THE CROWN ESTATE

Marine Estate Research Report

Energy Consumption of Marine Aggregate Extraction

Energy Consumption of Marine Aggregate Extraction

Research contract reference: OSR 06 03

Final report

Report prepared by:

Professor Roger Kemp FREng
Lancaster University

Administration Page

Contract Reference: OSR 06 03

Report version: Final

ISBN: 978-0-9553427-9-0

Published by The Crown Estate on behalf of the Marine Estate

Suggested citation:

Kemp, R. (2008) Energy consumption of marine aggregate extraction. The Crown Estate, 21 pages, February 2008. ISBN: 978-0-9553427-9-0.

Contents List:

Executive summary

This study has calculated the energy used in the extraction and transportation of marine aggregates (sand and gravel) from the Continental Shelf and compared the figures with the energy used in excavating and processing natural aggregates (sand, gravel and crushed rock) on land.

The operation of four vessels was analysed over a 1 month period and the energy used was broken down into the different phases of aggregate production, as shown in the following graph:

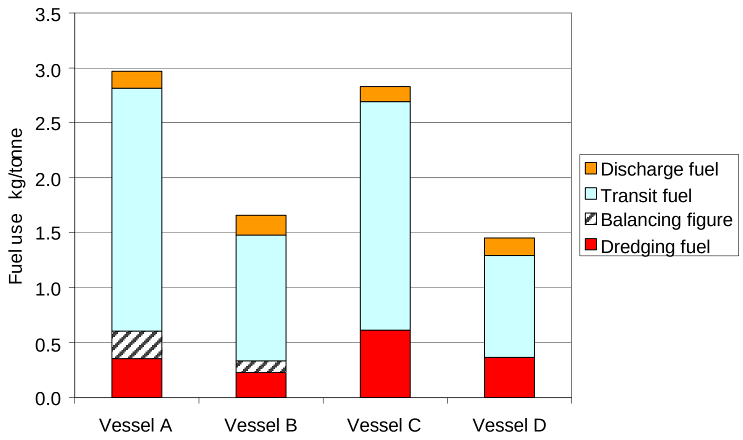

Figure 1 : Overall fuel used per tonne of product

It can be seen that most of the fuel is used in the transport of the aggregate from the licensed dredging area to the wharf (identified as "transit fuel" in the above figure).

Winning marine aggregates uses between 1.5 and 3 kg of fuel per tonne of product over the entire cycle of dredging, transit, discharge and screening. Including the electricity used on the wharf, the total energy used is between 20 and 35 kWh per tonne of product. This has been compared with the energy used in producing material from gravel pits or hard rock quarries and transporting it to the place of end use. It has been shown that there is not a great difference between these different sources but the main difference is linked to the distance the material has to be transported.[1]

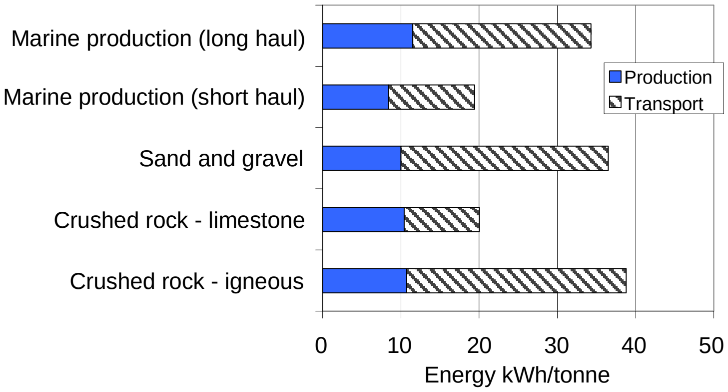

Figure 2 : Comparison with land-based production

---

[1] Fig 2 "Marine production" includes dredging, discharge, crushing and screening.

1 Background and research objective

The annual mass of material extracted from the bed of the English and Welsh Territorial Sea and Continental Shelf, under licence from The Crown Estate Commissioners is 24.3 Mt. Of this, 4.1 Mt is used for beach replenishment and 6.7 Mt is exported to other European countries (CROWN ESTATE 2006). The balance of 13.4 Mt represents approximately 21% of the sand and gravel requirements of England and Wales and 6% of overall aggregate demand (QPA 2007).

