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The Effect of Quality Differentials on Integration of the Seaborne Thermal Coal Market

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Abstract

This paper examines the structural components that characterise the price behaviour and perceived arbitrage of thermal coal delivered to India from Indonesia relative to prices from South Africa and Australia. Index coal prices favour imports of Indonesian brands however significant volumes are also imported from South Africa and Australia. The Indian energy market is characterised by homogeneous power plant technologies and coal procurement strategies which allows for seaborne coal brands to be benchmarked against a specific quality. In this study the index price of Australian, South African and Indonesian thermal coal is transformed using freight and quality adjustments to derive a measure for the expected electrical energy output known as delivered units of energy. The degree of market integration in the seaborne thermal coal market using the new price series is tested using cointegration analysis. The degree of convergence and the absolute level of arbitrage between major coal exporters is also tested using a recursive approach in the form of a Kalman filter. Using the transformation to units of energy the market is shown to be relatively integrated and the apparent arbitrage between exporters disappears when accounting for freight and coal quality differentials. This study challenges the common notion that thermal coal importers source material that has a freight price advantage and highlights the importance of coal quality differentials in power production.

JEL Classification: C12, C51, Q41
Key words: Arbitrage, thermal coal, energy, Kalman filter.

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1. Introduction

Liberalisation of the global seaborne thermal coal market in recent years due to standardised energy coal supply contracts, increased liquidity in coal forward contracts and consolidated freight routes has enhanced the ability for energy short countries to import energy coal economically. The integration of the coal industry across geographic regions has been shown to be sufficient to warrant the claim that a single economic market for thermal coal exists. Evidence of the strength of this integration is based on the stable long-run cointegration relationship of delivered (CIF) thermal coal spot prices to Japan and Europe in Warell (2006). Further evidence of global integration was uncovered via the strong convergence path demonstrated by long-run cointegration and Kalman filter analysis of free on board (FOB) thermal coal spot prices from Australia, China, Colombia, Indonesia, Poland and South Africa in Li et.al. (2010).

Thermal coal however is not a homogenous product so detecting the degree of price convergence for heterogeneous parcels of free on board (FOB) thermal coal may not offer the most precise measure of market integration. For instance Indonesian thermal coal is typically high in moisture and low in ash while Australian and South African thermal coals both generally exhibit the reverse. Both ash and moisture affect the energy content of the coal in specific ways. The move to index-based pricing of FOB thermal coal across main exporting regions has limited the variability between the supply of thermal coal and has, to some degree, standardised the quality of exported coal. However the quality specifications of individual brands of coal remain quite different and will generally sell at a significant premium or discount to the index price. Freight costs to thermal coal consumers also vary based on vessel size and voyage duration and constitute a sizeable portion of the delivered cost. Therefore the real delivered price of thermal coal depends on coal quality characteristics and freight costs. To accurately analyse the true degree of integration in the seaborne thermal coal market we therefore need to correct for freight and quality differentials. Hence we propose to transform the cost of delivered coal to a cost per unit of delivered energy and then test for the true degree of integration in the thermal coal market used for power production.

From the perspective of a thermal power plant, the procurement of thermal coal is essentially the procurement of delivered units of energy for consumption, rather than a given volume of thermal coal. Power producers quantify internal efficiency in terms of energy output which is highly dependent on the optimal quality of the delivered fuel. Power plants convert chemical energy to thermal energy, mechanical energy and then electrical energy. This analysis seeks more robust evidence of convergence across the global thermal coal market in terms of the output price of energy transformed from units of input fuel. The study employs cointegration analysis and Kalman filter testing seeking evidence of market convergence for thermal coal normalised into parcels of delivered energy from the perspective of a thermal power plant operator.

In order to select an appropriate market in which to examine price convergence using units of energy rather than parcels of coal, it is critical to focus on a region where the major coal consumers seek a relatively homogenous level of coal energy content. This means a region where the thermal power plants are similar in type and have similar fuel requirements, and where only very minor differences in quality need to be blended out prior to consumption. We therefore need to select a thermal coal importing country whose portfolio of power plants are relatively homogenous and each plant is generally indifferent to the source of the coal, so long as it meets the minimum specification upon delivery. Unlike power plants in Europe and Japan, many Indian coal plants are being designed and built using Chinese boiler technology aimed at a fairly specific grade of coal for consumption. The newer plant specifications dictate that Indian domestic coal is an unsuitable fuel for combustion due to the low energy content of domestic coal. This removes price pressures from domestic coal suppliers which impacts prices and may bias the analysis. All major Indian power producers employ similar boiler technologies so there are minimal differences across the required specifications of imported coal, and the fact that these major plants lie mostly on India’s coastline while domestic coal mines are located a significant distance inland highlights the imperative to rely on imported coal. The countries who export thermal coal to India are mainly Indonesia, South Africa and Australia with sporadic shipments of coal from other exporters such as Russia and Colombia. Observations of historical FOB coal prices from India’s main suppliers shows significant arbitrage advantages for Indonesian producers relative to Australian and South African producers. We seek evidence of persistence of price arbitrage in the thermal coal market which would undermine the prospects for an integrated seaborne coal market.

Thermal coal FOB prices for Australia, Indonesia and South Africa for the period 2006 to 2010 are used and added to the relevant voyage charter freight rates for Panamax size vessels for the routes Newcastle (Australia) to East Coast India, Kalimantan (Indonesia) to East Coast India and Richards Bay (South Africa) to West Coast India over the same period to obtain delivered (cost and freight or CFR) prices. Only Panamax freight costs are used since this is the maximum draft allowable for vessels at Indian coal ports over the observation period. The CFR prices are then converted into a corresponding cost per unit of energy based on coal quality and thermal power plant efficiency. The reference index for each source of coal is called delivered units of energy (DUE) which employs a thermal power plant energy conversion based on an energy content model, from which the true cost of fuel normalised against the electricity output is obtained.

Cointegration tests and convergence analysis using a Kalman filter of the resulting price series shows that the thermal coal market is significantly integrated when the coal prices are normalised to represent the true cost of fuel for electricity production. The results from Warell (2006) and Li et.al. (2010) detect a somewhat general level of thermal coal market integration however this study indicates that the market is strongly integrated when coal quality differences are eliminated through a conversion of FOB prices to delivered units of energy.

Section 2 discusses the nature of the seaborne thermal coal market and the range of thermal coal qualities that affect power plant efficiency and electricity output. Section 3 introduces the data and discusses the process for transforming parcels of thermal coal into delivered units of energy. Section 4 discusses the econometric methodology to detect the degree of market integration using a measure for cointegration. Section 5 presents the results and tests for the degree of convergence and arbitrage across each price series using a Kalman filter. Section 6 offers some concluding remarks.

2. Behaviour of International Coal Exporters and Indian Thermal Power Producers

In the Asian region it is anticipated that the acceleration of economic development will continue generate increased demand for thermal coal imports. A major new importer of thermal coal in the Asian region is India. India’s power sector is expected to face structural energy shortages as a result of expansions in the thermal power sector exceeding domestic coal production growth. Over the period 2004-10 Indian power producers embarked on a program to acquire thermal coal supply from the major coal exporting countries to fill the supply gap. The countries in close proximity to India with thermal coal available for export are primarily Indonesia, South Africa and Australia however other exporters such as Russia and Colombia have occasionally exported coal to India. The grade of coal required for the new generation power plants in India typically exceeds the quality specifications of domestic coal thus guaranteeing a market for imported coal.

The rapid growth in industrialisation and urbanisation has played a leading role in India’s rising demand for power. Indian thermal power production has undergone rapid expansion. Total thermal power generation capacity was 98GW in 2008 with coal-based capacity accounting for 80.4GW (82 per cent of total capacity) and gas-based capacity accounting for

16.5GW (17 per cent of total capacity), see IEA (2009a). Of the total energy capacity, state government-owned power units contribute 50 per cent, central government-owned units contribute 33 per cent and privately-owned plants contribute the remaining 17 per cent, see Swarup (2009). Thermal coal import growth to India has also increased as demand for higher grade seaborne thermal coal is consumed in sponge iron and cement production. The sponge iron industry consumes 4 per cent of the country's total thermal coal but accounts for 11 per cent of total imported coal and the cement industry accounts for 26 per cent of India's total coal imports. For this analysis we will focus on energy coal used in thermal power production only.

