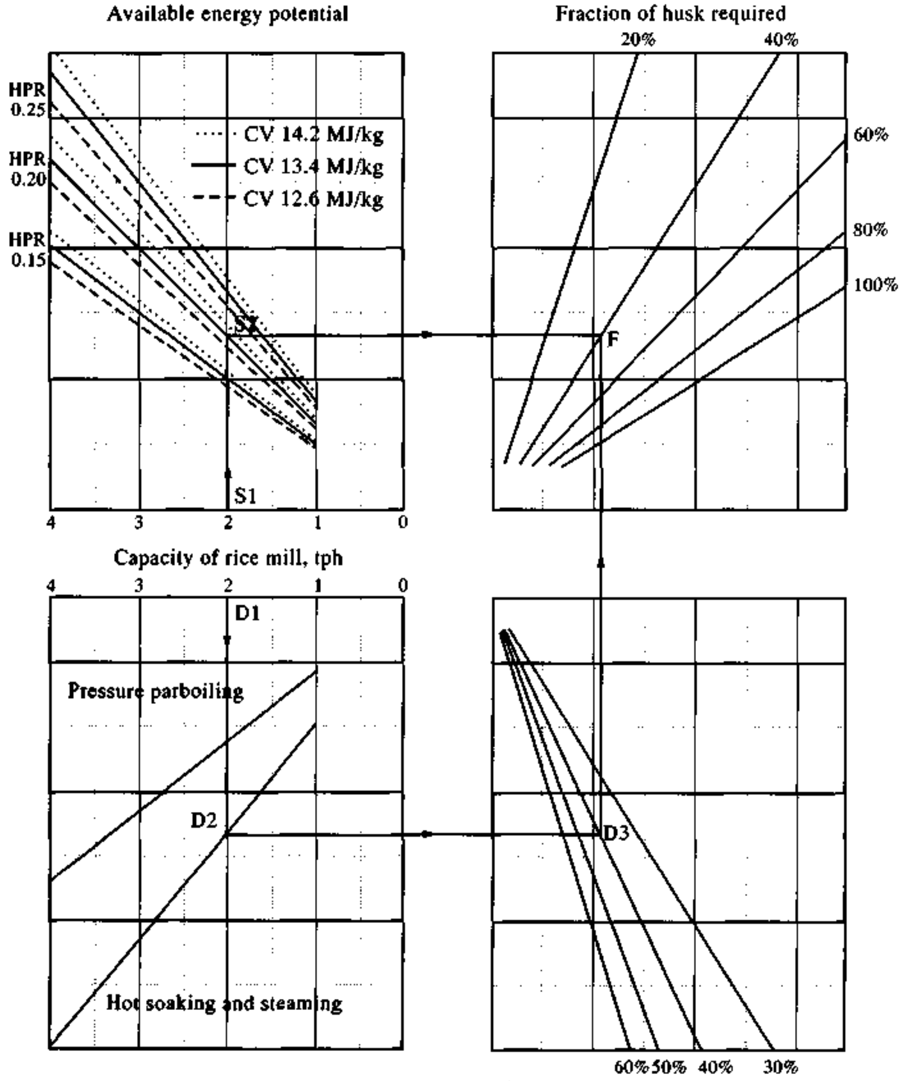
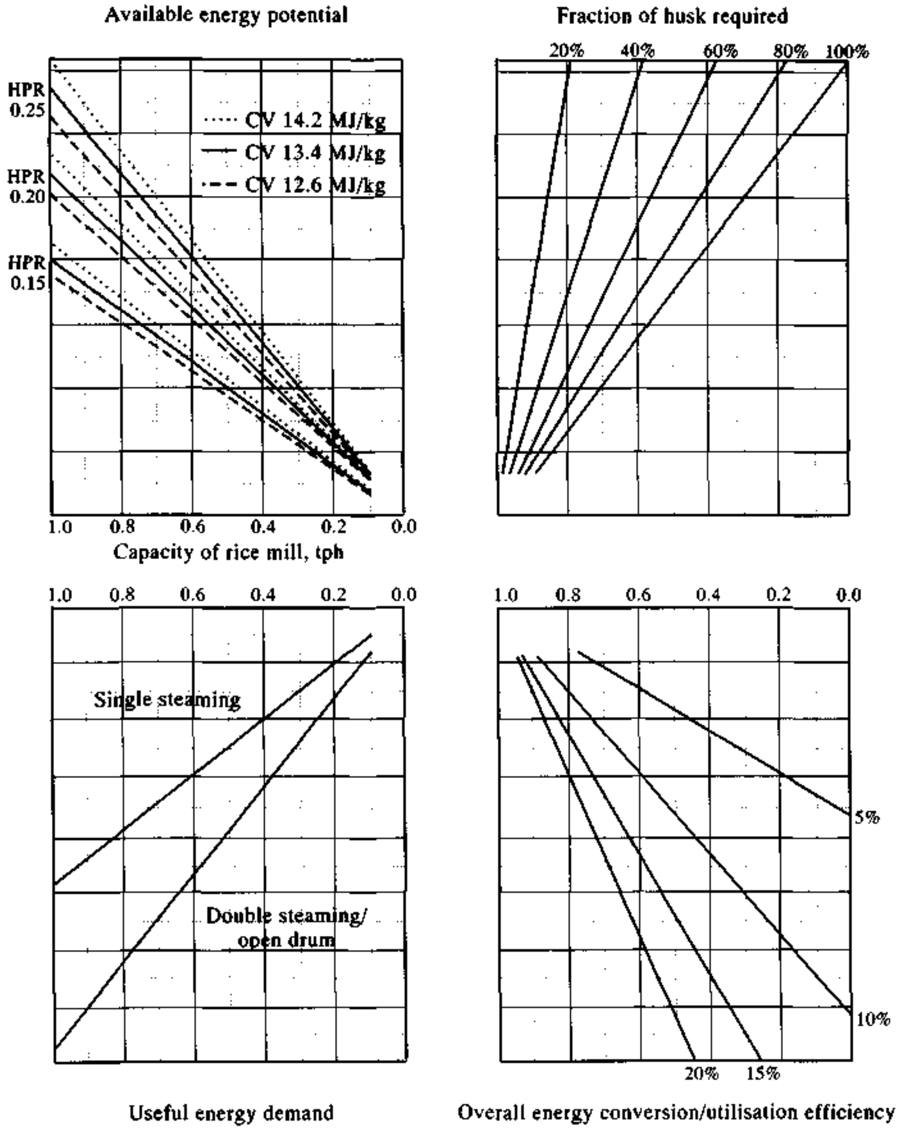