The aggregate from the sea bed is dredged, filtered, and transported to the wharf by purpose built dredgers and is then transported to its eventual destination by road, rail or barge. Each of these phases of production uses energy. There were two objectives of this study:

1. To analyse the energy used in the extraction, marine aggregates.
2. To make a comparison of the energy used in the extraction, processing and transport of marine aggregate with the equivalent figures for materials from land-based quarries.

The work used methodology and units as close as practicable to those in the *Energy Consumption Guide* used by the land-based quarry industry [DETR 1998]. This allows direct comparisons to be made.

2 Methodology

2.1 Principles

As far as possible, the analysis in this paper has been based on actual measurements of energy use, rather than results from previous studies and generic data. The production cycle has been analysed and the energy demand of the various stages calculated from the different inputs – mainly diesel fuel/gas oil and electricity. This has allowed the energy use to be calculated.

2.2 Data collection

The work has been undertaken in collaboration with the British Marine Aggregate Producers' Association (BMAPA) and with The Crown Estate. Discussions have been held with two aggregate producers, with two dredger captains and with the managers of several quarries. Two unloading wharves, one concentrating on gravel and the other on sand, have been visited and information has been received on the operational duty of five vessels.

2.3 Units

Reports on energy consumption use a variety of different units – volume of fuel, energy measured in kWh or GJ, the mass of fuel used, sometimes converted to tonnes of coal equivalent (tce) or the mass of carbon or carbon dioxide (CO_2) emitted, This can result in difficulty in making valid comparisons.

In analysing the energy use in the extraction process, the units are generally litres of fuel consumed and these units have been used in this report. When making comparisons with land-based quarries, figures have been converted to kWh/tonne, as these are the units used by in the *Quarry Energy Use Calculator* [DETR 1998].[2] Some vessels use marine gas oil while others use diesel fuel. To simplify the calculations, it has been assumed that marine diesel and marine diesel are have the same energy density and CO_2 emissions; the errors introduced by this simplification are small in comparison with the errors in other measurements.

3 Calculation of dredger energy use

3.1 Data on vessels

This report is based on data from 4 vessels. Identities have been suppressed and they are referred to as Vessels A to D: Main parameters are shown in Table 1:

Table 1 : Main parameters of vessels

		Vessel A	**Vessel B**	**Vessel C**	**Vessel D**
Commissioned	year	1990	1997	1989	1990
Displacement	tonnes	9031	4507	6234	1859
Capacity	tonnes	5200	2300	5000	1380
Length	metres	100	72	99	68
Beam	metres	17.4	15	17.7	13.3
Max draught	metres	6.7	5.2	6.9	4.1
Engines	type	Wartsila	Wartsila	Mirrlees	Caterpillar
	number	2	2	1	2
	kW	1,950	1,360	2940	530
Fuel	type	Diesel	MGO*	MGO	MGO
Service speed	knots	12	11	12.5	10.5
Dredge pipe	metres	48	44	55.9	46

* MGO is marine gas oil.

The vessels are of two types: Larger ships, typically 6000 t displacement, 100 m long and 18 m wide, used for long-haul and smaller ships, typically 1500 t displacement, 70 m long and 14 m wide used for short-haul coastal work. All the above vessels were built during the 8-year period 1989 to 1997 and are expected to have a 25 year working life.

---

[2] It should be noted that the figures for quarry energy use cannot be directly related to CO_2 emissions as the Energy Consumption Guide converts the total energy available in diesel fuel to kWh and then adds the electrical energy used. This does not take account of the efficiency of the electricity generation infrastructure (typically 30 – 40%) and so one cannot make a comparison of CO_2/tonne on the basis of kWh/tonne. The conversion from litres of fuel to kWh uses the same factors as the *Energy Consumption Guide*.

3.2 Fuel used during a representative month

The operators were asked to provide data on cargos and fuel used during a typical month for two types of dredger – (near-shore) short-haul vessels and (off-shore) long-haul vessels. The data are shown in Table 2.

Table 2 : Data for period

		Vessel A	**Vessel B**	**Vessel C**	**Vessel D**
Accounting period	month	Sep-06	Sep-06	Jun-06	Jun-06
Tonnage	tonne	106,682	85,518	103,950	57,118
Cargos		21	45	23	48
Total distance run	km	8,320	4,320	9,792	4,396
Fuel used	tonne	317	142	294	83

Figures of tonnage are for drained (dewatered) cargo landed.

From these figures, the overall energy use of the vessels was calculated.