Almost the entire Indian coal supply from domestic sources is of bituminous quality with less than 4500kg/kcal calorific value (CV) on a net as received basis (NAR). Even the newly allocated captive mines produce coal with a CV of less than 4500kg/kcal. However the growing power sector using newer boiler technologies require sub-bituminous and bituminous coal with a CV of between 5300-5500kg/kcal NAR to operate at optimal levels. Thermal coal with CV of 5400-6000kg/kcal NAR are the predominant grades of coal traded on the seaborne thermal coal market. The steep rise in demand for higher grade sub-bituminous and bituminous coal in India is driven by very large power plant construction (modestly referred to as ultra-mega power plants or UMPPs) on India's coasts each with a capacity of over 4GW. The main thermal coal requirements for these units are met through imports as they are located at considerable distances from existing domestic mines and are built to optimise power capacity using higher grade coal. Assisting the growth in India's power sector are key government initiatives such as import duty concessions on capital goods, waivers of local taxes and a 100 per cent tax rebate for ten years, as well as 100 per cent foreign direct investment being permitted under the automatic approval route, see Swarup (2009).

The range of specifications for higher grade imported coal has occasionally led to significant price differentials between the major exporting countries implying the existence of price arbitrage. The delivered price of Indonesian coal has historically been less than the price of South African and Australian coal due to both a cost of production and freight price advantage. Due to this price advantage it is generally assumed that Indian power producers have preferred Indonesian sourced thermal coal to South African and Australian coal. However imports from South Africa and Australia have accelerated over the period 2006-10 despite the large price differential. Figure 1 illustrates total coal imports to India by exporter and Figure 2 shows the price differential of Australian and South African coal relative to Indonesian coal on both a FOB and CFR basis from 2006-10. While absolute thermal coal prices fell during 2009 imports to India continued to grow in line with the price inelastic baseload electricity growth in thermal power production.

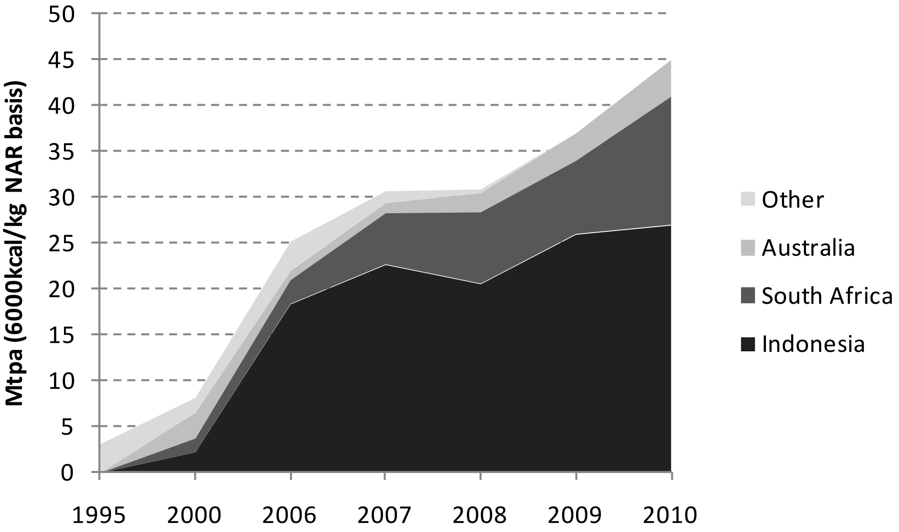

Figure 1: Import tonnages to India by exporter normalised to 6000kcal/kg NAR basis 1995-2010. Source: IEA Coal Information 2009, Wood Mackenzie.

This study will show that the delivered energy content and associated quality of coal used for power production are major factors that influence the true level of integration of the thermal coal market. Furthermore the persistent arbitrage in spot FOB prices across imports of thermal coal to India as shown in Figure 2 is not a factor of trading company buying behaviour or producer marketing behaviour but can be explained via the relative levels of delivered energy content.

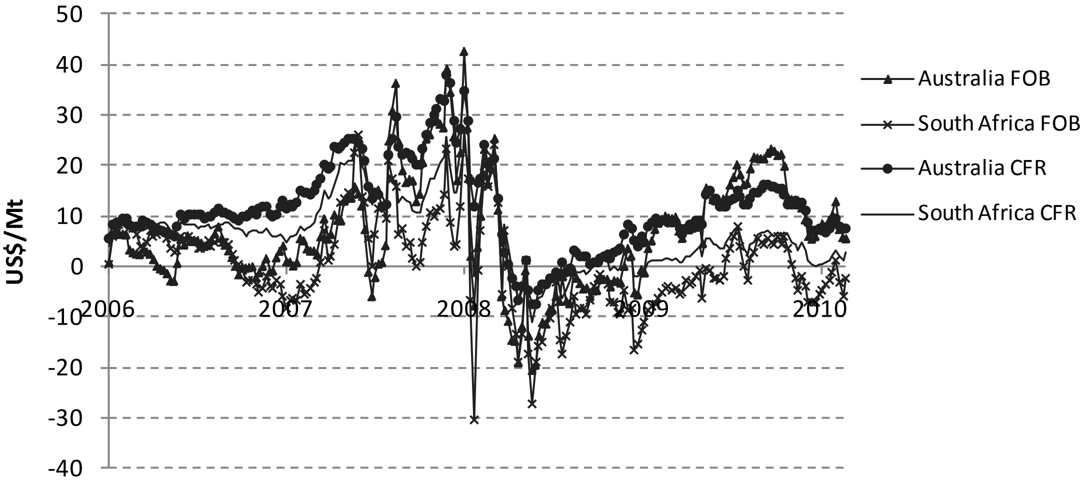

Figure 2: Energy-adjusted spot FOB and period-ahead CFR price differentials (US$/Mt) between Australia and South Africa to Indonesia over 2006-10.

2.1 Why India?

India is the ideal representative market to detect coal price convergence for a number of reasons. Firstly the consumption of imported thermal coal relies on shipments with relatively similar levels of energy content. While there are usually large differences in other quality features of coal exported from Australia, South Africa and Indonesia which affect the thermal efficiency during combustion, the fundamental energy content remains homogenous. Secondly there are only minor differences between plant technology (boilers, turbines and generators) relying on imported coal so variation between coal import qualities is much less than for other major importers such as Japan or Europe. Thirdly the major coal traders and large coal producers have increasingly migrated to multi-source coal supply off-take contracts with Indian buyers over the past six years which allows for some flexibility in the source of the coal. This flexibility is predominantly used by producers and traders to cater for logistics inefficiencies and coal supply shortages caused by rail and port bottlenecks rather than to take advantage of the spot price differential between regions, although it is difficult to qualify this assertion across the data. Fourth, vessels importing coal to India are nearly all Panamax (70-80,000DWT) size which creates a set of level freight costs across all freight routes. Finally coal supply to India over the period 2006-10 has been largely limited to spot sales rather than long-term sales contracts which allows for easier comparison among available index prices, see Swarup (2009).

3. Export Coal Properties and Energy Content Effects

The performance of power plants and the subsequent cost of power generation are influenced by various coal properties. Specifically, coal quality impacts the cost of coal production at the mine gate as well as net power output, operating and maintenance costs and waste disposal costs at the power plant. A number of complex power generation cost models have been developed to evaluate the impact of various coal properties and to assess the 'value' of coal properties, see Juniper and Pohl (1997), Swann et.al. (1999), Koerner (2001) and Mesroghli et.al. (2009). In the context of this study, coal value refers to the value of the property to the power producer in terms of the cost savings for beneficial coal properties and costs incurred for detrimental coal properties.

3.1 Coal Characteristics and Energy

Fuel cost is the single greatest component that determines the cost of coal-fired electric power, see West (2011). Since coal is the primary fuel used for power generation in India, utility companies are naturally concerned about the costs of delivered coal. Fuel cost is usually directly linked to the heating value of the coal, which is more or less equivalent to the coal's energy content. Determining the correct heating value becomes an important commercial issue and implicitly affects the profitability of a power plant. The heating value of coal depends on the combustible matter, mainly carbon and hydrogen, in the coal and how it reacts during the combustion process. Apart from combustible matter the other main ingredients that affect plant efficiency are ash, moisture and volatile matter.