Fig. 3. Nomograph for estimation of fraction of husk required to meet thermal energy demand of parboiling operation in modern rice mills.



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For estimating the fraction of husk that would be required to meet the energy demand of a particular operation by using the nomograph, one would need to know the capacity of the rice mill, HPR, CV of rice husk and overall efficiency of energy conversion/utilisation devices used. As an example, if the case of a 2 t/h rice mill is being considered for parboiling operation, then one would start from points S1 and D1 in Fig. 3. Following the upward arrow from S1 and selecting the HPR of the paddy being processed (say 0.20) and the CV of husk (say 13.4 MJ/kg), one reaches point S2 in the graph on "Available Energy Potential". Similarly, following the downward arrow from D1 and selecting the method of parboiling being practised (say hot soaking and steaming), one reaches point D2 in the graph on "Useful Energy Demand". From D2, following the horizontal arrow and selecting the overall increases with increase in annual hours of operation. When husk cost is Rs 1000/t it is not at all feasible to use it for electricity generation in preference over diesel generator sets. The break-even cost(s) of rice husk at which UCE from a diesel generator set is equal to the UCE from a rice husk gasifier-based power generation system is presented in Table 7. The calculations have been made for two typical values of annual operating hours, 1200 and 2400 h, which are the average annual operating hours of the huller/sheller and modern rice mills respectively in India.[5] In this table the values given against a particular power rating represent the maximum price which can be paid for the rice husk as feedstock for the gasifier–dfe–generator system without running into a financial loss as compared with the diesel generator system. For example, if the system operates for 1200 h in a year, the electricity provided by a 40 kW rice husk gasifier-based power generation system would always be cheaper than that provided by a diesel generator system of similar capacity, as long as the rice husk cost is less than Rs 300/t. As regards the effect of annual hours of operation for the same 40 kW system, rice husk costs up to Rs 515/t can be paid without incurring a financial loss compared to the diesel-generated electricity, if the annual operating hours are 2400. It may however be noted that for power ratings up to 10 kW, a rice husk gasifier-based power generation system operat-