Table 3 : Calculation of total fuel use per tonne of material

		Vessel A	**Vessel B**	**Vessel C**	**Vessel D**
Fuel used in period	tonne	317	142	294	83
Tonnage landed	tonne	106,682	85,518	103,950	57,118
Overall fuel use	kg/t	2.97	1.66	2.83	1.45

It can be seen that the results are similar for the two long-haul dredgers and for the two short-haul dredgers. Vessels A and C (long-haul) use an average of 2.85 kg of fuel per tonne of aggregate extracted; vessels C and D (short-haul) use an average of 1.55 kg.[3] Because of the closeness of the data points, it was decided that it was not necessary to seek data for other vessels in these categories but to concentrate on the analysis of these ships.

3.3 Breakdown of energy use

The following graph shows the fuel used during the production cycle broken down by the phase of the process:

---

[3] In this analysis no distinction has been drawn between marine diesel oil and marine gas oil – the differences are small compared with the other variability in the data.

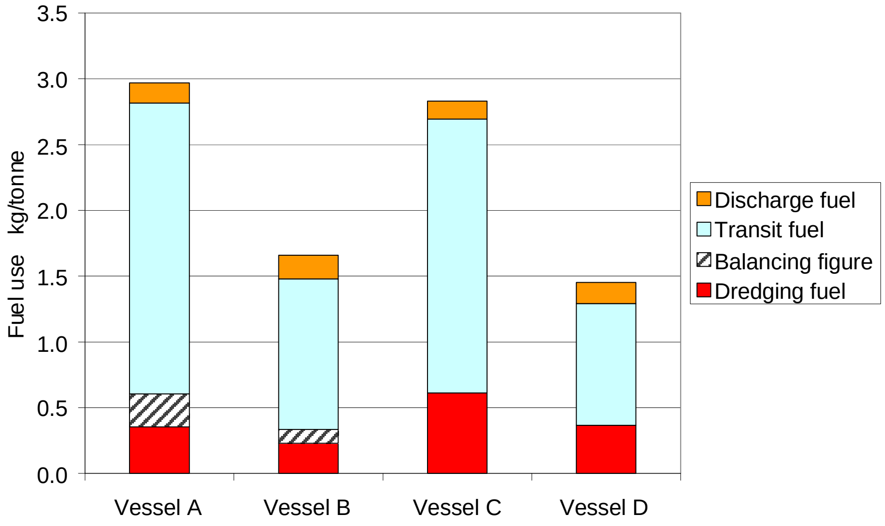

Figure 3 : Overall fuel use per tonne of product

The upper two sectors in each bar represent the fuel used during the transit from the dredging site to the wharf and the fuel used during the discharge operation. The bottom sector is the fuel used during dredging and the hatched area represents a balancing figure, being the difference between the total monthly use and the figures calculated for each of the other sectors, where the analysis of sector figures was not provided by the operator. This figure (less than 9% in all cases) probably represents fuel used during the dredging cycle as well as energy used during unproductive periods.[4]

3.4 Fuel used during the dredging operation

All four vessels have electrically operated dredge pumps. These suck up a slurry of sand, gravel and water from the sea bed, at a ratio of about 1 part solid to 10 parts water. The excess water is allowed to overflow through spillways in the cargo hold back into the sea and the solid material is retained onboard. Where the in-situ composition of the sand and gravel resource which is being dredged does not meet the requirements of the customer, the dredged material can be screened, while the vessel is loading, to alter the composition of the sand/gravel that is retained onboard. For gravel cargos, this is achieved by screening off a proportion of the sand to increase the gravel content of the screened cargo, however the process can be reversed to screen off coarse sediments. The use of screening while dredging has the effect of increasing the loading times, hence increasing energy use. Once the hold is full, the water is pumped out and the drained material is conveyed to the wharf.

Information was provided by the operators on the typical time taken to load aggregate and the power produced by the engine(s) during this operation. This allowed calculation of the amount of fuel used to dredge one tonne of material. The figure varies between

---

[4] The figures calculated in this section are comparable to those calculated independently by BMAPA in the September 2007 publication *Strength from the depth – a first sustainable development report for the British marine aggregate industry*. Fuel and production data was provided for 24 vessels operated during 2006, for which the average consumption was 2.44kg fuel per tonne landed, including dredging, transit and offloading energy.