Calorific value (CV) indicates the amount of heat that is released when the coal is burned. The calorific value varies by geological age, formation, ranking and source of the coal. Calorific value is expressed in two different ways on account of the moisture in the coal. Gross Calorific Value (GCV) is the total heat released when burning coal while Net Calorific Value (NCV) is the heat energy available after eliminating the loss due to moisture. When coal burns the moisture in the coal evaporates taking away some heat of combustion which is not available for thermal power use. The moisture is in two forms; first is the inherent moisture which is entrapped within the structure of the coal, and second is the moisture exogenous to the coal's structure. Part of this moisture can evaporate under normal atmospheric conditions during its transfer from the mines to consumption at the power plant. The amount of moisture determines how much heating is required to dry the coal before it is consumed. Moisture in coal is expressed as proportion of total weight so the change in the moisture content changes the proportion of the other coal constituents and importantly, the calorific value. The relationship between NCV and GCV at constant volume is given by

$$NCV = (GCV - 0.206H)\left[\frac{100-TM}{100-IM}\right] - 0.023TM \qquad (1)$$

where *H* is the percentage of hydrogen, *TM* is the percentage of total moisture and *IM* is the percentage of inherent moisture or air-dried moisture, see ISO (1976). Both NCV and GCV are expressed in megajoules per kilogram (MJ/kg) however multiplying by 238.89 converts the NCV to kilocalories per kilogram (kcal/kg) which are the units typically specified in coal supply contracts.

Ash is the residue remaining after the combustion of coal organic matter and oxidation of the mineral matter present. Ash is therefore the incombustible material and is measured as a percentage of the air dried coal sample. Higher ash content implies both higher transport and handling costs per unit of energy and waste that, in general, requires disposal.

Volatile matter measurements do not reflect the actual amount of a given substance but rather measures the thermal decomposition of coal during heating. For instance volatile materials liberated during the heating process are water, hydrogen, carbon dioxide and many others. Volatile matter is more important for coking coal pricing differentials than for thermal coal, but have a small impact on contract price premiums or discounts to an index.

In general terms the higher the calorific value of the coal, the lesser the amount of coal required per unit of electricity produced, depending on power plant specification. Higher calorific value also generally implies higher costs for the thermal coal due to greater washing and other processing by the coal producer. This cost tends to be offset by lower costs of logistics, storage and ash disposal.

3.2 Seaborne Thermal Coal Pricing

Thermal coal prices to India from Indonesian, South African and Australian ports have been derived using thermal coal FOB spot price data for 2006-10. Indonesian thermal coal prices are based on the weekly Argus Coalindo 5500kcal/kg NAR FOB Kalimantan price data, South African thermal coal prices are based on the weekly Argus McCloskey 6000kcal/kg API4 (FOB Richard's Bay) index and Australian FOB prices are based on the weekly 6000kcal/kg GlobalCOAL Newcastle (FOB Newcastle) index. The base level energy content of most Indonesian coal is thus about 10 percent less than the energy content of both Australian and South African coal sold in the seaborne market. Each index is based on delivery within 90 days which represents the closest thing to spot prices for the supply of seaborne thermal coal. Each coal index is based on thermal coal with the main specifications outlined in Table 1.

Source	Port	CV NAR	Ash	TM	Sulphur	Vessel
Indonesia	FOB Kalimantan	5500kcal/kg	< 10%	< 18%	< 0.8%	Panamax
South Africa	FOB Richard's Bay	6000kcal/kg	< 15%	12-15%	< 1%	Panamax
Australia	FOB Newcastle	6000kcal/kg	< 14%	< 15%	< 0.75%	Panamax

Table 1: Specification of Australian, South African and Indonesian FOB thermal coal indices.

The energy content of Australian thermal export coal ranges from 4,730 to 6,860kcal/kg on a gross as received (GAR) basis. But the weighted average energy content lies very close to the Newcastle benchmark export specification of 6,322kcal/kg GAR (6,000kcal/kg NAR). Only very few mines have an energy content that varies significantly from this benchmark and most mines therefore occupy a similar place on the adjusted cost curve as on the standard curve. Based on Wood Mackenzie and AME Group data only nine of Australia's 65 thermal export coals have energy contents that deviate by more than 5% from the weighted average. The cost position of most mines varies only slightly when prices are adjusted for energy content.

Similarly the energy content of South African thermal coal exports ranges from 4,850 to 6,725kcal/kg GAR with the weighted average close to the API4 benchmark export specification of 6,260kcal/kg GAR (6,000kcal/kg NAR). The cost position of most South African mines also varies only slightly when prices are adjusted for energy content.

The energy content of Indonesian export coal ranges from 3,125 to 7,850kcal/kg GAR. With an abundance of sub-bituminous and low rank coal reserves Indonesia's weighted average energy content of 5,362kcal/kg GAR is much lower than the standard Newcastle benchmark export specification of 6,322kcal/kg GAR. The cost position of most Indonesian mines varies more than Australian and South African mines when prices are adjusted for energy content. Indonesian low rank coal is marketed as a low cost energy alternative for the seaborne thermal coal market. Production from low rank coal operations is increasing and the availability of lower cost coal from Indonesia has grown significantly since 2001, see IEA (2009b). Indonesian producers focus on cost reduction to extract low rank coal deposits as part of their wider growth strategy. This cost reduction is crucial when considering the cost of production of these coal types, and with spot price discounts of up to 40 percent below the benchmark price even accounting for energy content, low rank producers can afford to sell at very low margins as they have a long term supply strategy fuelled by a large reserve base and low costs.

While the specifications in Table 1 for Australian and South African coal are typical for European and Japanese markets, they represent a coal grade that is in excess of the optimum energy level required for power plants in India. A critical difference between Indonesian sub-bituminous coal and Australian and South African bituminous coal is the relative levels of ash and moisture. Ash levels are typically higher in Australian and South African coal while moisture levels are generally much higher in Indonesian coal. As will be discussed formally below moisture has a significant impact on the energy content of coal during the conversion process to electrical energy, and is therefore an important consideration when benchmarking price differentials. The majority of Indian thermal coal imports for power production require imported bituminous or sub-bituminous thermal coal with the minimum specifications outlined in Table 2.

CV NAR	Ash	TM	Sulphur	VM
5500kcal/kg	< 17%	< 20%	< 1%	> 27%

Table 2: Benchmark imported thermal coal specifications for Indian power producers.

Sales of thermal coal from Australia and South Africa to India will be at prices below the quoted index levels on an energy-content adjusted basis due to the lower quality of the coal. As the energy content decreases the relative proportion of ash and/or moisture and other impurities must naturally increase. The energy content benchmark of the weekly Argus Coalindo 5500kcal/kg NAR FOB Kalimantan is used as the benchmark for thermal coal sales across all three suppliers for this analysis.

Figure 3 illustrates the energy-adjusted FOB price series for Australia, South Africa and Indonesia from 2006-10. There is significant disparity across the three indices indicating that arbitrage opportunities may be persistent in the market and at first glance the degree of market integration is questionable.

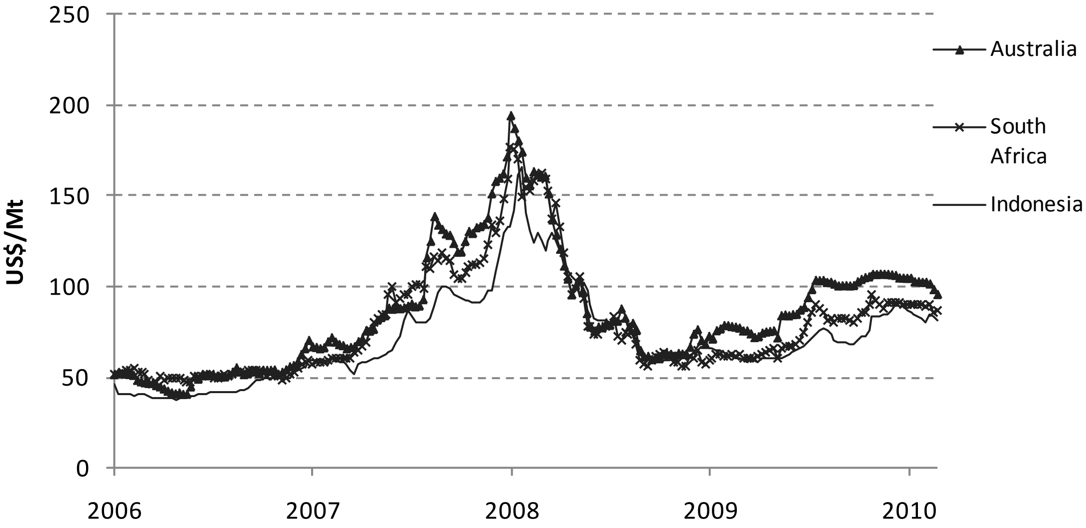

Figure 3: Energy-adjusted FOB prices (US$/Mt) for Australia, South Africa and Indonesia over 2006-10.

