Fuel and energy use in the fisheries sector

Approaches, inventories and strategic implications

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Glossary

BHP	brake horsepower
BTU	British Thermal Unit
CNG	compressed natural gas
CSW	chilled sea water
EEZ	exclusive economic zone
FFA	Forum Fishing Agency
GER	gross energy ratio
GHG	greenhouse gas
GRT	gross registered tonnage
HANPP	human appropriation of net primary production
hp	horse-power (bhp – brake horse-power) =
ISSCFG	International Statistical System for the Classification of Fishing Gear
IUU	Illegal, unregulated and unreported (fishing)
Joule	1 watt x 1 sec = 4.12 Calories; kJ = kilojoule; MJ = megajoule; GJ = gigajoule; TJ = terajoule
LCA	life cycle analysis
LCI	life cycle inventory
LNG	liquefied natural gas
LPG	liquid petroleum gas
MCS	monitoring, control and surveillance
ME	metabolisable energy (in human consumption)
MECO	materials, energy, chemical and other (inventory or analysis)
nm	nautical mile
SFC	Specific fuel consumption (of a vessel), expressed in gm/kW/min.
RSW	refrigerated sea water
TEU	twenty foot equivalent unit (transport container)
TOE	tonnes of oil equivalent
UNCLOS	United Nation Conference on the Law of the Sea.
W	watt; kW = kilowatt; MW = megawatt; GW = gigawatt; TW = terawatt

Summary of key energy related conversions:

Energy term/definition	Conversion	Energy term/definition	Conversion
Diesel, litres	10.74 kWh	Joule = 1Watt x 1 sec	0.239 Calories
Gasoline, litres	9.63 kWh	kWh = 1 kW x 1 hr	3.6 MJ, 860 kCal
Natural gas, m3	10.31 kWh		3,413 BTU, 1.35 hp-hr
Light fuel oil, litre	10.40 kWh	BTU = 1lb H_2O x 1^oF	~ 1055 Joules, 0.25kCal
Bunker C, litre	11.59 kWh	1 hp	~ 0.74 kW

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Foreword

The role of fuel and energy in the fisheries sector is an important yet so far little noted issue in natural resource, food and trade policy. While specific aspects of fuel use and cost have periodically concerned the fishing industry and its policy and management agents, the strategic issues of these have been relatively unquestioned until recently. However, in the midst of growing concern for rationalisation of fisheries management, for energy and greenhouse gas linkages in climate change mitigation, for competitive options for smaller scale producers, and for consumer appreciation of the environmental footprint of food choices, these issues deserve further exploration.

This review addresses the utilisation of fuel energy by the global fisheries industry. It is based on an initial working document produced by Andrew Smith, FIIT/FAO in response to short-term concerns associated with the oil price shock of the late 1990s, further extended to deal with wider issues of the industry. It explores the complete supply chain from aquatic raw materials to consumption, including capture fishing, aquaculture, post-harvest activities, distribution and retail presentation. This is the first such global overview, and although it has not been possible to set out complete and integrated value-chain perspectives, it provides initial data to demonstrate a range of critical characteristics and trends, with implications for sector development and relevant policy and strategic investment needs. As discussed more fully in the text which follows, there are important interactions to consider in policy and practice, not just in ensuring the viability of the fisheries sector, but in linking energy cost with competition between capture fisheries and aquaculture, with choices of fishing methods or aquaculture systems, with implications for fishing effort, resource pressure and management strategies, and with the costs of making food available to consumers at all levels.

1 Introduction; approaches and methodologies

1.1 Introduction

The fisheries sector, including fishing, aquaculture, post-harvest processes and product distribution, is highly dependent on the use of external energy, particularly in the form of fossil fuels. Over the last fifty years global fish output for human consumption has grown from some 25 million tonnes in 1950 to more than 115 million tonnes in 2008, with a total first hand sale value for all output of around USD 300 billion(FAO, 2010) Output from fish capture is probably close to its maximum and greater benefits from resources can only be achieved through better management, more efficient processes and less waste. Greater output to meet rising world food demand will have to come from aquaculture, which in recent decades has expanded very rapidly, in 2007 exceeding 50% of global production for human consumption and entering significantly into international trade.

In the last decade the cost of fuel and other energy sources has on a rising trend become increasingly volatile, and this instability has had a notably adverse effect on the viability of some fisheries. In 2001 fuel was estimated to account for some 21% of revenue from landed catch whereas in 2008, during the first recent period of high oil prices this increased to about 50%. Fuel use varies widely with fishing type and effort level, and profit margins depend on catches and sale values, but as one of the key cost elements over which the sector has little immediate control, profitability and livelihoods are potentially highly sensitive to energy cost.

Though aquaculture has less direct fuel dependency, its energy demands are important. Particularly for higher valued carnivorous species, and also for intensifying production of many of the less demanding species, feeds with significant fishmeal and oil content are widely used, resulting in a strong interdependence with capture fisheries. Apart from the resource issues of supporting meal and oil fisheries, the linkage also inescapably involves the energy costs of capture fisheries, together with energy required for processing, compounding and distributing the feeds produced. These also include energy costs associated with terrestrial feed sources. More intensive forms of aquaculture also commonly demands more water exchange and better water quality management, which add further energy costs.

Post harvest and processing activities, whether on board fishing vessels or ashore, are also heavily dependent on fuel, though less so than the catching sector. The great increase in fish trade over recent decades has created significant demands for frozen product, increased export of high value/low volume product (e.g. shrimp, lobster, marine fish etc.) to wealthier markets, and trade of lower value product (e.g. dried, canned fish) around most parts of the world. A greater emphasis on wider distribution of live or highly fresh seafood, more geographically dispersed supply chains and more sophisticated value added products also contribute to increased energy demands. The distribution and related supply chain energy costs are also significant, as ultimately are the costs associated with post-consumption wastes, both of the fish product and the associated packaging.

Future projections for energy supplies and for fossil fuel in particular, are challenging, with rising demands, finite oil resources, potentially costly alternatives, and prospects for increasing real-term prices. The catching sector is particularly vulnerable, having few short-term alternatives to fossil fuel, while the wider sector will also face increasing costs even if it has access to more energy options. There will be significant impacts throughout the supply chain, on the resources themselves, and to the food security of many dependent people. With this first stage in defining the scope of the problem, the trends, impacts and potential responses, at policy, implementation and investment levels can be set out.

1.2 Energy and the fisheries sector

The significance of energy and fuel in the fisheries sector, and its vulnerability to changing energy supplies and prices have highlighted the need to review the sector's energy and fuel needs and interactions, and their future trends. This needs to consider use levels in different areas and parts of the sector, financial and other impacts, and the options and potential for responding to and mitigating the effects of increased energy and fuel costs. In the broader context, energy and fossil fuel connections in food production have been subject to notable interest for some decades as farming system analyses started to explore implications of agricultural intensification. These have developed towards more complex and detailed analyses of energy in ecosystem support and the carbon footprints of various food commodities.

With increasing trade and globalisation, the perspective has also rapidly extended from the energy inputs specifically for food production, to the complete supply chain demands for inputs, products and related materials from original sources to consumers and to their wastes. Energy use is now increasingly important in comparative resource use analysis, potential trade trends, and in carbon and related greenhouse gas (GHG) impacts in climate change mitigation (see eg Poseidon 2011, FAO, 2012). It has received particular emphasis most recently due to the unprecedented instability in fossil fuel costs, and together with other factors, the sudden and potentially lasting impacts on the economic performance of various food production sectors. These impacts, and their implications for livelihoods, food supply and food security, also apply very markedly to the fisheries sector, and are likely to have profound consequences for production opportunities, for resource impacts and for food security across a wide range of consumers.

The aim of the review is to provide a preliminary approach to issues of energy and fuel use in fisheries as a basis for guidance and advice to fishing and aquaculture communities, processors, owners and governments. The issues are rapidly evolving, and more data and analysis can be expected in coming years, so at this stage, the review offers the key factors and dimensions, potential directions and ideas for further development. The sector is divided into capture fisheries, fish processing, aquaculture and transport sectors. The final section of the report describes future production / cost scenarios and options the fishing industry may need to consider reducing their reliance on fossil fuels

1.3 Approaches used in the supply/value chain

In the absence of standardised approaches, various practical means have been used to estimate fuel or energy use at a global level, where feasible differentiated for different systems, and validated with specific data sources. For consistency, energy use from a range of sources is expressed as far as possible in terms of equivalent tonnes of fossil fuel. This is also converted for comparative purposes into USD values, based on recorded or recent prices. To estimate fuel/energy use in the fish catching sector, various parameters of the global fleet are used to define size classifications, sub-sector definitions and the fuel utilisation of each sub-sector. This is validated by comparing with actual measurement reported for various national or regional studies, and by proxy estimates based on vessel operating costs. Financial returns, and the role of fuel costs are defined at two levels:

- gross profit: income less direct fishing costs, indicating the short term viability of the fisheries operation
- net profit: gross profit less depreciation of capital value and interest paid on loans, indicating longer term viability, and the ability to service investment and re-invest in future years.

Vessel and gear classifications are based as far as possible on designated categories, in Lloyd's Shipping Register, and in FAO statistical classifications. However, due to lack of data, rather than using the International Statistical Standard Classification of Fishing Gear (ISSCFG), a simplified range of gear descriptions is used, based on the specific studies undertaken. Artisanal fishing activities involving little or no fuel are excluded from primary global estimates, though the cumulative impacts of large numbers of small vessels with varying levels of motorisation are noted. Relationships between labour and fuel use are also noted, illustrating where fuel costs may impinge on earnings. Unlike other parts of the sector, fish catching is almost completely dependent on fossil fuels for energy needs, and has limited immediate potential for change.