0.2 and 0.6 kg of fuel per tonne of material. It is not surprising that there is a spread of 3:1 as:

- the vessels operate in different depths of water;
- in some licence area vessels may undertake static dredging (loading while anchored) while on other sites, licence conditions require vessels to undertake trailer dredging, where they move slowly forward while loading;
- some dredge sand/gravel while others dredge sand;
- some licence areas permit or require vessels to screen in order to load a commercially viable cargo, while others require the cargos to be loaded "all in". The former increases production times by up to 100%, with a concomitant increase in energy use.

3.4.1 Fuel used during transport to the wharf

The significant difference between the vessels is the distance between the area of extraction and where the aggregate is off-loaded. Vessel A undertakes a round trip of almost 400 km, while Vessel B sails only 100 km. For two of the ships, the proportion of the total fuel used for each phase was calculated by the operator, for the other two, this was estimated from the output of the engine, assuming a specific fuel consumption (SFC) of 0.2 kg/kWh[5]. The following graph shows the fuel used by the four ships per tonne-km of product delivery.[6]

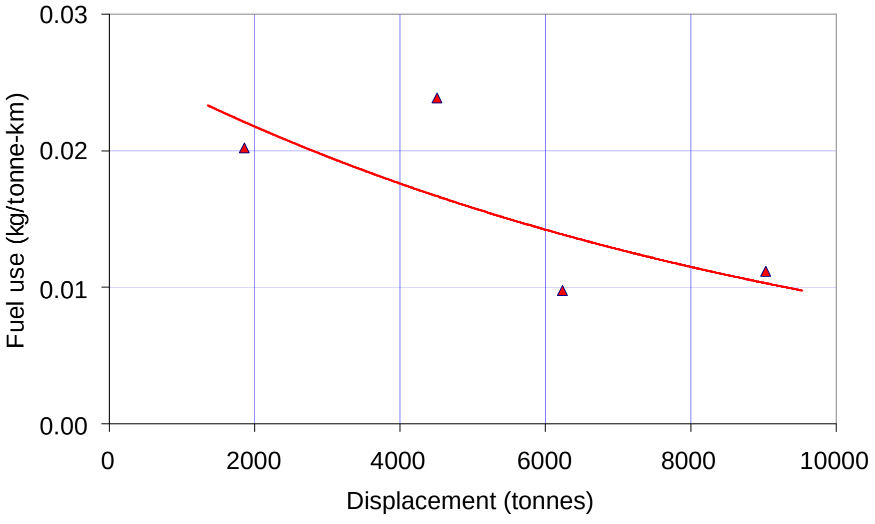

Figure 4 : Transit fuel use

It can be seen that the fuel used during transit is between 0.01 kg/tonne-km and 0.025 kg/tonne-km. The graph includes an exponential trend line of "best fit" – there is considerable deviation from this line; this is to be expected as the ships are operating in

---

[5] This figure is taken as typical for large marine/rail diesel engines.

[6] The calculation is based on how much energy is used for delivering 1 tonne of material 1 km. The energy used in returning to the dredging site under ballast is included in this figure.

different areas where the tides and currents assist or impede their progress to a different extent. Unsurprisingly, the graph shows that larger vessels are more efficient.

3.5 Fuel used during unloading

The data provided allow the calculation of the fuel used in the unloading cycle. A captain with experience on older vessels said that this used to cause a very intermittent load on the engine. However observation of the process on the sister ship of one of the above vessels noted that the power demand meter swinging from around 40% to 60% as the grab was lowered and raised suggesting that modern control systems and the relatively high conveyor load, compared with the grab, reduce these fluctuations.

Table 4 : Fuel used in unloading

Vessel Identifier		**Vessel A**	**Vessel B**	**Vessel C**	**Vessel D**
Av. Cargo Size	tonne	5080	1900	4520	1190
Fuel/tonne	kg/t	0.15	0.18	0.14	0.16

Thus the total amount of fuel used in the offloading cycle is between 0.14 and 0.18 with an average of 0.16 kg of fuel per tonne of material delivered. It can be seen that the larger vessels are about 15% more efficient, presumably due to “economy of scale”.