In order to reconstruct the price series for each index so that the FOB coal prices are adjusted for the above factors, we first need to assess the relative contribution of each factor to the energy content of coal from each region. A linear regression of specific energy (kcal/kg NAR) was conducted against total moisture (TM), inherent moisture (IM), ash, volatile matter (VM), fixed carbon (FC), sulphur (S) and hydrogen (H) to obtain an accurate estimate for the major contributions to specific energy in lower quality coal. Using a sales database compiled from the major thermal coal mining and trading companies engaged in mining and coal marketing operations in Australia, South Africa and Indonesia, an index for each country is constructed. This new index adjusts the FOB index from 6000kcal/kg NAR to 5500kcal/kg NAR and factors in further discounts for the higher levels of ash and other impurities. In practice prices are linearly adjusted downward for the reduced energy content on a NAR basis, while other seemingly arbitrary price adjustments are made for higher levels of moisture and ash as well as below specification levels for volatile matter, fixed carbon, sulphur and hydrogen.

Separate stepwise regression equations are estimated for Australian, South African and Indonesian thermal coal. In each case, the dependent variable is a measure of the NCV in kcal/kg. Following Hogan et al. (1999), a linear functional form is adopted to avoid multicollinearity problems associated with the inclusion of quadratic or higher order polynomial terms. The dataset used in this study comprises a cross section of quality characteristics for thermal coal brands exported from Australia, South Africa and Indonesia from 2006-2010. The data included 54 Australian thermal coal brands, 58 South African thermal coal brands and 56 Indonesian thermal coal brands. The results are provided in Table 3.

	Intercept	**TM**	**IM**	**VM**	**Ash**	**Adj R^2**
Australia	8878.31	-107.33	-69.18	-10.36	-91.07	0.94
	(50.19)	(-9.99)	(-5.41)	(-4.92)	(-13.08)	
South Africa	8424.47	-71.57	-125.47		-92.67	0.76
	(26.83)	(-4.52)	(-6.53)		(-9.31)	
Indonesia	8473.79	-96.36	-22.82	-19.64	-44.51	0.98
	(54.65)	(-15.72)	(-2.53)	(-5.09)	(-6.04)	

Table 3: Regression of total moisture (%TM), inherent moisture (%IM), volatile matter (%VM) and ash (%) against specific energy (kcal/kg NAR) for 54 Australian thermal coal exporters, 58 South African thermal coal exporters and 56 Indonesian thermal coal exporters, t-statistics in parentheses.

The contracted NCV is statistically significant for total moisture, inherent moisture and ash for all three exporters and volatile matter for Australia and Indonesia. Using the regression equations, the NCV for Australia and South Africa is adjusted recursively such that the NCV is equivalent to the Indonesia specification (5500 kcal/kg). Table 3 shows that increasing total moisture and ash have a similar negative effect on contract prices while volatile matter has a much smaller negative effect. Using the relative weights in the regression, the resulting estimates for total moisture, volatile matter and ash for both Australia and South Africa are obtained.

	TM (%)	**IM (%)**	**VM (%)**	**Ash (%)**	**NCV (kcal/kg)**	**Price Diff (%)**
Australia	11.46	3.70	34.28	15.88	5500	-2.88
South Africa	10.03	4.06	32.13	15.65	5500	-2.65
Indonesia	18.48	11.42	38.88	6.21	5500	0

Table 4: Resulting adjustment in specifications leading to aligned NCV for Australia, South Africa and Indonesia thermal coal brands. The price differential is a percentage discount to the quoted energy adjusted indices.

These results were calibrated to the sales database to determine the relative magnitude of the price discounts for moisture, ash and volatile matter that departs from the benchmark level. Using these specifications the adjustment factor made to each price index relative to each respective FOB price was obtained. Therefore appropriate discounts to the index for higher levels of ash and lower levels of volatile matter as well as premiums for lower levels of moisture were derived. The final adjustment to each price index is provided in Table 4. For ash disposal many Indian companies use it as an additive in cement manufacture but some is disposed of in ash dams or land reclamation at very low cost. The relative level of costs and benefits of ash are approximately equivalent in India, see Swarup (2009). Additional ash disposal costs to the power producer therefore will not be considered as the value-in-use estimate for ash is unclear and likely to be minimal.

3.3 Power Conversion

A given coal specification needs to be converted into a value-in-use measure for computing the actual cost to generate thermal energy. The method employed in this study converts a unit of energy in megajoules per metric tonne (MJ/Mt) or kilocalories per kilogram (kcal/kg) of coal into US dollars per megawatt-hour (US$/MWh) of electricity at the power station's transformer prior to any costs incurred through transmission to the grid. Both measures of energy are equivalent. Along the way conversions need to be made to obtain energy per unit of coal given a set of specifications measured in US dollars of delivered energy to the power station and then dollars per megawatt-hour of electricity ($/MWh) at the transformer.

Boilers within power generating units are typically designed for input fuel within strict quality boundaries however circumstances influenced by economics or market inefficiencies (for instance supply chain disruptions) sometimes dictates the combustion of fuel other than the optimal design fuel. Combustion of off-specification fuel alters unit performance and generation economics in terms of reduced load capacity, increased maintenance, higher auxiliary load, higher heat rate, increased consumables and more waste disposal. Failure to achieve superheat and/or reheat steam temperature or excessive superheat and/or reheat de-superheating spray flow are critical outcomes from off-design or non-design fuels, see Drbal (1996).

From Juniper et.al. (1997) the coal properties which have the most impact on boiler performance are specific energy, moisture content, coal reactivity, ash composition and mineral composition. The boiler, through combustion, converts the chemical energy in the coal to thermal energy and transfers the heat produced to convert water to superheated steam at high pressure and deliver it to the steam turbine/generator.

Power plants are designed to consume coal with particular characteristics and any departure from the specifications will force the plant to operate below an optimum level. Obtaining coal at a cheaper rate due to below-benchmark values of calorific value, ash or moisture will have a direct effect on the efficiency of the plant. The critical question arising from this circumstance is whether the less-expensive lower-grade coal imported from Indonesia or elsewhere represents a significant price advantage over the more-expensive higher-grade coal from Australia and South Africa. The higher-grade coal is simply a result of fewer impurities that detract from electricity production. The comparison between coal suppliers must therefore be benchmarked in terms of thermal efficiency at the power plant on a delivered unit of energy basis.

There are significant non-linear differences between the consumption patterns of various coal-fired generators. For instance a 600MW coal-fired power station operating at 38 percent efficiency and 75 percent utilisation will consume approximately 1.5 million tonnes of bituminous coal with a CV of 6000 kcal/kg NAR per annum in contrast to consuming 4 million tonnes of brown coal with a CV of 2250 kcal/kg NAR per annum. The quality of the coal is of prime importance in a plant's procurement strategy.

3.4 Freight Costs

The delivered price of coal is derived from the free on board (FOB) price of coal plus the cost of ocean freight. Freight rates are an important factor that determines the price competitiveness of coal against other fuels. While both Capesize and Panamax sized vessels are used for bulk freight to India, Panamax vessels predominantly supply the Indian thermal coal market due to draft restrictions at all thermal coal Indian ports. The three freight routes used to construct the price series for thermal coal supply to India are Richard's Bay to West Coast India, Kalimantan to East Coast India and Newcastle to East Coast India. Month-ahead voyage charter freight rates for all routes were sourced from a proprietary database compiled by freight trading companies and cross referenced against data provided by the Baltic Exchange. Some distance differentials were also applied to correct for differences between quoted and actual delivery ports. Ports for delivery on the east coast of India include Chennai, Ennore, Gangavaram, Haldia, Karaikal, Krishnapatnam, Paradip and Vizag and to the west coast of India are Kandla, Mumbai, Mormugao, Mundra, New Mangalore, Navlakhi and

Pipavav. An average of both east coast and west coast port distances from source countries was used in computing voyage charter rates.

3.5 Delivered Units of Energy

The delivered price of coal is calculated as the FOB off-take price per tonne of coal at port *i* plus the cost of freight *F* for delivery to port *k* in the next period *t* is computed simply as

$$P_{k,t}^{CFR} = P_{i,t-1} + F_{ik,t} \quad , \tag{1}$$

where *t-1* is the time of vessel loading and we assume vessel delivery takes place one period later. The price $P_{k,t}^{CFR}$ is known as the delivered price or CFR (cost and freight) price. The price of coal at different loading locations is based on a strict set of specifications. The prices are typically adjusted for calorific value, ash, moisture content, sulphur and nitrogen. As explained in Table 3 a thermal coal assay shows that calorific value, ash and moisture have the greatest effect on the efficiency of the coal when consumed and therefore on the magnitude of the premium or discount to the benchmark off-take price. Typically a floor or ceiling is placed on the other characteristics with outright rejection of cargoes within the buyer's rights should one or more of these characteristics exceed contracted value. Price differences in the form of penalties are uncommon and cannot be readily estimated through hedonic regression techniques as these below-specification cargoes become financially distressed and seek a buyer usually at substantially lower prices.