For the aquaculture sector, global and regional production reported to FAO is used along with a simple typology of production systems to estimate fuel and energy use. In this case the breakdown has been by continent and the species group being cultured. Estimates at this stage are rather crude but could in future be refined to specify the sector in more detail (e.g. to increase the present 5 species groups to the 30 or more key species, and to define systems more closely). The energy requirements for aquaculture can be met with a wider range of sources than capture fishing, though still have a strong linkage with fossil fuels, especially as most energy-intensive systems owe their dependence to use of manufactured feeds, in which fish meals and oils still play an important part.

The processing sector is downstream of both fish capture and aquaculture, and for global estimates, energy use ratios for various product forms are applied to total sector outputs (capture plus culture). Generic levels of energy use by different processing methods is relatively well documented, and in common with the aquaculture sector, a wider range of energy sources can be accessed. Usage is commonly expressed in KWh per tonne of product, though care is required to determine whether this based on input or output. In some cases, attribution to primary and secondary products also needs to be considered. The main processing methods are classified as fresh (using ice or RSW), frozen, canned, dried/cured and reduction to fish meal. An important secondary issue, with variable links to energy consumption, is water use, for which further information is also supplied.

An initial overview of the transport and distribution aspects of the sector is also set out. However, it has been difficult to develop this to regional and global levels due to the lack of reliable data on overall process yields, and on the proportion of output which is transported in whole or processed form. FAO statistics record landed weight only, while in many cases these landings are processed, with substantial weight reductions, prior to transport to reduce transport costs, preserve quality and add value further in the market chain. Overall data on transport flow of fisheries products by system type and distance is also difficult to define, and only general estimates can be made based on known trade links and quantities traded. A more complete perspective on energy use through the subsequent market stages to food service points and/or final consumers (and beyond to include energy associated with post-consumption wastes) was not attempted, though some indicators have been given. However these issues will have important implications for source competitiveness and trade opportunities and will deserve further attention, with full life-cycle analysis increasingly being sought (see Parker, 2012, FAO, 2012).

The penultimate part of the review addresses the means by which energy consumption could be mitigated or reduced, by various means from immediate practical responses to longer term, more strategic approaches. This focuses particularly on capture fisheries, for which energy consumption and fossil fuel dependency is most critical, but also extends to other areas. Finally, a brief outline is provided of the policy and development options associated with energy use, together with suggestions for future work in improving relevant data and information, and in supporting the fisheries sector in responding to the very wide-ranging effects that will be brought about by changes in the local and global energy economy.

1.4 Concepts and methodologies for defining energy use

Energy is used in the fisheries sector either directly – eg for heating or light, or more commonly to convert to work in the form of motive and propulsive power, lift, or in compression and cooling cycles. Energy is also applied in producing various capital items and raw material inputs, and in treating or disposing of various unwanted or unused wastes or byproducts. For the last, distinctions may also be made between energy actually used to treat wastes, or if no treatment is done, the energy required to avoid external impacts. Energy use can be defined and measured in a number of ways, and some standardisation of concepts and measures is needed to ensure sufficient comparability of data and implications across a complex and diverse sector such as that of fisheries. An outline is as follows:

- direct fuel use – primarily liquid petroleum products – diesel, LNG, petroleum – but in some cases materials such as wood or coal, defines the specific usage of a particular product in an activity or output, either by quantity or fuel value This is the simplest and most common focus of measurement, with immediate impacts of linking fuel prices to operating costs. This is most widely used in the review.
- total direct energy use – a wider system of measurement where the total of fuel, electricity and other sources of energy input are defined – usually in energy units relative to the specific activity or output. This gives a more complete picture of use and a wider means of comparison when fuel use is not the only energy element. This is also used in the review, particularly for aquaculture and processing, where a range of energy sources is involved.
- industrial energy use – assesses the energy required to produce or manufacture all the capital and operating inputs in the process, eg steel, timber, synthetic fibres, plastics in vessels, gear, aquaculture facilities and processing equipment, and including inputs such as fish feeds, chemicals and treated water. This total is then related to the outputs. These values are referred to occasionally in the review, to demonstrate the wider implications of the activity concerned.
- embodied energy (emergy) – takes a more holistic approach, and in addition to industrial energy, includes photosynthetic energy input into the biological processes of ecosystem support and food chain supply in fisheries resources and aquaculture processes, and ecosystem support for taking up process and consumption waste. These values are also noted occasionally, where available, to consider the strategic ecological efficiency of the sector compared with other food supply options. However, though important in strategic terms, methodologies and data are as yet relatively undeveloped.
- renewable and non-renewable energy use – in any of the above categories, identifies the specific sources of energy according to whether they are renewable – solar, wind, tidal, hydropower, or based on biomass crops, or derived from fossil fuels. This can be used to identify the potential sustainability of a specific sector, and its likely cost dependence on sources with finite supply.

Common units applied in these assessments are kW or hp for power (energy per time), kWh, hp-hr or MJ for energy (or MWh, GWh, GJ or TJ for sector wide or larger geographical area reviews. Comparative indicators include kWh/tonne for energy use per output, or kWh per unit of value. Applied energy can also be compared with the calorific energy of the product, to give an energy ratio (GER). In most fisheries activities this is well in excess of 1 (ie more energy goes in than is recoverable in product). These concepts also give rise to measures of the 'energy subsidy' – which are often specifically applied to the fossil fuel input per energy of output.

Each of these assessments can be applied to specific parts of the sector – eg fishing, aquaculture or processing, or can be applied to the complete supply chain. They can be applied, most commonly, to the activity carried out a particular time, or the output – eg harvested fish or consumer products, or can be compiled more comprehensively to develop more complete life-cycle assessments (LCA). These review all the inputs to a particular process and output, then link this with distribution, product form, packaging, preparation and serving processes, and the collection and disposal of byproducts and wastes (see eg Poseidon, 2011, Parker, 2012). In the case of the fisheries sector for example, a complete perspective could include disposal of capital items such as vessels, production facilities, gear and equipment, and also product packaging and food service or domestic catering waste. In this review, the main focus is on direct fuel consumption, though reference is made where available to other aspects of energy use, and to implications for the related themes outlined above.

1.5 Links with key/related issues

Related concepts, not developed here, but closely linked to fuel and energy themes and increasingly important for longer-term perspectives include:

- carbon footprint and food miles assessments; which connect the energy use in terms of carbon dioxide production, or link product supply with transport distances and hence energy inputs for transport;
- wider natural resource and ecosystem consequences; for key resources – eg feeds for aquaculture – the energy extracted from ecosystems in one part of the world, delivered to another, where in addition to producing food, they create wastes which are taken up in the destination ecosystem. Water resources (and the implied energy in sourcing and cleaning water) for aquaculture and processing are another area of importance.
- relationships with climate change processes and impacts; where use of fossil fuels may add to greenhouse gas (GHG) production, where mitigation features of various aspects of the aquatic supply chain could become important (potentially changing economic incentives), and where impacts of climate change will result in changing energy requirements in various parts of the fishery sectors.

A further issue concerns the sourcing of energy and the options available to do so. It is not within the scope of this review to detail the supply characteristics of the energy forms potentially accessible to the sector, or to consider their future availability and costs within changing scenarios of supply and competing demands. Energy supply to the fisheries sector is just one part of a much wider and more complex area of economic development and policy choice, in which not only energy sourcing but the impacts of use (eg in GHGs) are becoming more widely considered. Technology changes at various levels and within both supply and demand areas will also have significant impacts of future energy availability and price, while policy and strategic investment in energy capture or supply, together with changing market and geopolitical conditions, will also have a major effect on supply, price, and sectoral impacts. Nonetheless, some basic points are worth noting:

- The importance of accessibility, versatility, energy density (energy content per volume) and safety issues in energy supply. Use of auxiliary energy, from animal draught for hauling boats or nets, or carrying product, through wind power in sailing vessels, has had a long and diverse history, but it was not until coal fuelled steam power became reliable and practical that energy could be harnessed more widely and fishing effort increased substantially, with longer fishing periods, larger and heavier gear and the potential for on-board processing. This was quickly superseded by the use of the internal combustion engine, which with various ancillaries, directly powered or via secondary electricity generation, remains the primary energy system. The relative efficiency, wide availability and high energy density of fuel oils make them the primary option in almost all applications at sea, and limit the use of alternatives. Of current and emerging technologies, biofuels could offer a direct replacement for use, while hydrogen fuel systems can offer good energy density but are yet to satisfy a range of practical safety issues and will require major supply infrastructure. For these reasons, fossil fuel availability and price will continue to have a major impact in key areas of the fishing industry

- Net energy efficiencies at local and at wider levels are also important, with greater awareness required concerning the energy loss involved in transporting fuel materials or distributing centrally generated power (eg for electrical supplies). Thus fuel oil for fishing can have added energy costs related to its transport, and electrically driven pumps in aquaculture systems, though more efficient at point of application than their diesel equivalents, may be much less efficient in overall energy terms once substantial transmission losses are considered. In both cases, the efficiency by which the energy is then used also has a great bearing on the overall energy use/cost per output.

- The environmental implications for the choice of fuels are likely to be increasingly open to review, particularly with respect to greenhouse gas (GHG) emissions associated with the sourcing and use of fuels. Depending on policy conditions, financial and market incentives or penalties could increasingly be used to influence choices, and ensure that environmental costs of more damaging fuel options are reduced or sufficiently compensated. This is likely to have particular impact on those parts of the sector with high direct fuel usage.