4 Energy used in aggregate processing

After the gravel and/or sand is off-loaded at the wharf, it has to be processed before being shipped to the end user. When sand is unloaded there is little energy use before it is shipped out of the depot. Typically a single conveyor, with a 30kW motor driven from the mains electricity supply, is used to move the material from the ship’s conveyor to a stockpile at a rate of 1000 t/hr. This adds 30/1000 = 0.03 kWh/tonne to the offloading energy of around 0.8 kWh/tonne used by the on-board material handling equipment – between 2% and 3%.

With coarser aggregates there is greater processing energy demand, depending on the grade of the dredged material and the grading required by customers. On one wharf visited, the production process can be summarised as follows:

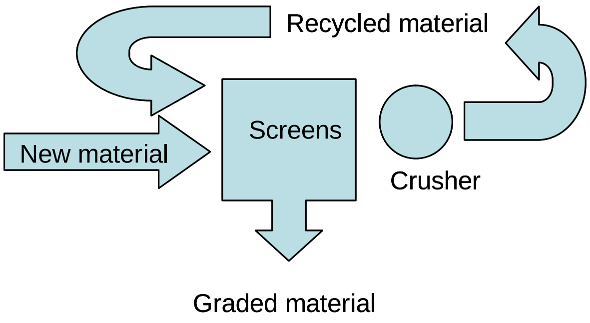

Figure 5 : Aggregate processing

The material is brought in from stockpile and is put through a series of grading screens. Material that is too coarse for any of the screens is fed into a crusher and then recycled, often via a further stockpile, back into the screens. Depending on the size of the original material and the grade of aggregate being produced, the material can be circulated 2 or 3 times through the process until it is all reduced to a suitable grade.

Data was provided on the energy use of the site and the material flows. In the following table the recycled material has been ignored. What is important is how many tonnes of aggregate pass through the site (the raw feed), not how many passes through the process are required to reduce it to a saleable size.

Table 5 : Energy used in processing aggregate

		Jun-06	Jul-06	Aug-06	Sep-06
Raw feed	tonne	37,500	36,000	34,200	30,200
Circulated recrush	tonne	10,500	9,000	12,500	9,000
total	tonne	48,000	45,000	46,700	39,200
Electricity used	kWh	53,258	51,407	57,127	46,026
Specific energy	kWh/tonne	1.42	1.43	1.67	1.52

It can be seen that the average for this 4-month period was 1.5 kWh/tonne of shipped material.

Unlike some land-based quarries, the processing of marine aggregates generates a low volume of waste product and so there is negligible energy demand in disposing of excess silt fractions or oversize boulders.

5 Comparison with energy used in land-based quarries

5.1 A fair basis of comparison?

Making a fair comparison between marine aggregate production, that delivers material to a wharf close to where it is used, and land-based quarry production, for which energy statistics are calculated at the quarry gate, is not straightforward.

Because of existing land use and planning restrictions, the distribution of land-based quarries does not match the geographic demand for aggregates. Rock suitable for use as an aggregate is unevenly distributed throughout the UK. Whilst Wales has a good distribution of crushed rock aggregate, southern and eastern England are largely devoid of surface resources. As a result, significant quantities of crushed rock are imported into this part of England from the Mendip Hills in the South West, from the East Midlands and from the UK's only coastal super-quarry at Glensanda, which is located on the northwest coast of Scotland. (QPA 2005)

On the other hand, marine aggregate wharfs tend to be in the part of the country that the material is used – or the material is used near where it is landed. This is shown in Figure 6, which excludes beach replenishment. (CROWN ESTATE 2006)

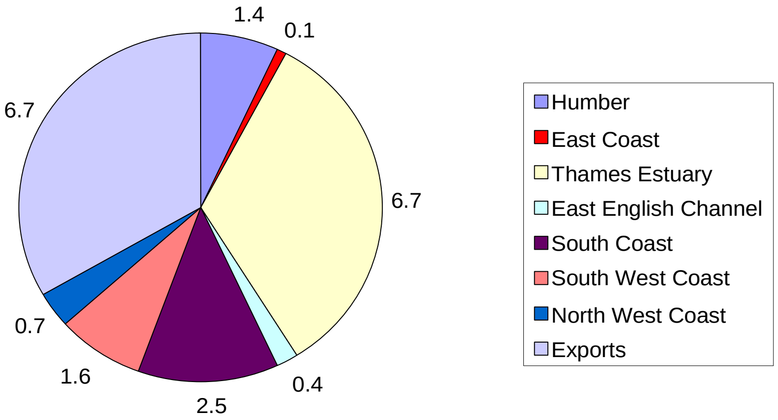

Figure 6 : Deliveries of marine aggregate (2006) Mt

To establish a fair comparison between different sources of production, the following calculation methodology has been adopted:

Firstly, data has been obtained of the energy used in aggregate production, in kWh/tonne, “at the quarry gate”. The marine equivalent ignores the component of dredger energy consumption used to transport the material from the dredging site to the wharf. Thus the dredger data matches, as closely as possible, the way in which production energy statistics are calculated for land-based quarries.