From (1) we then convert the delivered price of coal into delivered units of energy (DUE) measured as an output price for electricity in US$ per megawatt-hour (US$/MWh). The conversion equation used in this analysis is

$$P_{k,t}^{DUE} = P_{j,t}^{CFR} \frac{\theta}{CV} \frac{1}{\eta}, \tag{2}$$

where *CV* is the net calorific value of the coal on an as received basis in MJ/kg, θ is a conversion factor and η is the plant thermal efficiency for each type of delivered coal. The relevant sub-critical plant efficiency values for Australian and South African coal is around 0.38 and Indonesia is 0.36 based primarily on moisture content. A critical assumption of thermal efficiency for a power plant using sub-bituminous coal is 36 per cent while the thermal efficiency of a power plant using bituminous coal is 38 per cent. These efficiency rates are taken from Swarup (2009) and reflect the shift in efficiency for thermal coal due to high moisture levels. This differential in efficiency will have only a minor impact on DUE prices. The conversion parameter θ is benchmarked against 3600MJ/MWh for coal with 10 percent total moisture and 25 percent volatile matter, see GWC Coal Handbook (2004). The conversion parameter is then scaled to adjust for differing moisture and volatile matter contents of each coal source obtained from the analysis in Table 4. Figure 4 shows the price series of DUE for Australia, South Africa and Indonesia.

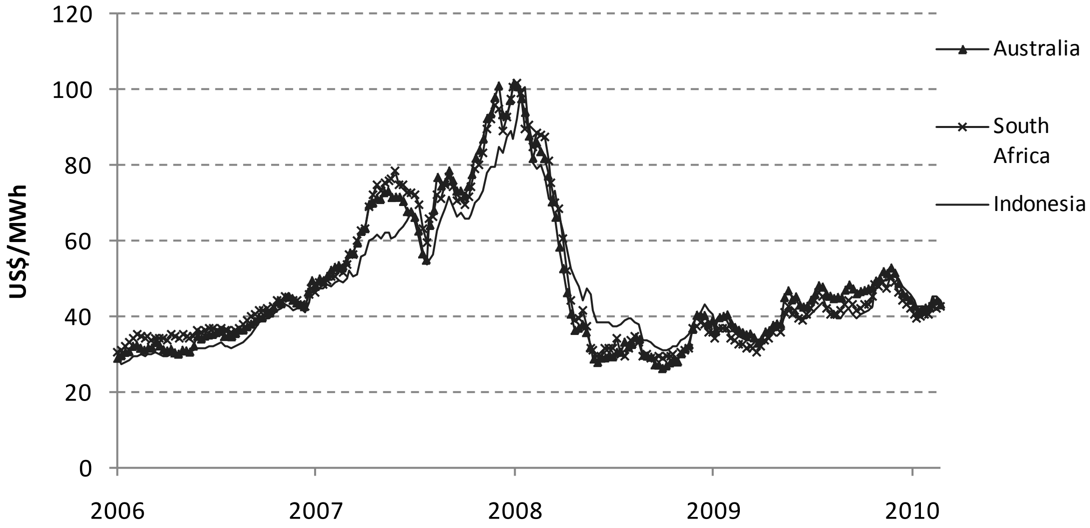

Figure 4: Delivered units of energy (US$/MWh) to India by exporter 2006-2010. Delivered units of energy are estimated as FOB thermal coal plus freight and then converted using coal quality analysis adjustments for Australia, South Africa and Indonesia.

Figure 4 shows that the price differentials when measured in DUE are substantially less than the energy-adjusted FOB prices illustrated in Figure 3.

4. Econometric Methodology

As shown in King and Cuc (1996) arbitrage will ensure that a single price holds across a network of geographically dispersed markets for a homogenous good assuming transport and transaction costs are zero, all market agents have full information and each market is connected to every other market. This is the so-called law of one price. Under the law of one price arbitrage will continue to guarantee price differences within the bounds of transaction and transport costs when such costs are non-zero.

Take two price series P_i and P_j that are individually non-stationary, integrated of order one I(1), and must be differenced at least once to obtain stationarity and be invertible. A linear combination of the two series may result in a series u_t that is stationary I(0) such that

$$u_t = P_{j,t} - \alpha_{ij,t} - \beta_{ij,t} P_{i,t}, \tag{3}$$

where $\alpha_{ij,t}$ is the relevant transaction and transport differential between country *i* and *j* at time *t*. If this linear transformation exists then the time series are considered cointegrated. The regression will indicate that the difference between each time series $P_{j,t} - \beta_{ij,t}P_{i,t}$ varies randomly around a fixed level, see Engle and Granger (1987). As described in King and Cuc (1996), if we consider (3) in a stochastic regression framework where u_t is a random error term with mean zero and covariance matrix H_t, the law of one price implies that $\beta_{ij,t} = 1$ for all *t: t=1,2,...n* over the long run, implying some level of convergence. The β coefficient can be interpreted as a proxy for the degree of market integration between source *i* and *j* through a measure of price convergence with any persistent differential equivalent to or less than total transaction and transport costs. Convergence strictly occurs at $\beta_{ij} = 1$ and while the difference between two series may continue to vary, such differences must become arbitrarily small or converges to some constant through time such that $\lim_{t\to\infty}\{P_j - P_i\} = \alpha$ where α is a constant.

To examine the level of market integration of FOB, CFR and DUE price series we will employ two distinct techniques to examine the degree of difference between each price series P_i and P_j and seek evidence of convergence for all *i,j*. We test for strong form convergence in the three geographically diverse series for FOB, CFR and DUE prices using the Johansen cointegration test and to eliminate errors due to structural changes in the market we will also employ recursive analysis in the form of a Kalman filter to complement the cointegration results.

The cointegration methodology of Johansen (1988) is used to test for corresponding variations between FOB, CFR and DUE price series. Johansen (1988) proposed two tests: the trace test and max-eigenvalue value test. Both tests are likelihood ratio (LR) tests and are based on the eigenvalues of the matrix $\beta_{ij,t}$ such that the number of eigenvalues which are significantly different from zero corresponds to the number of cointegrating relationships. The null hypothesis that there are at most *r* cointegrating vectors becomes

$$H_0\colon \lambda_i = 0 \quad i = r+1, \dots, h, \tag{4}$$

where only the first *r* eigenvalues are non-zero and *h* represents the number of lags. The trace test for the null hypothesis in (4) can be defined as

$$\lambda_{trace} = -2\log(Q) = -T\sum_{i=r+1}^{h}\log(i - \hat{\lambda}_i), \tag{5}$$

where Q is the ratio of the restricted maximum likelihood (ML) to the unrestricted ML, see Johansen (1988) and Johansen & Juselius (1990). To simplify the presentation of results in this analysis we only provide the trace test results to assess the level of cointegration between price series.

If the error term remains stationary over the test period while each price series is non-stationary, then arbitrage should ensure that the differences in price become arbitrarily small. As transaction and transport costs have been incorporated in both CFR and DUE price series the differences should in fact converge to zero. King and Cuc (1996) applied a test for North American natural gas prices using the Engle and Granger (1987) methodology and found evidence for increased price convergence during the mid-1990s. The King and Cuc (1996) analysis highlighted that convergence must have already occurred in order to detect cointegration, and so they employ a Kalman filter technique to cater for dynamic structural change in the market. The distinction between cointegration and convergence is further considered in Ashe et.al. (2001), Warell (2006) and Li et.al (2010), where the latter reference highlights that the cointegration technique should be avoided during periods of structural change in the market under consideration. Following Li et.al. (2010) we test for pair-wise cointegration across the three price series and also test for stability in the cointegration relationship using a recursive analysis.

5. Empirical Results

5.1 Unit Roots

To confirm that the price series are I(1) prior to testing for cointegration we conduct unit root tests on the logarithm of FOB prices, CFR prices and DUE prices using the Augmented Dickey-Fuller test for up to four lags, see Dickey and Fuller (1979). Table 5 summarises the results. As shown each price series is found to be non-stationary in levels but stationary in first differences, which means all series are integrated of order one. The necessary condition for cointegration is therefore met.