- Investment and conversion needs – alternative forms of energy require investment both at the supply level and in terms of devices capable of using these. At best, simple small conversions may be all that is required for changing sources – eg diesel to biofuels, but significant capital replacement may be needed for other changes, particularly if efficiency of energy use is to be optimised. This has impacts both in time and money.

- Political and consumer acceptability will also have a bearing on future energy options. Fisheries, like all other food supply sectors is increasingly subject to social and political scrutiny in its actions and impacts, and through shortening and more concentrated supply chains, consumer demand for positive social and environmental performance will also favour suppliers who can demonstrate more efficient and protective use of resources. This could impact both on the choices of fuels and the efficiency in which they are used.

2 Capture fisheries

2.1 Introduction

Fishing activities around the world are very diverse and range from the simple hand-collection of shellfish or seaweeds onshore, cast nets and handlines in water margins, to small boats and canoes with varying levels of mechanisation, to versatile, technically modern mid-sized vessels, to very sophisticated large fishing vessels with entire processing systems on board. These large vessels require substantial investment, in the order of 40 – 50 million USD, well trained crews and extensive support infrastructure, and have evolved in response to opportunities to catch and sell substantial global fishery resources. Energy use clearly varies widely across the sector, and to describe the global industry more effectively the features and characteristics of its subsectors need to be considered in further detail.

2.2 Systems/structural descriptions,

Although a wide range of classifications and definitions can be used for capture fisheries, a simple three-class system is applies here, broadly reflecting the different levels of capital and energy intensification applied. As shown later, the implications of these input levels can be significant, and changing fuel costs are likely to apply in different ways to each class of fishing activity.

Small-scale/artisanal/inshore fisheries [1]

These fisheries embrace a range of practices, but are typically traditional activities involving fishing individuals or households, (as opposed to commercial entities) using small amounts of capital, and relatively simple gear, in some cases only shore based, but commonly with small fishing vessels, making short fishing trips, close to shore. Harvests are mainly destined for human consumption, varying parts of which are for own use [2] or marketed. Fuel use is primarily associated with motorised vessels, for outboard or inboard engines, though ancillaries such as lamps and lights may also be involved (and could have important implications for some fishers), together with post-harvest fuel use associated with ice supply, cool storage, drying and smoking (see later), whose viability will affect sale prices and hence fishing opportunity.

Some 59% of the global fleet are motorised, of which 86%, 2.2 million vessels, are less than 12m in length (FAO, 2010). Because of their small size, the area of operation is limited and is generally carried out on a daily basis within a coastal or lakeside zone (e.g. 12 nm), catching an average of 1-3 t of fish per person annually. Based on a global total of 34.1 million people engaged in fishing, and assuming pro rata employment levels across all vessels, some 17.3 million people, plus their dependents, would be associated with this category of fishing. Five countries - the People's Republic of China, Indonesia, India, Bangladesh and the Philippines – have particularly high numbers of small scale fishers and account for more than half of the global total for the sector. Many countries have laws limiting activities of larger fishing vessels within these zones to preserve resources for local coastal communities, but small scale fishers are particularly at risk from competition from the increased fishing effort of larger vessels in inshore waters, for which IUU (illegal unregulated and unreported) fishing is a very widespread issue, and may also increase with higher fuel costs.

Artisanal fishers can be very conscious of their environment in terms of seasonal cycles, lunar phases and fish habitat and aware of the effects of changes in the local ecosystems. Traditionally, their

[1] definitions vary – ranges from very marginal part-time/seasonal fishing to moderately capitalized full time occupational activity. See also the FAO/World Bank/Worldfish report on the 'Big Numbers Project, 2008)

[2] commonly described as subsistence fishing, though in practice in most parts of the world at least a certain part of catch is sold or exchanged

number and fishing effort were seasonally controlled by resource availability, but with population pressures and/or limited resources within the traditional fishing grounds, greater fishing effort, migration to other grounds and longer fishing ranges have become much more common. Although artisanal fishing communities are rarely viewed as heavy energy consumers, their numbers and their fishing impacts mean that total fuel use and its linkage with fishing effort can have important consequences in terms of local livelihoods, resource impacts and strategic policy choices.

Coastal industrial fisheries

The continental shelves are very productive fisheries zones, estimated to account for some 90% of marine production. Historically, fisheries have developed where medium-sized local vessels have readily been able to access resources. This is most apparent in Europe where resources have now been regarded as fully exploited, if not over-exploited, for a number of years. Other coastal regions are also identifiable, and a similar fishing type and level also occurs in larger lakes and inland seas.

At the semi-industrial level, there are estimated to be about 2 million people fishing in vessels between 12 and 24 m in length (FAO 2010). These vessels are able to fish further from the shore, but sometimes also encroach in inshore waters. They have to catch significantly larger amounts of fish to recover investment and operating costs, and might in some areas fish outside their national waters, or compete in their own waters with other fleets. The definition and control of EEZs has to some extent curtailed the activities of foreign vessels from nearby fleets and distant water fishing nations, though access agreements with coastal states have been relatively common during the last twenty years, and IUU fishing in some areas remains a significant factor in effort and pressure on stocks.

In many fisheries, vessels in this size range have become increasingly powerful and capital intensive, partly to be able to fish further and for longer, and partly in response to vessel size restrictions introduced in fisheries management regimes. Investment and running costs are correspondingly higher and require greater catch and income levels to maintain viability.

Distant water fisheries

The offshore sector (usually vessels more than 24 m/100 t GRT[3]) involves an estimated 500,000 people producing around 40 t/person/year, often operating thousands of kilometres from their registered bases, in international waters or licensed EEZ areas in distant waters, for trip periods of several months to more than a year, landing or transhipping periodically in a range of locations.

Earlier strategies for expansion and development of fisheries anticipated a continuing process of building larger vessels to fish in distant waters. However this was substantially reversed in the early 1990s with the collapse of Soviet bloc economies, whose major presence in the sector was curtailed, with a large proportion of fleets laid up and subsequently scrapped. However, large distant water vessels are still operational and financially viable in some areas, mainly where smaller vessels are not feasible and local infrastructure is not present. Fisheries in the polar regions of the North Atlantic and North Pacific are harvested by large stern trawlers of which many have on board processing facilities. Tuna purse seiners operate in virtually every ocean and the numbers and size of recent new vessels being built indicate perceptions that the industry is very profitable. The Patagonian toothfish industry operates widely across the Southern Oceans, with many vessels equipped with

[3] GRT – based on usable volume (1T = 100ft3 or 2.83m3) ; measurements are now governed by the IMO International Convention on Tonnage Measurement of Ships, 1969 (London-Rules), applying to all vessels built after July 1982.; GT, the gross tonnage is a function of the moulded volume of all enclosed spaces of the vessel. This class of vessel size is recorded on the Lloyds Register of Vessels.

processing plant, storing catch until landing at convenient ports. Others tranship to fish carriers and are supported by supply vessels for fuel and stores.

Distant water fisheries are also common off West Africa where European vessels fish for tuna and white fish and Chinese and Korean vessels fish mainly for tuna. In the Pacific, Japanese, Korean and Chinese vessels fish for tuna under agreements with the Forum Fisheries Agency (FFA) or in open waters. The large size and fishing capacity of these vessels, and their relative mobility, often focusing on major pelagic stocks, coupled with the political and technical of difficulties of effective MCS (monitoring, control and surveillance) operations and enforcement actions, have opened this category of fishing to persistent concern for damaging stocks through over fishing.

2.3 Key energy elements and linkages

The primary energy elements are those for fuel for propulsion, and for larger vessels, power supply for a range of ancillaries. The relationship between fishing effort, fishing methods, distance to fishing grounds, vessel speed and fuel efficiency of hulls, engines and propulsion systems are all key factors. Linking with stock conditions and market values these are all reflected in operating costs, the profitability of fishing and the level and choice of activity. There are important linkages with fisheries management consequences – whether fishers are compelled to overfish in the push for financial returns, whether rationalisation will reduce cost and increase returns, whether changes in fishing gear will have impacts on stocks and ecosystems, and whether fuel subsidies are justified as means of retaining local employment or food supply.

Fuel costs in most forms of fishing activity have direct implications for viability. Types of fishery, conditions of fishing and market prices will all determine the impact of fuel prices, as will specific conditions of the fishing enterprise. Impacts of rising fuel prices and reduced profitability, including the value of capital assets used in the sector can extend widely. Shorter-term changes can be accommodated by scrapping older or more inefficient vessels, selling and writing down capital values (and hence financing and depreciation costs), or by laying up vessels in the hope of future profitability. Poor profitability will inhibit the building of new fishing vessels, and would decrease fleet size even at global level. In the absence of external actions such as fuel subsidies or market interventions, rising fuel prices will drive out unprofitable fishing businesses, and will tend to reduce fleet size. Depending on the nature of the fishery, this may reduce output, or improve vessel yields and overall economic and fuel use performance. However, various forms of inertia - time lags in market responses and shorter-term support actions, might delay these changes.