Secondly, calculations have been made of the energy used, in kWh/tonne-km, transporting aggregates on board a dredger, on a large freighter, by lorry or by train (these being the means by which aggregates can be moved from where they are won to where they are used.)

Thirdly, these have been brought together to make a comparison between five different means of supplying material to a site in the London area – near-shore aggregate extraction, off-shore aggregate extraction, transport by freighter of crushed igneous rock from a Scottish super-quarry, transport by rail of crushed limestone from the Mendips and transport by road of alluvial gravel from a quarry in Bedfordshire.

5.2 Comparison of aggregate production

Data on specific energy consumption of different extraction processes has been calculated in the report *Energy use in the minerals industries of Great Britain* (DETR). The averages for the three main sectors (sand and gravel, crushed limestone and crushed igneous rock) are shown in green on the following graph, along with the values calculated in section 4 of this report for marine extraction, which are shown in orange:

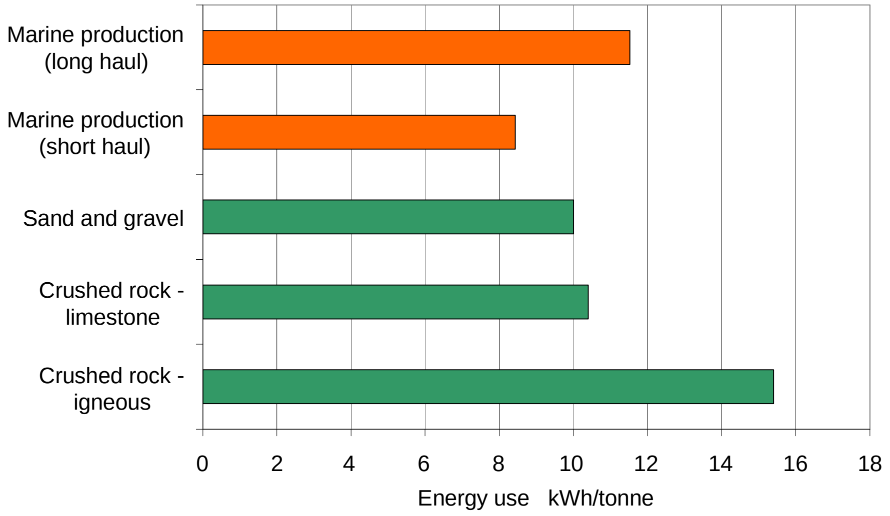

Figure 7 : Energy use in material extraction

The above figures have been carried forward into the estimates of total energy use; however, while the figures for limestone and sand and gravel refer to generic quarries, there is only one “super quarry” in the UK so the production figure taken forward into the summary tables have been recalculated for this specific example.

Glensanda Quarry produces crushed igneous rocks on the west coast of Scotland. The granite is won by conventional large-scale quarrying methods and primary crushing operations are carried out above the 520 metre level. The primary crusher feeds a 300m deep 3.3m diameter vertical shaft which enables the transportation of crushed rock from 500m above sea level without conveyors. The stone is taken through secondary and tertiary crushing at the lower level.

There is no road or rail connection to Glensanda, therefore all the aggregate is distributed by sea. Around 50% of the output goes to mainland Europe and 50% into England and Scotland via depots at Glasgow, Liverpool, the Isle of Grain in Kent, and Southampton. From Southampton and the Isle of Grain the aggregate is distributed by sea - in smaller vessels - and rail as well as by road.[7] The following data for 2006 have been provided by the operator:

Table 6 : Energy used in Glensanda Quarry

Energy use in super quarry			**converted to kWh**
Total production	6,049,937 t		
Electricity used	18,433,834	kWh	18,433,834
Gas oil used	4,398,530	litres	46,624,418
Total energy			65,058,252
Specific energy consumption			**10.75 kWh/t**

---

[7] Information taken from Aggregate Industries (previously Foster Yeoman) website.