	Australia			**South Africa**			**Indonesia**			
	FOB	**CFR**	**DUE**	**FOB**	**CFR**	**DUE**	**FOB**	**CFR**	**DUE**	**Critical value**
Level										
Constant	-1.66	-1.62	-1.62	-1.52	-1.51	-1.57	-1.57	-1.78	-1.79	-2.87
	(1)	(1)	(1)	(1)	(1)	(1)	(2)	(1)	(1)	
Const + trend	-1.61	-1.64	-1.65	-1.46	-1.61	-1.62	-1.48	-1.76	-1.75	-3.43
	(1)	(1)	(1)	(1)	(1)	(0)	(2)	(1)	(1)	
First Difference										
Constant	-9.54	-9.51	-9.52	-11.77	-10.12	-10.11	-9.64	-9.70	-9.69	-2.87
	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(0)	(0)	
Const + trend	-9.54	-9.54	-9.53	-11.76	-10.15	-10.14	-9.64	-9.73	-9.72	-3.43
	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(0)	(0)	

Table 5: Augmented Dickey-Fuller tests for unit root for Australia, South Africa and Indonesia thermal coal brands on a FOB, CFR and DUE basis, parentheses indicate the number of lags using the Akaike Information Criterion (AIC).

Unit roots were also tested using the Phillips and Perron (1988) test and the results directly correspond to the ADF test results in Table 5 with units roots observed for all price series. These results have been excluded here in the interests of brevity.

5.2 Cointegration and Convergence

The Johansen (1988) and Johansen and Juselius (1990) approach is used to detect cointegration in FOB, CFR and DUE price series for Australia, South Africa and Indonesia. The bivariate cointegration results using Johansen are presented in Table 6. We employ bivariate estimates to observe the relationship between single competitors in the Indian thermal coal supply market. The null hypothesis of no cointegration is rejected for each price series at 5 percent significance apart from the Australia and South Africa FOB price pair where the null hypothesis of no cointegration is rejected at the 10 percent level. The trace test significance level as represented by the p-value increases as the price series is transformed from FOB to CFR to DUE prices for the Australia and South Africa price pair and the Australia and Indonesia price pair. In contrast the p-values decline when prices are transformed from FOB to CFR and DUE for the South Africa and Indonesia price pair indicating that FOB prices may be more integrated than delivered prices between these competitors to India. We will reserve full discussion on this point until the error-correction and recursive analysis results are presented.

Pair	**Lags**	**Trace**	**P-value**
FOB			
Australia - South Africa	1	**28.530***	0.069

Australia - Indonesia	1	**38.813****	0.019
South Africa – Indonesia	1	**44.390*****	0.008
CFR			
Australia - South Africa	2	**45.232*****	0.008
Australia - Indonesia	2	**44.458*****	0.008
South Africa – Indonesia	2	**37.127****	0.027
DUE			
Australia - South Africa	2	**45.219*****	0.008
Australia - Indonesia	2	**44.461*****	0.008
South Africa – Indonesia	3	**37.128****	0.027

Table 6: Bivariate cointegration tests of pairs for FOB, CFR and DUE thermal coal sales to India from Australia, South Africa and Indonesia; p-values based on critical values from Osterwald-Lenum (1992); bold numbers indicate statistical significance at the *** 1 percent level, ** 5 percent level and * 10 percent level.

Co-integrated variables are characterised by having an error-correction representation which means that the relationship among the variables may be expressed in a way that combines the advantages of modelling both levels and first differences. In error-correction models the dynamics of both short-run changes and long-run levels are modelled simultaneously. To complement the Johansen cointegration test we also examine the degree of market integration using the error correction mechanism (ECM) popularised by Engle and Granger (1987). This model examines movements in prices of goods in different regions to test the hypothesis of a long-run cointegrating relationship while distinguishing from any short-run relationship. The generalised ECM is given as

$$\Delta P_{j,t} = \beta_j \Delta P_{j,t-k} + \beta_i \Delta P_{i,t-k} + \delta \hat{\Psi}_{t-1} + \varepsilon_t, \qquad (6)$$

with k lags and speed of adjustment term δ where the error correction term $\hat{\Psi}_{t-1}$ caters for any deviation from the long-run equilibrium represented by the form

$$\hat{\Psi}_{t-1} = P_{j,t} - \alpha - \beta_i P_{i,t-1}, \qquad (7)$$

where the β coefficients are the short run components of the full solution in (6). The Engle and Granger test employs a standard OLS estimate. For each pair the normalised long-run coefficients for the ECM are shown in Table 7.

Pair	δ_i	t-statistic	β_i	t-statistic
FOB				
Australia - South Africa	0.011	0.245	0.131	1.436
Australia - Indonesia	0.036	1.310	-0.047	-0.664

South Africa – Indonesia	-0.012	-0.306	0.102	1.348
CFR				
Australia - South Africa	**0.181****	2.606	**0.311***	2.437
Australia - Indonesia	**0.152****	6.573	-0.124	-1.167
South Africa – Indonesia	**0.167****	5.716	**0.280****	3.297
DUE				
Australia - South Africa	**0.182****	2.613	**0.309****	2.433
Australia - Indonesia	**0.116****	3.383	**-0.112****	-3.683
South Africa – Indonesia	**0.183****	5.736	**0.279****	3.302

Table 7: Normalised long-run coefficients of pairs for FOB, CFR and DUE thermal coal sales to India from Australia, South Africa and Indonesia; bold numbers indicate statistical significance at the ** 1 percent level and the * 5 percent level.

The results in Tables 6 and 7 indicate that in general the thermal coal market becomes more integrated the further along the consumption channel an observer stands, that is, as the price is transformed from FOB to CFR to DUE prices. The ECM results show that the level of cointegration of FOB thermal coal prices are largely mixed depending on the price pair, while CFR and DUE price pairs are highly significant. As discussed the implied degree of integration between FOB South African and Indonesian price pairs using the trace statistic is high however the presence of a long-run error correction coefficient that is not statistically significant indicates that any deviations in the long-run price are not necessarily resulting in price adjustments. Similar results for the level of integration between Australian FOB prices and Indonesian and South African FOB prices where a degree of market integration is present but long-run price adjustments implied by the error correction mechanism appear absent.

For the CFR and DUE price series, both market integration via the trace statistics and long-run price adjustments are generally statistically significant across all pairs. The DUE results are indeed stronger that the CFR results. This suggests that when thermal coal is transformed to a price measure on an energy content basis at the power plant transformer connecting to the grid, the degree of market integration is generally high.

All three thermal coal exporting countries used in this analysis compete in other markets such as Europe, Japan, Korea, Taiwan and more recently China where changes in demand directly affect price independent from the demand effects of Indian importers. The level of market integration as shown through the cointegration analysis of the seaborne thermal coal market in Warell (2006) for CFR prices and Li et.al. (2010) for FOB prices is generally strong and when extended to the newly emerging Indian market we observe a similar level of integration. Based on the significance levels of the cointegration results as price pairs are transformed from FOB to delivered and consumed prices, we conclude that the degree of market integration to India gains in strength when delivered prices are used and variations in quality that affect power production are eliminated from the analysis. To cater for potential structural changes in the emerging thermal coal market to India it is necessary to complement cointegration analysis with a test for price convergence. Using a Kalman filter in line with King and Cuc (1996) will provide a purer test for convergence and also permit the examination of the true level of arbitrage between each price pair over the observation period.

5.3 Kalman Filter

To detect the degree of convergence and arbitrage between each price series a Kalman filter is employed. As noted in King and Cuc (1996) an important feature of the Kalman filter approach is that it allows the computation of time-varying estimates of the parameters in (3) for a time period without concern for the accuracy of the coefficient estimates themselves. Cointegration is not a necessary condition for the efficient operation of the Kalman filter and estimating $\alpha_{ij,t}$ and $\beta_{ij,t}$ can be superior to coefficient estimates using standard OLS, particularly for developing markets.

Convergence implies that $E\left(\lim_{t\to\infty}\{P_j - P_i\}\right) = \alpha_{ij}$ for all *t* where P_i and P_j are FOB prices for each thermal coal source and α_{ij} represents the freight differential between coal sourced from country *i* and country *j*. Upon conversion from FOB to CFR and DUE prices using freight rate estimates and thermal plant efficiency assumptions we expect $E\left(\lim_{t\to\infty}\{\alpha_{ij}^{CFR}\}\right) = 0$ and $E\left(\lim_{t\to\infty}\{\alpha_{ij}^{DUE}\}\right) = 0$ while $E\left(\lim_{t\to\infty} \beta_{ij}\right) = 1$ for FOB, CFR and DUE price series. The expectation $E\left(\lim_{t\to\infty}\{\alpha_{ij}^{CFR}\}\right) = 0$ may not be realistic if there is justification for quality differences between price series contributing to permanent price differentials. However the ability of thermal power plants to blend coal qualities to achieve a common input quality level may eliminate quality and respective price differences and therefore eliminate arbitrage opportunities. Due to the differential in FOB prices we expect $E\left(\alpha_{ij}^{FOB}\right) = c_t$ where c_t is a time-varying constant whose absolute value lies within the bounds of zero and the total transaction and transfer costs between markets. Using a Kalman filter we test each price pair and present the results graphically.