At the shore side, a decrease in fleet profitability can affect the related economy, particularly in small rural economies, where impact can be significant. In some conditions this can lead to port and other infrastructure elements becoming unviable. Thus when large fishing ports (e.g. Hull, Fleetwood, Bremerhaven, Rostock or Boston) started to lose vessels, decline happened very quickly. As fleet size decreases, shore-side facilities become relatively inefficient and costly. Depending on factors such as fishing ground and port locations, market conditions, national boundaries and policy environments, it may quickly become cheaper for vessels to land catches and obtain services elsewhere. Various estimates suggest that each job at sea can support up to seven or eight jobs ashore, depending on the extent of services and post-harvest activity involved. (FAO 2008). Thus in Scotland in 1999, with 7,774 people directly employed in fishing, 10,405 were in processing, compared with a total of 44,000 direct, indirect and induced jobs (Scottish Govt 2002). A more recent review by the Australian Bureau of Statistics calculated an economic multiplier of 2.424 for commercial fisheries (DPI, 2010) In Senegal, the sector was reported to employ 125,354 people, including 59,428 full-time artisanal fishers, 2,850 people in 76 processing plants, and 59,976 employees in craft workshops for processing, maintenance, construction of boats and gears, transportation, marketing, etc. (MRAG, 2009) Even with lower multiplier levels, the loss of a fishing port activity can result in very high local unemployment, with workforces which may be difficult to retrain. However if the processing infrastructure is competitive and accessible to national and other markets, these functions may be retained, with raw material supplemented from other locations.

2.4 Summary of findings/emerging work

A small range of studies focusing on fleet costs and earnings, and on size of fishing vessel and type of gear has provided the basis of current estimates.

Historic data

Tables 1 and 2 summarise details of the first such analysis (FAO 1992), based on 5 vessel size classes, and a range of estimates of days at sea, installed power, specific fuel consumption and operational constants (% of full activity level while at sea). This included for the first time an analysis of financial viability of the global fishing fleet, but these were limited by the quality of various assumptions. Capital values were based on new build costs, whereas fleets were subsequently found to have an average age of over 20 years in a life cycle of around 30 years. This in turn led to overestimates of related expenditures such as maintenance cost. However fuel cost, estimated here at USD 300/tonne, was independent of fleet age and considered to be broadly accurate.

Table 1: Estimates of fuel consumption by the global fishing fleet , 1992

GRT classes	Days at sea	Specific fuel con-sumption, g/kWhr	Total instal-led hp	Operat-ional constant	No of vessels	Fuel consumption (tonnes)		Annual fuel costs USD million* per vessel class
						Per vessel	Per vessel class	
>1000	250	160	3 000	0.60	3 010	1728.00	5 201 280	1 560.4
500-999	250	160	2 000	0.60	2 100	1152.00	2 419 200	725.8
100-499	220	180	800	0.55	30 600	418.18	12 796 300	3 838.9
<100 decked	180	200	50	0.40	1 100 000	17.8	19 008 000	5 702.4
<100 un-decked	180	200	20	0.20	2 100 000	3.456	7 257 600	2 177.3
Total							46 682 380	14 004.4

Source: Marine Fisheries and the Law of the Sea: A Decade of Change FAO 1992) * at USD 300/tonne

The review concluded that at an average of 15%, fuel costs were a significant part of fleet budgets, and that the global fleet operated at a substantial loss. The very large numbers of smaller vessels (< 100t GRT), though consuming much less per vessel, accounted for a substantial part of fuel demand. As shown also in Table 3, the small scale sector accounted for substantial numbers of people and their livelihoods, and using the estimated ratios in the review, fuel use per person employed increased substantially from 1.15t for <100t undecked vessels, to 28.8t per person for vessels above 500 t GRT.

Table 2:   Global fleet operating costs by factor.

Operating cost element	Total costs (USD million)	As %age of total costs
Labour	22 700	26
Fuel	13 300	15
Maintenance	26 400	30
Insurance	4 800	6
Fishing gear and supplies	18 500	22
Total	85 700	100

Source: Marine Fisheries and the Law of the Sea (FAO 1992)

Table 3: Labour costs in the global fish catching sector

Tonnage	No of Vessels	Crew per vessel	Total crew	Estimated earnings per person, USD	Total labour costs (Million USD)	Fuel cost as %age of labour cost	Fuel use (t) per person employed
>1000	3 010	60	180 600	15 000	2 709	57.6%	28.8
500-999.9	2 100	40	84 000	15 000	1 260	57.6%	28.8
100-499.9	30 600	30	918 000	8 000	7 344	52.3%	13.9
<100 decked	1 100 000	5	5 500 000	1 500	8 250	69.1%	3.46
<100 undecked	2 100 000	3	6 300 000	500	3 150	69.1%	1.15

Source: Developed from Marine Fisheries and the Law of the Sea: A Decade of Change 1992)

Further to this, three studies (FAO, 1999, 2001, 2005)investigated selected fisheries over a period of about 10 years, including Antigua and Barbuda, Argentina, Barbados, China, France, Germany, Ghana, India, Indonesia, Malaysia, Norway, Peru, the Republic of Korea, Senegal, South Africa, Spain, Taiwan (Province of China), Thailand and Trinidad and Tobago. Gears were classified as:

- Active demersal gears; including bottom trawls, shrimp trawls, dredgers, beam trawls, and hydraulic dredgers. The vessel fishes for a stock that is generally spread over a large area and the method effectively processes large volumes of water (or areas of sea-bottom) to catch a relatively small quantity of product. Because of towing resistance, and as the time spent in the fishing process is high compared to the time going to or from the fishing ground or searching for catch, fuel consumption is relatively higher than for other gears.
- Active pelagic gears: including purse seines, mid water trawls, ring net and lampara; pelagic fish tend to form very dense schools, and fishing is usually unviable if a school has not been located. This means that vessels spend much of the time searching for schools, compared to time catching fish, taking it on board and landing. Some such vessels can catch thousands of tonnes of fish within one hour, i.e. more than some countries catch in a year.
- Passive fishing gears, including gill and trammel nets; tangle nets; longlines, trap nets and pots, and lift nets; use very little power in fishing and in some cases no mechanical energy. Although travelling, setting and retrieval of gear may use some energy, target stocks are attracted by bait or are carried to the gear or encounter it by chance and are trapped. Methods such as pole and line have been mechanised but even these have low power consumption compared to the other two categories

The first analysis (FAO 1999) showed significant overlap between the three categories. However notable differences were found between fisheries in developing and industrialised countries (Table 4) the former spending a far higher share of revenues on fuel (almost twice as much in 2002/2003).

This suggested that fisheries in developing countries would be far more susceptible to increased fuel prices, though it may also relate to sales prices and earnings being lower. In most cases, particularly in developed countries, active demersal fishing had a higher %age of fuel costs in earnings. This was normally followed by active pelagic fishing, then passive gear, which for developing countries had much higher fuel cost % ages. The difference between developed and developing countries is most discernable for passive gears, varying by more than a factor of three for all three studies, though there were also substantial differences for active pelagic fishing. The average ratio of fuel cost/landed revenue increased from 14.83% to 18.53% from 1996 to 2002 a rise of almost 25%. This may also have been influenced by declining earnings but these are not thought to have changed as much. At a global level, allowing for the relative weightings of the countries surveyed, fuel costs are nearer the developing country levels than those for the developed countries, and many more people would stand to be affected by higher fuel costs.

Table 4: Cost of fuel as a percentage of landed revenue for different fisheries

Category	FAO 1999		FAO 2001		FAO 2005	
	1995/1997		1999/2000		2002/2003	
	No of fishing units	Fuel as % of gross earnings	No of fishing units	Fuel as % of gross earnings	No of fishing units	Fuel as % of gross earnings
Averages	88	14.83	108	16.70	75	18.53
Developing countries	46	18.52	70	20.65	55	21.63
Industrialised countries	42	11.08	38	9.78	20	10.02
Fishing types						
Dev Country/Active Demersal	20	17.19	25	30.28	22	26.15
Dev Country/Active Pelagic	17	17.33	15	19.35	8	16.99
Dev Country/Passive Gear	20	18.78	29	17.06	25	19.33
Europe/Active Demersal	25	10.57	22	8.64	11	14.37
Europe/Active Pelagic	n/a	n/a	5	7.65	1	5.48
Europe/ Passive Gear	6	5.57	12	4.95	8	4.61

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Table 5 gives the average fuel costs for the fisheries reviewed in specific countries in the last of these studies (2002-03)[4]. While this can also be influenced by the types of fishery, this illustrates the great disparities between developed and developing countries, with particularly high fuel cost levels in Senegal, India and Thailand. The disparity in fuel costs relative to earnings is not unique to fisheries, as more generally, developing countries are less able to convert energy utilisation into an increase in GDP. Various factors could contribute to this, including poorer infrastructure, less efficient capital installations, higher real fuel prices, less value-added production and more restricted market access. A number of these factors are also relevant to fisheries, and could potentially be identified more closely. For 87 fisheries reviewed (FAO 1999), none had negative gross profits, but 15 showed a negative net profit and were unviable in the longer term.

Table 5: Fuel cost as percentage of revenue by country (FAO 2005)

Country	Fuel costs as % of landed value
Norway	8.01
South Africa	9.0
Caribbean	12.73
France	13.7
Rep. of Korea	18.29
Argentina	21.4
Senegal	27.7
India	28.57
Thailand	38.09
Average	15.66

Consequent EU reviews

A detailed series of EU reports, “Economic Performance of Selected European Fishing Fleets”, addressed key costs. The last of these, published in 2006 concerned data for 2004. Data were collected from EU countries with substantial fisheries together with Lithuania, Estonia and Latvia (subsequently EU members), the Faeroe Islands, Iceland, and Norway. These aggregated data for all vessels within each chosen sector and covered 20 countries and 86 fisheries, representing 60–70% of the European fishery sector in terms of value and volume. The 2004 EU study gave an average ratio of fuel cost/landed value of 13% (Table 6). However, reporting levels varied, with some countries giving 100% coverage and others as low as 3%. Comparison with the previous year’s figures (2003-2004), showed that average fuel costs had increased from 13% to 18% of landed value.