6 Calculation of transport energy

6.1 Rail energy consumption

Medium-distance mineral trains in the UK are typically 3,000 tonnes hauled load. Typical fuel consumption of a Class 66 locomotive is 0.5 mpg. Information from operators is that the fuel use is affected at least as much by wind direction and the aerodynamic drag caused by empty mineral wagons as by train loading and thus, for the route from the Mendips to London, this figure is appropriate for either the loaded direction (with the prevailing wind) or unloaded (against the prevailing wind).

Table 7 : Calculation of rail energy use

Rail from Mendips to London	
Total hauled load (excluding locomotive)	3000 t
Mass of aggregate	2500 t
Fuel consumption	0.5 mile/gal = 5.7 litres/km
Round trip Mendips – London and back	400 km
Fuel use	= 5.7 x 400 ÷ 2500 = 0.91 litres/tonne

6.2 Road energy consumption

It has been assumed that road transport of aggregates is in 32-tonne GVW, 5.7m wheelbase, rigid tipper lorries, such as the Iveco Trakker, DAF CF85 or Scania CB series. (Greater efficiency would be possible using 44-tonne articulated lorries but these have difficulty of access and stability problems on certain sites.)

Fuel consumption of HGVs is not as readily obtainable as for private cars, because body styles differ. Extrapolation of trends from a report on lorry environment costs (NERA) gives a fuel consumption of 37 litres/100 km. Work in Australia (Parajuli) suggests 39 litres/100 km, laden, and 31 litres/100 km, unladen (average = 35). Figures from BMAPA[8] suggest rigid vehicles give 7.5 mpg, which is 38 litres/100km.

The three vehicles listed above have kerb weights of 9.2, 9.5 and 9.1 so 9 tonnes has been taken as typical.

---

[8] e-mail from M. Russell, 4 May 07

Table 8 : Calculation of road energy use

Road from Biggleswade to London	
Vehicle GVW	32 tonnes
Tare weight	9 tonnes
Payload	23 tonnes
Fuel consumption	37 litres/100km
Round trip to London and back	150 km
Fuel use	= 38 x 150/100 ÷ 23 = 2.5 litres/tonne

6.3 Sea freighter consumption

Information has been provided on the fuel used to ship crushed rock by the *Yeoman Bridge* or the *Yeoman Bontrup* to the Isle of Grain in Kent, a site comparable to those used for the landing marine aggregate. Two fuel consumption figures have been given – the "eco-speed" when the ship is operated at a fuel-efficient speed and the full service speed. Usually the eco-speed is used and these figures have been used in subsequent comparisons.

Table 9 : Calculation of freighter energy use-

Sea from Glensanda to London	**Full speed**	**Eco-speed**
Total cargo per voyage	86,000 tonnes	86,000 tonnes
Fuel consumption	304 tonnes	182 tonnes
Round-trip distance	2,300 km	2,300 km
Specific fuel consumption	3.5 kg/t = 4.4 litre/t	2.1 kg/t = 2.6 litre/t

7 Overall energy use

7.1 Production and transport data

This section brings together the data for aggregate production and transport to the London area for five alternatives described earlier: short-haul aggregate extraction, long-haul aggregate extraction, transport by freighter of crushed igneous rock from a Scottish super-quarry, transport by rail of crushed limestone from a site 200 km from London (the Mendips) and transport by road of alluvial gravel from a quarry 75 km from London (Bedfordshire).

The following graph summarises data from previous sections:

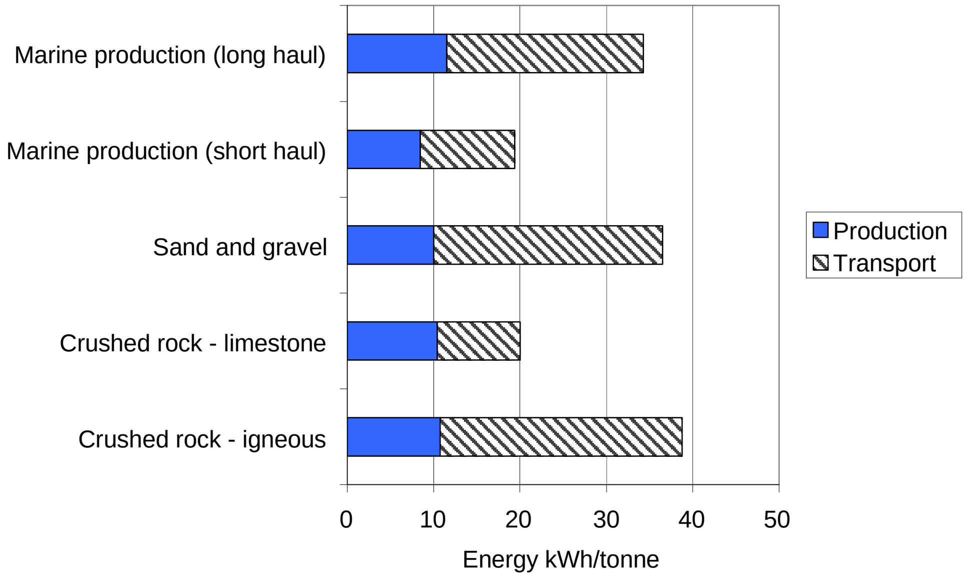

Figure 8 : Overall energy use

7.2 Commentary on results

In looking at the above graph, it has to be remembered that all the calculations are either typical or have included approximations of one sort or another. The intention of the report is provide a “ball park” comparison of different routes for obtaining aggregate, not a detailed auditable calculation as one might want for an inventory of fissile material in the nuclear industry. There is no practical difference between a figure of, say, 25 kWh and 28 kWh. The actual values for a particular delivery will depend on the exact location of a quarry, the distance of the end-use site from the unloading wharf or railway siding, the size of lorry that can access a particular site, traffic congestion, driving style, wind, tides and so on.

It can be seen that the energy used in production is much the same for all sources of material and transport energy dominates the comparison. In overall energy terms, short-haul marine production is as efficient as bulk rail haulage of crushed limestone from the Mendips; long-haul marine production is as efficient as obtaining crushed granite from a Scottish super-quarry or gravel from a quarry 75 km away using road transport.

It is evident from the dominance of the transport energy use that the shorter the distance from a quarry to the end user, the lower will be the overall energy consumption. A comparison with a quarry in Brentwood, rather than Biggleswade would show a greatly reduced energy use, comparable with the transport energy for bulk rail or short-haul marine extraction.

Bearing in mind the limited resources of aggregates near the point of end-use, use of marine aggregates in construction has been shown to be as energy-efficient as other sources of production. The data and methodology in this report can be used to investigate the energy efficiency of specific contracts or proposals.

8 Acknowledgements

Thanks are due to the members of BMAPA, to quarry operators and to many people in the QPA, The Concrete Society and other bodies for their willing assistance and the information they provided.

8.1 References

Alexander, M and Mindless, S, *Aggregates in Concrete*, pub. Taylor and Francis, 2005, pp 178 – 182, ISBN 0 414 25839 1

DEFRA 2005 - Based on the National Atmospheric Emissions Inventory for 2003 and the UK Greenhouse Gas Inventory for 2003 developed by Netcen

DETR 1998 - Energy Use in the Minerals Industry of Great Britain 01-03-1998 Available from The Carbon Trust, reference ECG070[9]

US Department of Energy, *Energy Matters* May 1999. http://www.eere.energy.gov/industry/bestpractices/energymatters/articles.cfm/article_id=186

DTI – Digest of UK Energy Statistics 2005, Chart 5.3

Mamlouk, M S and Zaniewski, J P, *Material for Civil and Construction Engineers*, pub. Prentice Hall, 2006, pp. 164-65. ISBN 0 13 147714 5

NERA report on lorry track and environment costs, DfT, May 2005

Parajuli A, Modelling Freight Modal Energy Use, Transport Research Group QUT

Quarry Products Association – Sustainability report on website 2007 http://www.qpa.org/sus_natres_cons01.htm

Quarry Products Association – Planning4Minerals: A Guide on Aggregates, 2005

The Crown Estate. *Marine Aggregates, The Crown Estate Licences, Summary of Statistics 2006* http://www.thecrownestate.co.uk/43_landing_port_statistics_2006.pdf

UK Energy Statistics 2005, Table 5C

---

[9] It has not been possible to find the Government Department “owning” this DETR report since the organisation was broken-up.

The Crown Estate
16 New Burlington Place
London W1S 2HX
Tel: 020 7851 5080
www.thecrownestate.co.uk

ISBN: 978-0-9553427-9-0