The FOB, CFR and DUE price series were passed through a relatively standard Kalman filter with the dependent and independent variables deriving nine distinct time varying paths for α_t and β_t. The technical details of Kalman filter construction are outlined in Harvey (1982) and King and Cuc (1996). Our analysis employs similar initial conditions used in Harvey (1982) including variance and parameter estimates determined using standard OLS for the first three observations.

5.4 Convergence

Figures 5 to 7 show the time-dependent paths of β_t using maximum likelihood to optimise the parameter estimates for the Australia and South Africa price pairs, the Australia and Indonesia price pairs and the South Africa and Indonesia price pairs. The values for β_t generally converge to 1 however there are distinct fluctuations away from unity during the thermal coal price spike observed in mid-2008. Strong convergence is observed in the Australia and Indonesia price pairs and the South Africa and Indonesia price pairs for both FOB and delivered/consumed prices, however there are large fluctuations away from unity for the Australia and South Africa price pair.

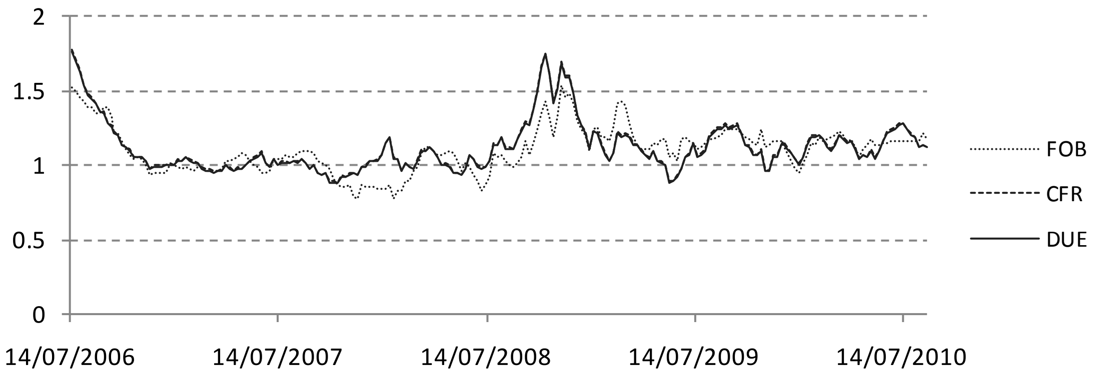

Figure 5: Maximum likelihood estimates of β_t using a Kalman filter approach for Australia and South Africa thermal coal FOB (US$/Mt), CFR (US$/Mt) and DUE (US$/MWh) import prices to India 2006-10 (Australia is the dependent variable).

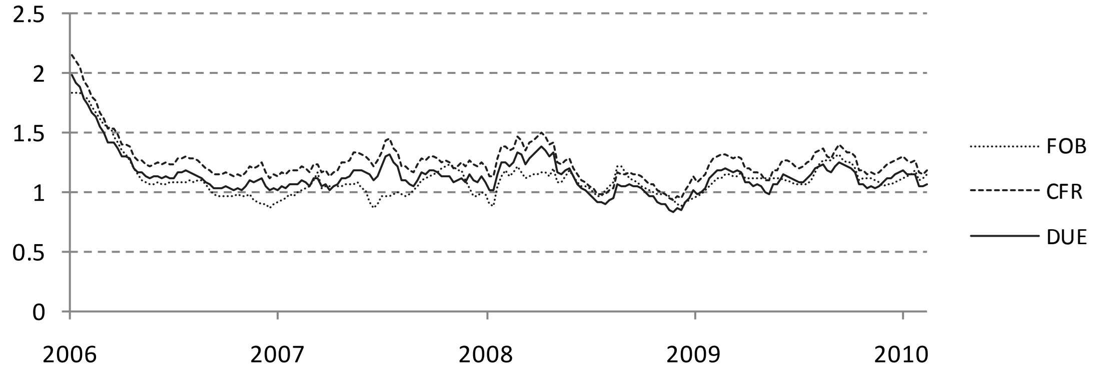

Figure 6: Maximum likelihood estimates of β_t using a Kalman filter approach for Australia and Indonesia thermal coal FOB (US$/Mt), CFR (US$/Mt) and DUE (US$/MWh) import prices to India 2006-10 (Australia is the dependent variable).

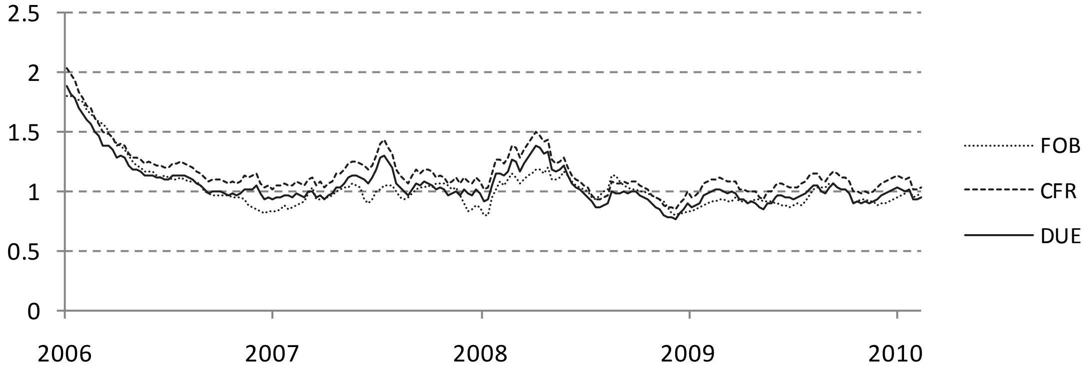

Figure 7: Maximum likelihood estimates of β_t using a Kalman filter approach for South Africa and Indonesia thermal coal FOB (US$/Mt), CFR (US$/Mt) and DUE (US$/MWh) import prices to India 2006-10 (South Africa is the dependent variable).

5.5 Arbitrage

As for the estimates for β_t Figures 8 to 10 show the time-dependent paths of α_t using maximum likelihood to optimise the parameter estimates for the Australia and South Africa price pairs, the Australia and Indonesia price pairs and the South Africa and Indonesia price pairs. The values for α_t generally converge to zero however there are distinct fluctuations away from zero during the thermal coal and freight price spike observed in mid-2008. Freight prices over this period increased to over ten times the long-term average and some routes were vastly more expensive than others. A rapid rate of mean reversion occurs when α_t drifts far from zero indicating that arbitrage is eliminated relatively quickly. Apart from the extreme freight rates experienced in mid-2008 which had a large effect on CFR prices, Figures 8 to 10 clearly indicate declining values in the apparent degree of arbitrage when thermal coal prices are transformed from FOB to CFR and then to DUE prices in line with expectations. As freight and quality characteristics are incorporated into the full value-in-use measures used for fuel procurement contract price negotiation by Indian power plant operators, the differentials in price pairs drops significantly and the further away from zero the price drifts the faster the rate of reversion to zero. From these graphs there is a strong argument for the null hypothesis that alpha is statistically different to zero should not be rejected. This implies that arbitrage, while at times present in the FOB market although not persistently, is eliminated when freight and energy adjusted consumption costs are incorporated.