[4] Note that this is not the average across the country concerned, but only that for the fisheries reviewed

Within aggregated data, the numbers of vessels in each sector were defined, allowing the average for each fishery to be calculated. Raw data showed that the limited number of fisheries and vessels from the Baltic States (Poland, Lithuania, Latvia and Estonia) had significantly higher levels of fuel cost/landed value than others, and these were excluded in the initial analysis. There was also some difficulty in defining a pelagic fleet in the Baltic as demersal trawls in the relatively shallow sea caught most pelagic resources (eg herring). The Baltic is also much less saline and subject to considerable icing in winter, much reducing fishing in some years. Belgium's high figure is due to its beam trawler fleet, which has very high fuel consumption, and has been very vulnerable to recent increase in fuel prices. Recent reports describe beam trawlers being decommissioned or changing to other methods of fishing, potentially leaving the plaice resource in the southern North Sea relatively unharvested.

Table 6: Fuel cost and revenue for European fisheries

Country	Fuel as % age of revenue	Country	Fuel as % age of revenue
Faeroe Is.	6.3	Germany	14.0
Denmark	7.3	UK	14.3
Iceland	7.7	Estonia	14.7
France	8.5	Portugal	14.9
Norway	9.1	Netherlands	16.0
Finland	9.9	Greece	17.9
Sweden	11.5	Belgium	20.4
Italy	12.0	Latvia	21.3
Spain	12.4	Poland	23.4
Ireland	12.6	Lithuania	24.6
	Average	13.0	

Table 7: Comparison of FAO and EU estimates of fuel cost/revenue

Fleet sector	EU data		FAO data	
	No of vessels	Fuel as % of gross earnings	No of vessels	Fuel as % of gross earnings
European demersal fleet	8676	15.42	11	14.37
European pelagic fleet	911	11.15	1	5.48
European passive fleet	16280	7.43	8	4.61
Baltic demersal fleet	330	29.30	na	na
Baltic passive fleet	144	26.06	na	na

Comparing these results with FAO data (Table 7), although based on far fewer vessels and at an earlier date, figures were of a similar order of magnitude.

Within Europe there were broad similarities for Baltic States, Northern European, North Sea and Southern European countries, explained in terms of their characteristic fisheries. However, average output per person in Iceland, Norway and the Faeroe Islands was EUR 154,500, compared with only EUR 58,800 in the EU-15, and EUR 31,500 in the new member states (i.e. Baltic States). This can partly be explained by capital and energy intensity, at 94 kW/person in the northern non-EU countries, 48 kW/person in the EU-15 and only 36 kW/person in Poland and the three Baltic States. The ratio of annual output value to kW of capacity also varies, at 1644, 1225 and 875 EUR per kW for northern European, EU-15 and Baltic States respectively, suggesting that more highly capitalised fleets are generating more value per energy input. However, this is also influenced by resource access, management regime, fishing type and market opportunity, and higher capitalisation may also be a consequence of these factors.

The development of national reviews

Imputed national data can be obtained from FAO/FISHSTAT databases, with detailed catch by country, species and area of capture. This can be cross correlated with national reports, checking reported catch value against quantity and type of fish landed. Where available, FAO Country Fishery Profiles can supplement this, to generate estimates of fuel cost and use, though care is required to link registered with operational vessels, and to consider the impact of flag of convenience activities. As noted earlier, fuel use per fish caught will vary with fishing type. Thus a study by the Institute of Fishery Technology in Trondheim (Table 8) indicated that otter trawlers used four times as much fuel per tonne of fish as coastal gill net and line vessels. Coastal vessels also employed more people relative to weight of fish caught.

Table 8: Norwegian data on productivity and fuel use

Fishing method	Catch/person/ year (tonnes)	Tonnes fuel used/ tonnes fish caught
Coastal net and line	30-40	0.075
Offshore: long line	40–50	0.140
Distant water factory ships	90-110	0.290
Offshore fresh fish trawlers	90-110	0.370

If no direct measures are available, national agencies can use their data on the number of vessels in each class, installed power, average days spent at sea, and local fuel costs to estimate fleet fuel consumption. These are more likely to be accurate than global derived estimates, as they can account for national fleet features (e.g. seasonal fisheries, specific fleet or gear characteristics etc.)

For the European study data, a constraint was that some countries only reported fuel costs on some of their fisheries. However as there is also data on the percentage of fisheries not covered, total values could be extrapolated (Table 9). However this yielded a wide discrepancy between EU reported figures and those from the FAO global methodology, despite good agreement of aggregate estimates.

Table 9: EU data/FAO estimates - European fleet fuel costs

Country	Cost of fuel, EUR million (EU Study)	% value of fisheries reporting	Adjusted, converted USD million	FAO fleet estimate USD million
Belgium	22.1	95	33	23
Denmark	51.3	84	86	113
Finland	2.4	100	3	47
France	80	22	509	182
Germany	42	93	63	63
Ireland	32	87	51	72
Italy	224	100	314	247
Netherlands	82	100	115	131
Portugal	22.3	32	98	187
Spain	72.1	22	459	540
Sweden	16.7	98	24	46
UK	162.8	52	438	230
Faeroe	23	95	34	63
Iceland	72.7	100	102	14
Norway	5.4	46	16	354
Latvia	4.8	100	7	36
Lithuania	20	100	28	36
Poland	12.9	100	18	71
Totals			2397	2455

Much more can be found in closer detail. For example for Finland (Table 10), the EU report stated that there were 3393 registered fishing vessels but not all were active and that 100% of the value of landing was made by only 330 vessels. The FAO estimate was based on the total registered figure; using the corrected number of 330 vessels, this correlates far more closely with measured consumption.

By contrast, the Netherlands reported fuel consumption was much higher than the global methodology estimate. A national breakdown is shown in Table 11, which shows a main discrepancy for the seventeen pelagic freezer trawlers. In most cases, energy used for freezing the catch can be ignored but these vessels freeze almost half a million tonnes of low priced pelagic fish (i.e. herring, mackerel and blue whiting), with a high energy consumption. This has not been included as the kWh was estimated only based on the prime mover, ie engine and propulsion system, excluding power required for freezing, etc. Note also that the high energy cost and low market value of the product will also influence the overall energy:value ratio for the national fleet. This may become more important if fuel costs rise.

Table 10: FAO fuel consumption methodology applied to the Finnish fishing fleet

Type of vessel	Size of vessel (m)	Days at sea	Total kW	SFC	Constant	Number of vessels	Fuel con-sumption, tonnes	Cost of fuel (USD million)
Trawlers<24m	<12m	180	6000	180	0.20	4	933	0.56
	12-24m	200	13300	190	0.40	47	4852	2.91
	24m	200	800	200	0.50	2	384	0.23
Trawlers>24m	24-40m	200	14800	200	0.40	22	5683	3.41
	>40m	250	2100	180	0.50	2	1134	0.68
Gill-netters	<12m	180	600	180	0.20	3	93	0.06
	12-24m	200	2700	200	0.40	12	1037	0.62
Coastal	<12m	180	19000	180	0.20	227	2955	1.77
	12-24m	200	1900	200	0.40	11	730	0.44
Total							17801	10.68

Table 11: FAO fuel consumption methodology applied to the Netherlands fleet

Type of vessel	Size of vessel	Days at sea	Total kW	SFC	Constant	Number of vessels	Fuel con-sumption, tonnes	Cost of fuel (USD million)
Shrimp trawler	12-24m	200	8000	200	0.40	54	1659	1.00
Beam trawler	12-24m	200	37000	200	0.40	171	24296	14.58
	24-40m	250	44200	180	0.50	32	7638	4.58
	>40m	250	167000	160	0.60	99	95230	57.14
Trawlers	24-40m	250	9000	180	0.60	15	875	0.52
Pelagic freezer trawlers	>40m	250	98900	160	0.60	17	9684	5.81
Total							139381	84.00

Current estimates of fuel use and cost

A number of more recent surveys have been carried out at sectoral or national level, providing further information on the relative importance of fuel costs in current fishing operations. On a complete inventory basis, Thrane (2004 a) reported that the Danish fishing sector consumed 197 million litres of diesel in 2000, based on 1528 firms contributing to more than 99% of the total turnover in the sector, representing an average 0.13 litre (0.11kg)/kg caught fish or 0.14 litre (0.12kg)/kg landed fish. He also noted that in the previous year, the average was 0.15 litre/kg caught fish, the difference arising because of increased landings of industrial fish in 2000. A systematic lifecycle analysis approach, using 9 species groups and 9 fishing categories yielded a range of estimates for fuel use by species group (Table 12). The most energy-intensive practice was

Table 12 Relative fuel consumption in Danish fisheries (litre/kg)

Allocation method	Cod	Flatfish	Prawn	Shrimp	Nephrops	Mussels	Herring	Mackerel	Sand-eel
Mass	0.47	0.56	0.54	1.02	1.16	0.01	0.14	0.08	0.1
Value	0.86	0.92	0.89	1.22	3.95	0.08	0.07	0.27	0.04
Sys exp	0.36	0.97	0.76	1.03	6.05	0.01	0.18	0.06	0.06

Source: Thrane 2004; values based on method of allocating fuel use across mixed landings.

that for fishing Norway Lobster (nephrops), with consumption estimated at up to 6 l/kg caught, and accounting for nearly 16% of total Danish fleet consumption. Fisheries targeting shrimp, prawn and flatfish were also relatively energy intensive at around 1l/kg caught. In absolute terms the last was responsible for 20% of the total fuel consumption. By comparison, cod and herring fisheries, which made up some 25% of total fuel consumption had much lower relative consumption, respectively at 0.36 and 0.18 l/kg while mussel, mackerel and industrial fisheries are the least energy intensive, 0.06 l/kg for the latter two, and as low as 0.012 l/kg caught mussels (including shells). Though mussels and mackerel are insignificant, industrial fish made up a third of total fleet fuel consumption. In methodology terms, the choice of allocation method in mixed fishing enterprises has a particular effect on the species-based results, depending on whether energy use is allocated by catch weight, value, or by theoretically expanding the system to separate out the species concerned. It was proposed that estimates could vary by 25% according to species mix, and 35% as a function of vessel size or fishing gear (Thrane, 2004).