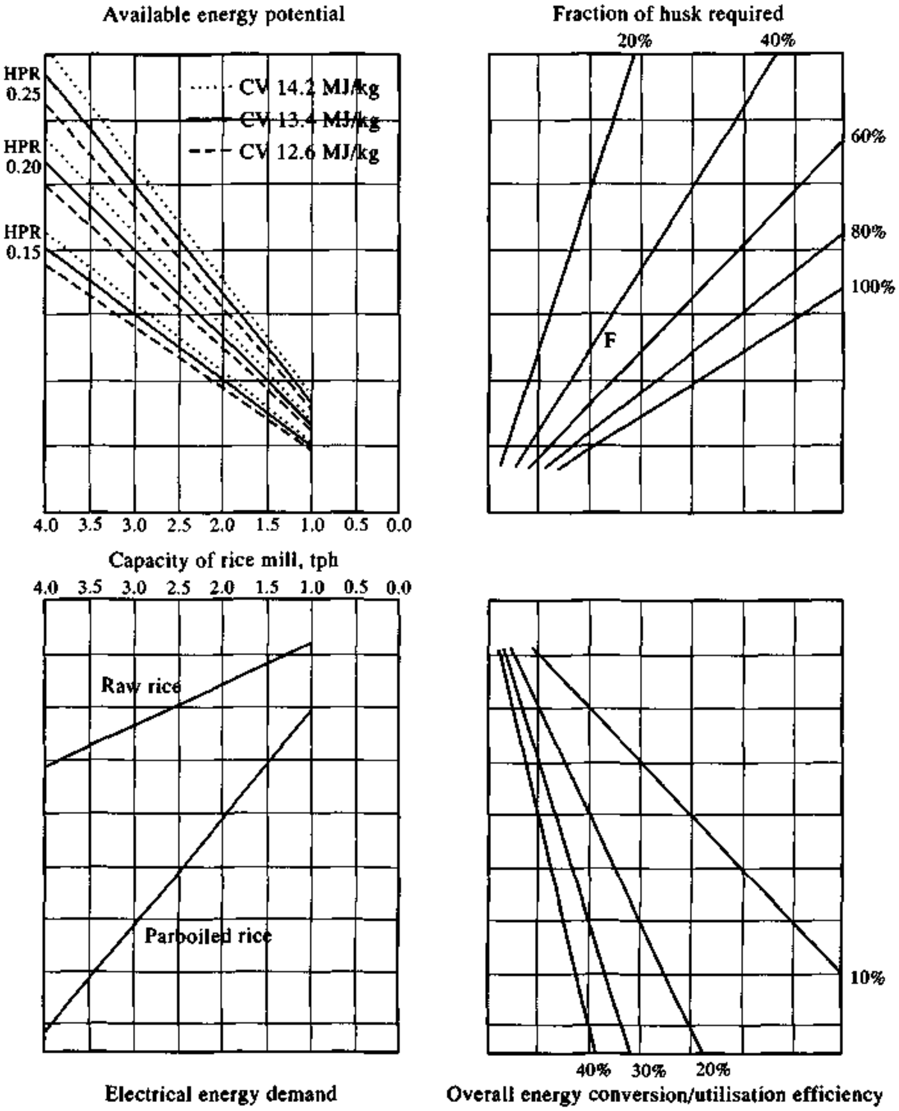

Fig. 5. Nomograph for estimation of fraction of husk required to meet electrical energy demand in modern rice mills.