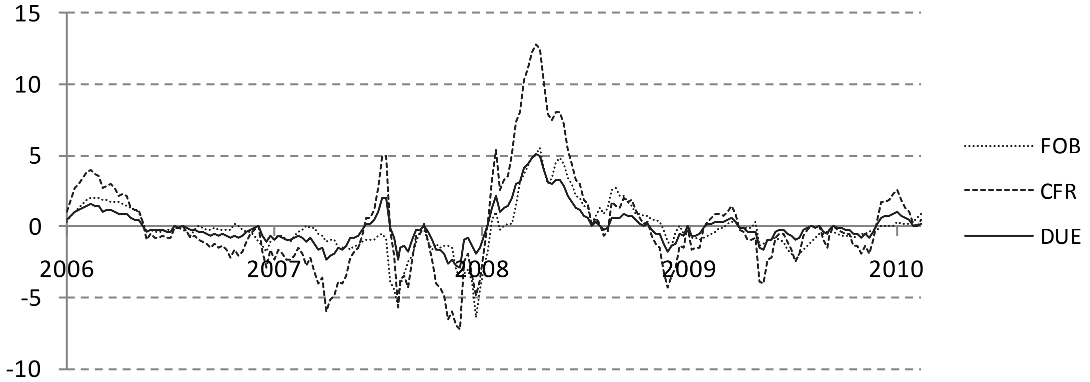

Figure 8: Maximum likelihood estimates of α_t using a Kalman filter approach for Australia and South Africa thermal coal FOB (US$/Mt), CFR (US$/Mt) and DUE (US$/MWh) import prices to India 2006-10 (Australia is the dependent variable).

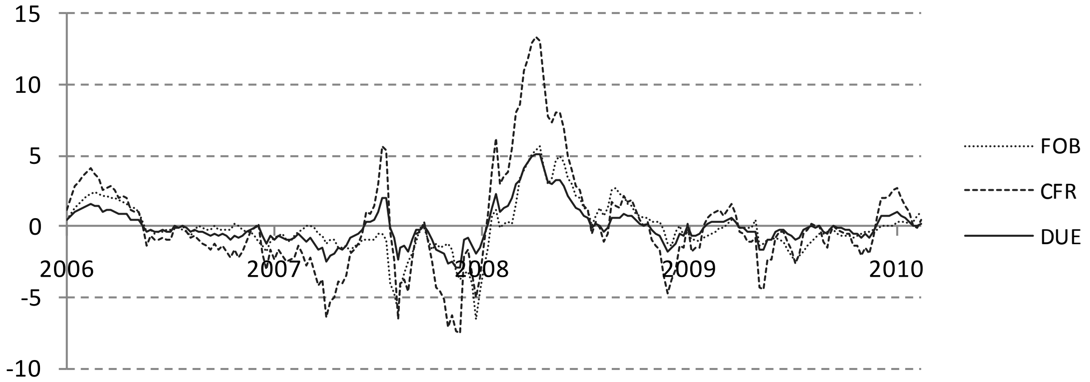

Figure 9: Maximum likelihood estimates of α_t using a Kalman filter approach for Australia and Indonesia thermal coal FOB (US$/Mt), CFR (US$/Mt) and DUE (US$/MWh) import prices to India 2006-10 (Australia is the dependent variable).

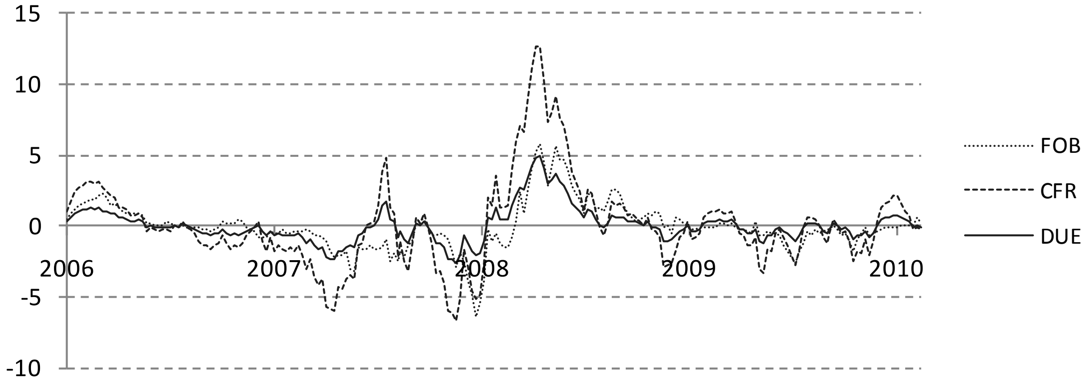

Figure 10: Maximum likelihood estimates of α_t using a Kalman filter approach for South Africa and Indonesia thermal coal FOB (US$/Mt), CFR (US$/Mt) and DUE (US$/MWh) import prices to India 2006-10 (South Africa is the dependent variable).

5.6 Discussion

The Australia and South Africa CFR and DUE price pair exhibited a strong level of cointegration and almost zero arbitrage but less convincing results for convergence using the Kalman filter. In contrast the South Africa and Indonesia CFR and DUE price pair exhibits stronger convergence and zero arbitrage than degree of cointegration. The Australia and Indonesia CFR and DUE price pair demonstrates both strong convergence and a high degree of cointegration along with zero arbitrage. The volume of Australian exports to India have been significantly less than South African and Indonesian volumes over the 2006-10 period. Due to the historical coal trade links with Indonesian and South African coal producers, Indian importers tend to only source Australian coal when DUE prices are favourable and the low import volumes of Australian coal prior to 2008 highlight this behaviour. The disparity between the level of integration based on cointegration tests and convergence based on a recursive analysis can be partly explained by such volumetric differences. The disparity between the stronger convergence result and the weaker (although statistically significant at the 5 percent level) degree of cointegration in South African and Indonesian CFR and DUE price pairs suggests that true convergence as shown in Figure 10 was only achieved towards the end of the observation period. The Kalman filter is unaffected by structural changes in price series relations see Harvey (1982), and it is clear from this result that the nature of the seaborne thermal coal market to Indian has undergone a transformation over the observation period.

In summary the recursive analysis shows that when each grade of delivered coal is transformed into a delivered price and then further transformed into an electrical power output price using a value-in-use conversion, price convergence was generally observed and the perceived arbitrage across Australia, South Africa and Indonesian export prices converges to zero. By transforming the value of imported energy coal to a delivered unit of energy the price arbitrage disappears and Indian power producers should be generally indifferent to the source of the imported coal. The historical increase in imports from Australia and South Africa relative to Indonesia suggest that this transformation has occurred over the period 2006-10 and that thermal power producers account for quality differentials as much as FOB price and freight prices in their procurement behaviour.

6. Conclusions

This study has examined the degree of integration in global thermal coal markets based on delivered units of energy to account for quality differentials that feed through to electricity output. The conversion of spot thermal coal FOB prices to electricity output at the power plant transformer in the form of a DUE price normalises both quality and freight differentials. The analysis was conducted using Indian power plant procurement prices due to the homogeneity across Indian thermal producer technology which aligns import specifications and generally results in a common strategy of procuring coal with similar energy content.

As suggested by previous research in this field, when price convergence is still occurring and is possibly slow, methodologies based on cointegration techniques alone are insufficient and other recursive techniques should be employed. The Kalman filter has been used in the past to supplement traditional tests for cointegration and is employed in this study. As an added advantage the Kalman filter not only detects the degree of convergence precluding any concerns over the validity of the cointegration between price series, but was used to examine the absolute level of arbitrage based on price differences over an observation period.

This study conducted an empirical test of market integration in two stages. Firstly, we examined the unit root and cointegration properties of the data and concluded that a single unit root was present in each time series. The level of cointegration between price pairs gained in relative strength when spot thermal coal prices were augmented by freight rates to obtain a delivered price and further augmented by transforming to units of energy consumed in a thermal power plant. Quality differentials were critical for this conversion. The capacity to transform input fuel prices to electricity output prices is enhanced by the high level of homogeneity across thermal power production technology in India and the absence of domestic supply influencing buyer behaviour when import prices rise. As discussed the level of cointegration is highly dependent on the price series having achieved convergence in the sense that price differentials have stabilised at a relatively constant and small value.

The second stage of the study employed a Kalman filter using a similar method used by King and Cuc (1996) and Li et.al. (2010) to visually detect a pricing relationship between price pairs based on the time-varying coefficient β_t as an indicator of strength. A useful by-product of the Kalman filter is the capacity to also observe the time-varying values for α_t which serve as useful proxies for the level of arbitrage between price series. The results demonstrate that α_t generally converges to zero however there are distinct fluctuations away from zero during the thermal coal and freight price spike observed in mid-2008. A rapid rate of mean reversion occurs when α_t drifts far from zero indicating that arbitrage is eliminated relatively quickly during periods of significant price differentials.

The results of the study demonstrate that based on cointegration testing techniques the thermal coal market is generally integrated and that this level of integration strengthens as prices are converted from FOB to CFR and DUE based measures. The general level of integration is based on the high degree of price convergence achieved in the recursive analysis and from the strong relationship observed in the cointegration tests. Furthermore arbitrage between markets is eliminated as prices are converted from FOB to CFR and DUE prices. This study challenges the common notion that thermal coal importers source material that has a relative freight advantage despite quality differentials.

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