In the UK, the industry support body Sea Fish Industry Authority has developed a generalized Profit Forecast Model (Seafish 2008) which generates estimates of segment level annual landings, activity, costs and earnings. Information on fuel price, fish prices, quotas, quota uptake level, and days at sea upper limits, are used for scenarios of catch and price conditions, fuel costs and other factors. A review of potential impacts of UK cod recovery plans noted that in 2009 lower fuel prices (~ USD 700/tonne) had significantly reduced cost pressures for all segments and compensated for lower fish prices and cuts in days at sea. Over 24m demersal boats were particularly sensitive to fuel price, and had these increased to UK£0.55 per litre (~ USD 1000/tonne) they would make an operating loss.

Based on a full sector census, Table 13 also illustrates the variation in fuel costs and profitability within various UK fishing segments (Seafish 2010), showing a significant range of performance and fuel cost impact from lower to upper quartiles, and loss levels in the lower quartiles of demersal trawls and nephrops twin-rigs.

Table 13 Fuel costs(profit) as % of revenue, UK segments

Vessel category	Upper quartile	Average	Lower quartile
Demersal trawl, single rig >24m	19.8 (3.3)	22.8 (0.9)	31.5 (-7.3)
Demersal pair/trawl seine	13.9(3.2)	16.0 (3.4)	20.1 (2.7)
Nephrops twin-rig	18.3(0.0)	22.0 (2.6)	28.8 (-6.8)

A more detailed assessment of the impact of fuel consumption and costs on European fleet profitability was carried out by MARES (2009), from which Table 14 summarises key features. Based on fuel costs of USD900/tonne, estimates are also developed of fuel costs per kg of fish landed in each of the different fleets. This illustrates significant variations in fuel consumption (and fuel use per unit of effort) and cost across fishing method and fleet sectors, fuel use ranging from 0.2 to 4.6 litres/kg catch, and from 0.9 to 8.6 litres/kWday of effort.

Reviewing 32 diverse fishing activities reported over an approximate 20 year period (early 1980s to late 1990s, Tyedmers (2001) found a wide range of fuel use levels, including fuel use from 420-530 litres/tonne for N Atlantic demersal trawl to 2300 l/t for flatfish; herring/mixed species seine fishing 100-140 l/t and 1000 l/t, salmon (range of techniques) 360-830 l/t, tuna/swordfish/billfish 1400-3400 l/t; shrimp trawl 920-3000 l/t, squid jig 1700 l/t, scallop dredge 350 l/t, crab trap 330 l/t, hand gathering of clams 300 l/t, and nephrops trawl 1030 l/t. These levels are broadly similar to those shown in the EU study in Table 14 above, though for the latter, demersal and beam trawl energy consumption levels were higher. A more specific review of environmental footprints in the Galician fisheries sector (Iribarren et al 2010), based on questionnaire surveys of fishing operators, demonstrated similar variability in energy use with fishing method and location (Table 15). This is extended to show potential cost per kg, based on a fuel cost of USD 900/tonne, and also includes data for extensive raft culture of mussels (see next section), showing the greatly reduced levels of fuel consumption and costs.

Table 14: Fuel use in European fleet segments , 2005-06;

Country Gear	Length m	Litres /kg fish	Fuel cost		Litres / kWday	Target species
			/kg fish*	% of income		
BEL TBB	12-24	3.1	2.34	33%	8.566	Sole, other (40%)
	24-40	3.5	2.7	36%	4.439	Sole, plaice, other (45%)
DNK DTS	12-24	0.2	0.18	12%	1.693	Sprat, cod, plaice, other (30%)
DNK PGP	00-12	0.3	0.27	5%	1.679	Cod, other (80%)
FRA DTS	12-24	1.9	1.44	20%	3.674	Angler, cuttlef., nephrops, other (75%)
FRA PGP	00-12	3.4	2.61	5%	0.900	Other (90%)
IRL DTS	12-24	1.4	1.08	19%	4.553	Whiting, nephrops, other (50%)
	24-40	1.7	1.26	20%	3.441	Whiting, nephrops, other (70%)
IRL PTS	24-40	0.2	0.18	8%	6.551	Herring, horse mackerel
	40-	0.1	0.09	12%	3.659	Blue whiting, mackerel, herring, horse mackerel
ITA DTS	24-40	4.4	3.33	28%	3.366	Shrimp, hake, other (50%)
ITA PGP	00-12	1.7	1.26	11%	2.379	Other (90%)
ITA PTS	24-40	0.3	0.27	11%	2.394	European anchovy
ITA TBB	24-40	3.2	2.43	21%	4.246	Sole, molluscs
NLD TBB	12-24	1.8	1.35	19%	7.316	Shrimp
	24-40	4.6	3.51	36%	6.087	Plaice, sole, other (25%)
	40-	3.8	2.88	39%	4.549	Plaice, sole, other (25%)
GBR DTS	12-24	1.0	0.81	16%	3.194	Haddock, nephrops, other (20%)
	24-40	1.1	0.81	20%	3.808	Haddock, other (25%)
	40-	1.4	1.08	29%	6.117	Cod, saithe, other (45%)
GBR PTS	40-	0.2	0.18	11%	3.228	Herring, mackerel, blue whiting
GBR TBB	24-40	2.5	1.89	33%	3.438	Plaice, angler, other (30%)

Source : STECF4SGECA 08402 Note: % between brackets refers to 'other' species caught. * Calculated at USD900/tonne BEL=Belgium; DNK = Denmark; FRA = France; IRL = Ireland; ITA = Italy; NLD = Netherlands; GBR = United Kingdom; TBB = Beam Trawler; DTS = Demersal Trawl; PTS = Pelagic Trawl; PGP = Passive Pelagic

Table 15 Comparison of Galician fishery systems

Fishing system	t fuel/t	USD/kg
European hake, offshore longline	1.551	1.40
Atlantic horse mackerel, coastal trawl	0.316	0.28
European pilchard coastal purse seine	0.175	0.16
Anglerfish offshore trawling	2.547	2.29
Tuna deep sea purse seine, Indian ocean	0.313	0.29
Mussels extensive aquaculture	0.013	0.01

In many cases, several fishing methods are deployed to catch a particular species, commonly resulting in wide variations in energy efficiency (see Thrane 2006, Tyedmers 2001, Tyedmers 2004, Ziegler et al. 2003, Ziegler and Valentinsson 2008; Ziegler et al. 2009). Thus, in broadly comparable conditions, flatfish can be caught using purse seine, gillnets, bottom trawls or beam trawls, the last requiring 15 times as much fuel per kilo as the Danish seine (Thrane 2006). On the basis of a series of reviews, Tyedmers (2004) also proposed that energy efficiency in many fisheries worldwide had declined over recent decades, despite technical improvements in localising fish stocks, potentially due to considerable over-exploitation of many of the stocks concerned over that period. In a recent analysis of a number of Norwegian fisheries over time, Schau et al (2009) drew a similar conclusion. However, without detailed records of operating conditions and fishing decisions it is not possible to make absolute determinations, nor to generalise across into other fisheries, though clearly while fuel costs allow some possibility of profit, fishing activity will continue to be driven.

Current global fleet estimates of fuel cost

In the absence of direct measurements, estimates can be used for global fuel consumption and cost. Based on FAO catch data for 2000, and species-based estimates of direct fuel use per tonne of catch, Tyedmers et al (2005) proposed annual fuel use of some 50 million m3, 1.2% of total global oil consumption, or at a fuel density of 0.85, 42.4 million t. With marine fish and invertebrate landings at 80.4 million t global average fuel use intensity was 620 L (527kg) per live weight tonne, or some 1.9 t of catch per t of fuel. Fishing vessels released some 134 million kg of CO_2 into the atmosphere at an average of 1.7 kg of CO_2 per tonne of live-weight landings. They further noted that these were likely to be serious underestimates, as they did not account for freshwater fisheries or for substantial illegal, unreported, or unregulated (IUU) catches. This average level of fuel use is also considerably lower than many of the EU fisheries reported in Table 13 above. Based on these levels, global fisheries were estimated to use 12.5 times the amount of fuel energy as their edible-protein energy output, which though significantly inefficient, compared well with a number of other animal protein production systems.

Using a systematic vessel-based approach, the 1992 FAO methodology (Table 1) is updated in Table 16. The size parameter for FAO vessel statistics has since changed from tonnage to length, which is far simpler to measure, allowing better estimates for vessels less than 100 t. In this case, simplified vessel data from FAO (2011) is used, with 3 size categories, as although the Lloyds Vessel Register database provides size categories as 24-30m;30-36m;36-45m;45-60m;60-75m and >75m, total numbers recorded for 2010 for all fishing vessels in service (including support, vessels, carriers, etc) are 18,493, compared with the FAO total for > 24m vessels, of 43,767.