Table 5. Surplus/deficit of rice husk in typical rice mills after meeting electrical energy demand of raw rice milling

S. No.	Type of rice mill	Average capacity, t/h	Average annual operating hours	Annual availability of rice husk[a], t	Annual electrical energy demand, 10^3 kWh	Overall efficiency of conversion into electricity, %	Annual surplus (+) or deficit (-) of husk,[b] t
1	Huller	0.25	1200	60	12	5	(−) 4.48
						10	(+) 27.76
						15	(+) 38.51
						20	(+) 43.88
2	Sheller	0.75	1200	180	27	5	(+) 34.93
						10	(+) 107.46
						15	(+) 131.64
						20	(+) 143.73
3	Modern mill	2.00	2400	960	105.6	5	(+) 392.60
						10	(+) 676.30
						15	(+) 770.87
						20	(+) 818.15

[a] Based on HPR of 0.20.
[b] Calculations are based on CV of rice husk = 13.4 MJ/kg.

ing for 1200 h annually will be costlier than diesel generator system even when the husk is available free of cost.

The sensitivity analysis of unit cost of electricity from the husk gasification generation route was carried out for power ratings of 10, 20 and 100 kW, which are suitable for huller, sheller and modern rice mills of 0.25, 0.5 and 2 t/h capacity respectively. The UCE is most sensitive to the efficiency of gasification, followed by derating factor, useful life of gasifier, diesel replacement factor and the discount rate. Results of sensitivity analysis in respect of 100 kW unit are depicted in Fig. 7.

7. CONCLUSIONS

Available energy potential of rice husk in India is of the order of 300 PJ per year. There are seasonal, geographical distribution and other variations in the availability of this potential. Its use in the rice processing industry avoids the need (and hence cost) of handling and transportation etc. A substantial proportion of the energy demand of rice processing operations in India can be met with the currently available technologies for exploitation of the energy potential of husk. Nomographs developed in the present work can be used to estimate the fraction of husk required to meet

Table 6. Numerical values of parameters used for financial analysis

S. No.	Parameter	Value
1	Capital cost, gasifier	Rs 32 000–550 000
2	Capital cost, DG set	Rs 34 000–950 000
3	Capital cost, total	Rs 66 000–1 500 000
4	Discount rate	12%
5	Useful lifetime, gasifier	24 000 h
6	Useful lifetime, DG set, in dual fuel mode	16 000 h
7	Useful lifetime, DG set, in independent mode	48 000 h
8	Maintenance cost, fraction of total cost	10%
9	Unit cost, diesel	Rs 8900/t
10	Unit cost, husk	Rs 200, 600 and 1000 per tonne
11	Diesel replacement factor	0.70
12	Derating factor	0.75
13	Efficiency of diesel engine	0.33
14	Efficiency of gasification	0.55
15	Efficiency of generator	0.875
16	Calorific value, diesel	42 700 MJ/t
17	Calorific value, husk	13 400 MJ/t
18	Power rating	3–150 kW
19	Annual hours of operation	1200 and 2400 h

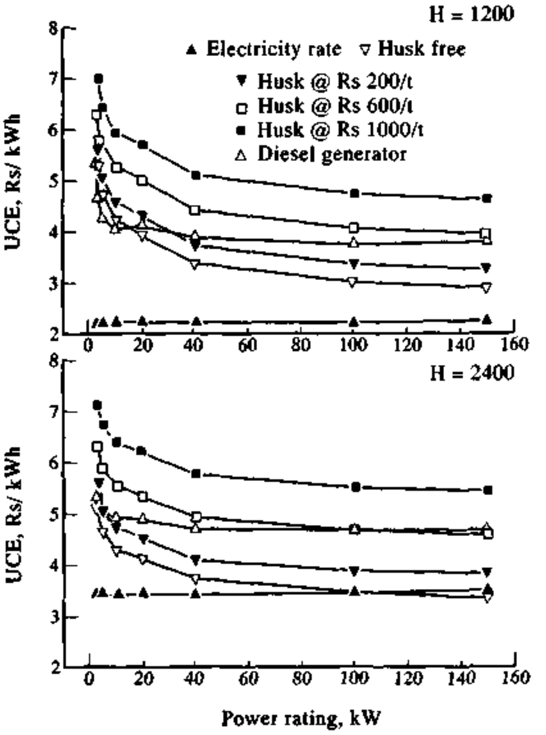

Fig. 6. Variation of unit cost of electricity (UCE) with power rating at 1200 and 2400 annual operating hours.

the energy demands of parboiling, drying and milling operations. The unit cost of electricity generated by the husk gasification–dfe–generator route varies between Rs 2/kWh and Rs 7/kWh at different power ratings (suitable for most of the rice mills in India), annual operating hours and costs assigned to rice husk. With the cost and performance data assumed, it may be concluded that the rice husk-based power generation is not financially attractive compared with utility-supplied electricity, but it compares favourably with diesel-generated electricity, particularly at higher power ratings and annual operating hours. Of course in future, with the availability of more realistic input data based on increased field experience, the method outlined in the present work can be used to arrive at more specific conclusions.

Table 7. Breakeven cost of rice husk for meeting electrical energy demand of rice processing through rice husk gasification–dfe–generator route compared to diesel generator set

		Breakeven cost of rice husk, Rs/t	
S. No.	Power rating, kW	H = 1200	H = 2400
1	3	*	85
2	5	*	171
3	10	*	289
4	20	98	379
5	40	299	515
6	100	446	606
7	150	535	661

*In these cases UCE from husk gasification–dfe–generator route is higher than that from diesel generator, even when the husk is available free of cost.

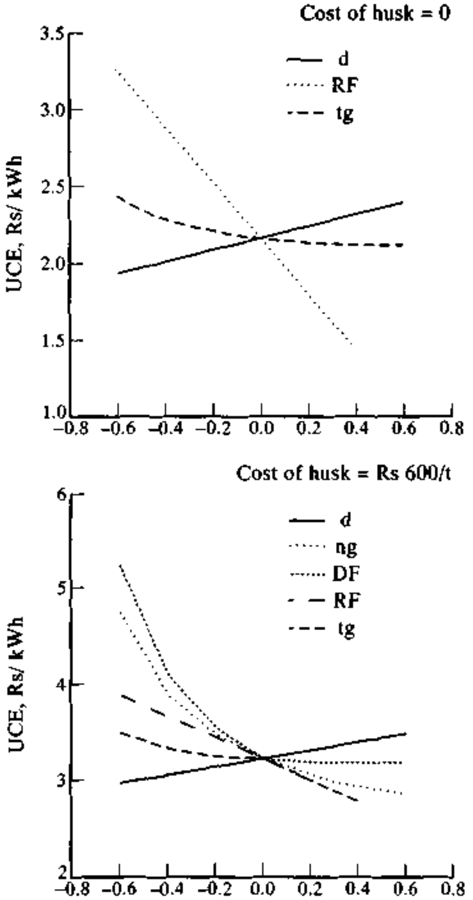

Fig. 7. Sensitivity of unit cost of electricity (UCE) generated from 100 kW rice husk gasifier–dfe–generator system.