Table 16: Global fuel utilisation estimates from vessel power in global fleet

Vessel size classes	No of vessels	Total installed KW	Days at sea	Operat-ional constant	SFC, g/kWhr	Fuel consumption (tonnes)		Annual fuel cost (USD '000 per vessel, USD million per class)	
						per vessel	per vessel class	per vessel '000 USD	per vessel class
>24m	43,767	27,803,318	180	0.6	180	296.39	12972101	266.75	11674.9
12-24m	320,997	31,469,963	140	0.4	220	28.99	9305703	26.09	8375.1
<12m	2,157,888	33,716,479	100	0.3	240	2.7	5826298	2.43	5243.7
Total	2,522,653	92,989,760					28104102		25293.7

Other factors are as per the 1992 review. An additional specification - a 'fleet capacity index' was considered, estimating the proportion of the vessel category group which is actively fishing. This would allow the three fuel use modifying factors – days at sea, proportion of full power use, and capacity use to be independently specified. However, in the absence of good independent data it was eliminated from this calculation, and the 'days at sea' figure was simply modified to create an overall fleet average, allowing for tie-up, etc. Unpowered vessels, although possibly using some fuels (eg for lamps) are omitted. At prices of USD 900 per tonne, fuel costs of the global fishing fleet were calculated to amount to USD 25.3 billion. These results are highly dependent on the accuracy of vessel numbers, as well as on estimates of utilisation and the specific fuel consumption. However, by focusing on vessels, underestimates of total fuel use associated with IUU fishing, bycatch, or other sources of error for catch-based fuel use are to some extent avoided. Most notably by comparison with the 1992 estimates, with apparently reduced numbers of larger vessels, a much larger part of fuel consumption and cost is taken by the smaller scale sector.

As a further estimate, using the FAO (2005) data for 2002 fuel costs, calculated as 18.5% of gross revenue, ie USD14 billion out of USD78 billion, and assuming average fuel consumption has not changed, with fuel price in the first six months of 2008 approx 160% as high as 2002 levels, and 2008 levels of gross revenue, total fuel costs would be some USD36 billion. However this estimate is based on the 2002 fleet description of larger numbers of large vessels, though this may be compensated by the growth in numbers of smaller vessels and increases in installed power. A further cross-check can be made using the World Bank/FAO 'Sunken billions' (WB/FAO 2008) study of fishing capacity and subsidies. Table 17 extrapolates from 6 countries for which specific data was developed.

Table 17 Global fuel use and cost estimates – from World Bank/FAO 2008

	% global catch	No vessels	MW	GT per vessel	Catch/ GT	Catch/ kW	SFC g/kW-hr	Fuel use Million tonnes	Fuel cost Billion USD
China	17	509717	15506.7	14	2.3	1.04	280	8.68	7.82
EU-15	6	85480	6941.1	22	3	0.82	270	3.75	3.37
Iceland	2	939	462.8	199.2	10.2	4.11	250	2.31	0.21
Norway	3	8184	1328.9	48.2	7.3	2.18	250	0.66	0.6
RoK	2	87203	16743.1	8.3	2.6	0.11	260	8.71	7.84
Russ Fed	3	2458	2111.3	789.2	1.5	1.37	250	1.06	0.95
Total selection	33	693981	43094.0	17.6	2.6	0.73		23.09	20.78
Global est	100							69.97	60.00

A further country in the WB/FAO study, Japan, was excluded as kW data was unavailable. At USD900/t this data suggests global costs of USD 60 billion. This estimate uses higher SFC values – potentially better allowing for poorer engine efficiency, but may overstate global use, due to the weighting of countries with larger vessels and high fuel use per production, notably the Republic of Korea, which if removed from the table yields fuel global use of 46.3 million t, worth USD 41.76 billion. Overall, balancing the methodologies employed, and assuming higher SFC values for Table 15, global fuel consumption of 30-40 million tonnes, valued at USD 27 to 36 billion could be expected, equivalent to an average of USD 0.29-0.39/kg of global landed catch.

2.5 Implications and actions

Though not developed further in this review, the methodologies outlined here can be taken to a more detailed level, and used to explore various scenarios. These could include the comparison of performance within vessel/gear classes, assessment of the effects of fleet size/composition changes, or defining or testing the impacts of specific decommissioning targets, fuel subsidy costs and other management/policy areas. These can also be linked more specifically into comparative areas such as energy use for other food resources, and for added value per fuel input. Within supply and value chains, where fishing costs typically represent only a part of total costs and value, further indicators can be developed of factors such as fuel cost per final sale value, and tradeoffs eg between fishing fuel costs from different locations and systems, or from comparative aquaculture sources, and those incurred downstream.

The capture sector is open to competitive pressure to optimize operation and retain or improve profits, whether by increasing fishing capacity and potential revenues, or by improving financial efficiency through catch selection, value retention, and control of operating costs, of which labour

and fuel normally constitute more than 50% of the total. However the balance between these differs with location, influenced not just by local prices, but by cost structures. In general, for fisheries close to the coast or base of operation, smaller-scale operations tend to predominate, with lower technologies, lower fuel costs but relatively high labour costs. In distant waters or fishing areas remote from operating bases, industrial fisheries are more common, with higher technology and capitalisation, high fuel costs but relatively low labour costs. Clearly, externally driven shifts in the cost base of either of these will influence competitiveness between these sectors, and ultimately their potential for catching and landing fish and the social impacts of employment and food access.
Though not further developed here, fuel costs together with impacts on resources and their location, are also the primary area of climate change interaction for the capture sector (FAO, 2012), and although energy is embodied in vessels and gear, most of the CO_2 emissions (and hence GHG impacts) are related to fuel use. Data on fuel use per kg of catch can therefore be potentially used directly to estimate GHG impacts of supply (Parker, 2012), and most significant reductions of GHG output can be linked with lower fuel use per catch.

2.6 Conclusions

Fuel use and cost is a significant issue across most of the world's capture fishery sector. Specific conclusions from data so far available include:

- Except for non-motorised vessels, fuel represents a significant input cost in most fishing operations, across all scales of output. Its importance depends on distance to grounds, fishing activity and type, together with vessel and management factors.
- Recent cross-fleet data is limited, but these, together with generic information from earlier studies suggest that trawlers, beam trawlers, and dredgers are highly vulnerable to rising fuel prices while vessels fishing with passive gear or for small pelagics will be less affected.
- Fuel price impacts will vary with location and economic conditions, with greater effects on developing countries, and greater impacts on distant water than on coastal fisheries, and greater impacts in poorer market conditions. Increases in transport costs will also have an impact on exporting countries, in which developing countries hold a significant role.
- Reviews suggest that financial margins in many fisheries are barely positive. However the inflexibility of capital placed in vessels will tend to keep fleets running as long as direct operating costs can be covered. However, the inability to service capital will tend to lock older and more inefficient vessels into fleets, and hinder technical and operational improvements.
- Relatively small rises in fuel costs will move parts of many fleets into unprofitability, as without landed catch price rises, operating costs cannot be covered. In many cases returns to labour also fall as crew shares are reduced to attempt to compensate. Vessels may be laid up for periods if there are prospects of better catches or prices, or fuel price falls.
- Where processing takes place on board fishing vessels, associated energy costs are usually included in overall vessel budgets (see later). In some cases, particularly when freezing below capacity, this can lead to considerably greater fuel demands
- A range of downstream/sector support implications can be identified, from reduced landings and throughput to a decline in demand – or ability to pay – for services, with consequent effects on revenue, and in some cases the loss of 'critical mass' of economic activity needed to keep ports and other functions viable.
- Implications for fishing effort and resource levels are more difficult to define, though the potential exists for rising fuel prices to result in reduced effort and for catch per effort to stabilise or even increase. This relationship will also be subject to other variables including ecosystem status and management regimes.
- Data on fuel consumption and costs can be extrapolated to give broad indications of fleet, national and global levels of fuel use and cost. By monitoring fleet economic performance, countries have the potential to make rational decisions on the development and possible

economic scenarios for their fishing fleets, including resource rent and efficiency considerations.

- The issue of increased fuel prices should not be merely regarded as a problem of owners or fisheries administrations but should also be considered in the wider context of national fuel, energy and currency balances, social impacts, added value, and food security.
- Countries should recognise the longer-term nature of investment in their fishing fleets and support structures, and implications for food supply and economic output. In selected cases, and if fleet operators cannot fund this directly, there may be justification for support during periods of exceptional input price rises or economic downturn, but this should not become a structural cause for overfishing.

3 Aquaculture

3.1 Introduction

The sector has seen a considerable growth, from 28.6 million tonnes in 1997 to around 52.5 million tonnes in 2008 (68.3 million including aquatic plants) worth USD 98.5 billion (USD 106 billion including aquatic plants) and accounting for around 50% of the world's fish food supply (Table 18). Asia dominates production, with 89% by volume and 79% by value, with China by far the largest producer (32.7 million tonnes in 2008). Production in inland water and coastal/marine waters grew by 44.7% and 44.4% since 1997, by 2006 reaching 31.5 and 20 million tonnes with values of USD 41.4 and 37.3 billion, and average prices of USD 1.31 and 1.86 per kg respectively.

Table 18 Aquaculture production and value, 1997-2006

	million tonne		Average annual % change	USD billion		Average annual % change
Area	**1997**	**2006**		**1997**	**2006**	
Total	**28.61**	**51.65**	**4.96**	**44.10**	**78.76**	**4.89**
Asia	25.21	45.96	5.02	35.51	60.08	4.54
China	19.32	34.43	4.88	20.36	38.42	5.22
Latin America	0.40	1.23	7.51	1.18	5.43	8.70
Europe	1.36	1.93	3.29	3.37	6.44	5.30
North America	0.52	0.64	2.03	1.01	1.69	4.49
Africa						
Egypt	0.09	0.60	9.51	0.18	0.95	8.96
Oceania						
New Zealand	0.08	0.11	3.17	0.05	0.23	8.82
Other countries	0.95	1.19	2.24	2.80	3.94	3.21

Table 19 shows trends in key producing countries, and the higher growth rates associated with particular species in countries such as Vietnam (pangasius catfish), Chile (salmon) and Egypt (tilapia).