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APPENDIX: DETERMINATION OF UNIT COST OF ELECTRICITY FOR A RICE HUSK GASIFIER-DUAL FUEL ENGINE–GENERATOR SYSTEM

As mentioned in the main text, the rice husk-based power generation unit considered in this work consists of a gasifier, a dual-fuel engine and a generator. Dual-fuel engines (dfe) are normally diesel engines modified to operate in dual-fuel mode. The efficiency of such modified engines (η_{dfe}) is generally less than that of the diesel engine (η_d)[21] (though some researchers have reported an increase in efficiency). Therefore, the efficiency of the engine in dual-fuel mode can be expressed as a product of the efficiency in diesel mode and a derating factor (DF), i.e.

$$\eta_{dfe} = \eta_d \times DF \tag{A1}$$

The required total energy input (E_T, in MJ) to a dfe–generator system for generating one unit of electricity (1 kWh = 3.6 MJ) can be expressed as

$$E_T = \frac{3.6}{\eta_{dfe} \times \eta_a} \tag{A2}$$

where η_a is the efficiency of the generator. Substituting eqn. (A1) in eqn. (A2), we have

$$E_T = \frac{3.6}{\eta_d \times DF \times \eta_a} \tag{A3}$$

The performance of a dfe is characterised by a diesel substitution or diesel saving[21, 22] or diesel replacement factor which, in effect, indicates the proportion of diesel input that is replaced by the second fuel. With RF representing this factor, the energy input in the form of diesel (E_d, in MJ) to the dfe to generate one unit of electricity (3.6 MJ) can be expressed as

$$E_d = \frac{3.6}{\eta_d \times \eta_a} \times (1 - RF) \tag{A4}$$

The contribution of the producer gas (E_{pg}, in MJ) to the total energy input to the dfe–generator system can therefore be expressed as

$$E_{pg} = E_T - E_d \tag{A5}$$

$$= \frac{3.6}{\eta_d \times \eta_a}\left[\frac{1}{DF} - (1 - RF)\right] \tag{A6}$$

The quantities of diesel (Q_d, in kg) and husk (Q_h, in kg) required for generating one unit of electricity (3.6 MJ) can now be expressed as

$$Q_d = \frac{E_d}{CV_d} = \frac{(1 - RF) \times 3.6}{\eta_d \times \eta_a \times CV_d} \tag{A7}$$

$$Q_h = \frac{E_{pg}}{\eta_g \times CV_h} = \frac{\left[\frac{1}{DF} - (1 - RF)\right] \times 3.6}{\eta_g \times CV_h \times \eta_d \times \eta_a} \tag{A8}$$

respectively. CV_d and CV_h represent the calorific values of diesel and husk respectively (in MJ/kg) and η_g represents the thermal efficiency of rice husk gasification.

Having worked out the quantities of fuels required, UCE (in Rs/kWh) can now be calculated from the following expression:

$$\begin{aligned} UCE = {} & \frac{1}{PR \times H}[(CC_g \times CRF_g) \\ & + (CC_{dg} \times CRF_{dg}) + (CC_T \times F_{mc})] \\ & + \frac{UC_d \times (1 - RF) \times 3.6}{\eta_d \times \eta_a \times CV_d} \\ & + \frac{UC_h \times \left[\frac{1}{DF} - (1 - RF)\right] \times 3.6}{\eta_g \times CV_h \times \eta_d \times \eta_a} \end{aligned} \tag{A9}$$

with

$$CRF_g = [\{d \times (1 + d)^{(tg/H)}\}/\{(1 + d)^{(tg/H)} - 1\}] \tag{A10}$$

$$CRF_{dg} = [\{d \times (1 + d)^{(tdg/H)}\}/\{(1 + d)^{(tdg/H)} - 1\}\} \tag{A11}$$

In eqns (A9) – (A11), CC_g and CC_{dg} represent the capital costs (in Rs) of gasifier and dfe–generator set respectively, CC_T the total capital cost (in Rs) of the gasifier–dfe–generator system; F_{mc}, maintenance cost expressed as a fraction of CC_T; UC_d and UC_h, unit costs (in Rs/kg) of diesel and husk respectively; PR, power rating (in kW) of the husk gasification–dfe–generator system; and H, the annual operating hours; CRF_g and CRF_{dg} respective capital recovery factors for gasifier and dfe–generator set; d the annual discount rate (in fraction), tg and tdg the useful lifetimes of gasifier and dfe–generator sets in hours respectively.