Table 19 Trends in major producing countries (> 500,000t)

	million tonne		Average annual % change	USD billion		Average annual % change
Producer	**1997**	**2006**		**1997**	**2006**	
China	19.32	34.43	4.9	20.36	38.42	5.2
India	1.86	3.12	4.5	2.13	3.43	4.2
Viet Nam	0.32	1.66	9.0	0.68	3.32	8.8
Thailand	0.54	1.39	6.8	1.91	2.22	1.6
Indonesia	0.66	1.29	5.4	2.05	2.25	1.0
Bangladesh	0.49	0.89	5.1	0.97	1.36	3.2
Chile [5]	0.27	0.80	7.3	0.92	4.43	8.8
Japan	0.81	0.73	-1.1	3.52	3.10	-1.5
Norway	0.37	0.71	5.3	1.05	2.72	6.8
Philippines	0.33	0.62	5.3	0.89	0.98	1.0
Egypt	0.09	0.60	9.5	0.18	0.95	9.0
Myanmar	0.08	0.57	9.5	0.83	1.79	6.0
Korea Rep	0.39	0.51	2.6	0.92	1.42	3.9

The sector is very diverse, the FAO Fishstat database listing over 400 species cultivated worldwide, with a great variety of enterprise types, ranging from part-time subsistence activities for rural families, to publicly traded international corporations. However, the bulk of production is in a smaller number of species, (Table 20) for which there is a substantial range in first sale values. Freshwater aquaculture, on which the bulk of global output is based, is usually lower priced, and hence potentially less able to support input costs, while marine species are typically in medium-high price ranges and can potentially command a diverse range of resources, including fuel and energy inputs. On average, aquaculture has higher first sale value levels than capture fisheries, but its input costs and strong market competition leaves small margins in many subsectors, and profitability is also very sensitive to fuel and energy cost changes.

[5] Now, by 2009/10 substantially reduced due to stock losses from ISA (infectious salmonids anaemia)

Table 20 Most significant species (> 1m tonnes in 2008), by quantity and value

Species	No. count-ries	Output, million tonnes	% Change 1 yr	% Change 10yr mean	Value, billion USD	USD per kg 2008	% Change 1 yr	% Change 10yr mean
Silver carp	50	3.85	5.5	2.8	4.86	1.26	13.4	8.5
Grass carp	57	3.78	4.3	4.0	4.80	1.27	12.2	9.5
Cupped oysters*	18	3.39	-4.5	3.1	2.02	0.60	7.8	-1.3
Japanese carpet shell	13	3.14	3.2	13.4	3.19	1.01	14.7	7.7
Common carp	100	3.00	5.5	3.7	3.76	1.25	7.2	6.7
Nile tilapia	74	2.33	8.6	22.2	3.21	1.37	8.2	27.5
Bighead carp	28	2.32	7.2	6.3	2.98	1.28	14.2	13.0
Catla	5	2.28	7.9	31.1	3.30	1.45	11.4	49.7
Whiteleg shrimp	36	2.26	-1.7	106.7	8.99	3.98	-0.8	78.1
Atlantic salmon	31	1.46	5.6	11.2	7.20	4.93	1.0	23.6
Pangas catfishes*	5	1.38	52.4	220.1	1.99	1.43	49.1	197.8
Freshwater fishes*	97	1.25	-25.1	-1.2	1.78	1.42	-29.1	1.6
Roho labeo	6	1.16	19.6	7.6	1.33	1.15	20.1	-0.5
Scallops nei	7	1.14	-2.4	9.9	1.62	1.42	9.1	10.2

* including other unclassified stocks in same species grouping

Unlike capture fisheries, where diesel fuel for propulsion greatly dominates energy demand, aqua-culture's fuel and energy inputs are more diversified. This is particularly related to the production system and the degree of yield intensification, related directly with external feeds, which are a primary factor in energy content, together with water supply and water quality management. Hence over an increasingly wide range of species being cultured, system intensity provides the simplest cross-cutting means of estimating energy use, and also of defining the typical production cost profile.

3.2 Systems/structural descriptions,

A broad categorisation of structural and system definitions is provided in Table 21. These can in turn be linked with key species. Intensive aquaculture is typically conducted in tanks, ponds or open-water cages, with high stocking density, high water exchange and/or oxygen management, and complete feeds. Higher value carnivorous species such as salmon, sea bass, groupers, eel, turbot and cod are typically farmed intensively. Although they are omnivorous, penaeid shrimp are often grown in intensive pond systems with prepared feeds. In contrast extensive and semi-intensive systems, used for most lower value detritivorous, herbivorous and omnivorous fish species (carps, milkfish, tilapia etc), rely more on food produced within the culture environment, usually fertilized with either inorganic fertilizers or agriculturally derived by-products. In the last decade, many of these systems have been become more intensified, with greater stocking levels and external feed application to increase production (Bostock et al 2010). As the capital costs of new site and system development also require relatively intensive output, the expansion of aquaculture is expected to be associated with more intensive and energy-demanding systems.

However, while these trends can be recognised, and although attempts have been made in various initiatives to develop more complete profiles of the range of systems employed in national or global aquaculture, and their relative intensity and input levels, data is rather scattered. However, with increasing competition and converging technologies some species/system configurations (eg for cage culture of Atlantic salmon, or of seabass/bream, or for pond culture of shrimp) have tended to become more standardised, and so more generic characterisations can be made. Nonetheless, and particularly for the very high-volume groups such as freshwater carps, it is still difficult to define the actual levels of intensification, though indirect approaches, such as estimating total feed use for particular subsectors (see FAO 2010) can provide indications .

Table 21 Aquaculture system classifications (by increasing intensification).

Category/system	Key features/characterised by
(A)Aquatic plants, mollusc systems, extensive ponds for fish or crustacea	(1) use of natural water bodies (eg lagoons, bays, embayments); minimal rope, netting, simple timber structures, floats, artisanal boats to modern service vessels, low initial costs, low-medium technology; (2) local or external stocks; natural, often unspecified, food organisms, (3) uncontrolled water exchange, low degree of control of the environment, nutrition, predators, competitors, disease agents; (4) very limited fuel and energy in construction materials, servicing – though more in industrialised larger scale mollusc culture systems
(B) Semi-intensive to intensive ponds for fish and crustacea	(1) partially to completely constructed culture systems in coastal or inland zones, mainly earth, concrete, some plastic, metal components; moderate initial costs and level of technology (2) usually externally stocked, range of dependence on natural foods, enhanced with fertiliser, towards complete feeding (3) low to moderate degree of control on environment; rainfed, gravity-supplied to pumped water, moderate water exchange, varying levels of aeration in more intensive systems (4) range of fuel/energy inputs in fertilisers, feeds, pumping, aeration, some in construction materials, servicing.
(C) Intensive cage for fish	(1) constructed systems in coastal bays, lagoons, lakes, some offshore areas, steel, timber, plastics, netting, floats, moorings, service rafts, vessels; moderate to high initial costs, technology; (2) externally stocked, completely fed (3) low degree of control over water quality and disease agents; occasional aeration (4) fuel/energy in feeds, control/feed delivery systems, service vessels, some in construction materials
(D) Highly intensive flow-through tank/ pond for fish, crustacea	(1) constructed systems in coastal/inland zones, concrete, steel, plastics; high initial costs, high technology; (2) externally stocked, completely fed; (3) High degree of control over water quality and disease agents; high water exchange with aeration and oxygenation, pumped or gravity-supplied water; (4) fuel/energy in feeds, pumping, aeration, also control/feed delivery systems, construction materials .
(E) Recirculated, closed-systems, primarily for fish	(1) constructed systems in coastal/inland/peri-urban zones, concrete, steel, plastics; very high initial costs, high technology; (2) externally stocked, completely fed; (3) High degree of control over water quality and disease agents; high water exchange with aeration and oxygenation, filtration, conditioning, possible temperature control; top-up pumped or gravity-supplied water; (4) fuel/energy in feeds, pumping, aeration, treatment systems, also control/feed delivery systems, construction materials .

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3.3 Summary of findings/emerging work

Generic energy and LCA studies

A number of energy accounting studies have reviewed aquaculture operations, primarily to define energy subsidies and make comparisons with other food production sectors (see eg Troell et al, 2004). A wider range of LCA reviews have explored energy and other resource/environment interactions (see eg Henriksen, 2011, Parker, 2012). Table 22 summarises features of a range of production systems, and relates industrial energy input (ie inclusive of all inputs – capital structures and operating inputs) with whole fish or protein outputs. To provide a basis for equivalence with capture fisheries, energy input levels are also defined in diesel fuel equivalents, costed at USD 900/tonne. Compared with capture fisheries, total values of tonnes of fuel equivalent /tonne product for fed and fertilised systems, at 0.27 to 2.37 (0.32 to 2.79 litres/kg), are similar to direct fuel consumption values for capture fisheries, though direct fuel/energy use is normally much less.

These imputed fuel cost levels are also considerably higher than those encountered by producers, as they include all inputs, with substantial non-market cost component. To set these industrial energy levels in context, values can be compared with other food systems; thus Stewart (1995) notes total energy use for broiler chicken production at 370 GJ/t, intensive pork at 595-718 GJ/t, closed feedlot beef at 513 GJ/t and open feedlot beef production at 1350-3360 GJ/t. More recent improvements in all of these farming systems, also related to feed sourcing and efficiency have reduced total energy demands, but relative performance is broadly similar.

Table 22: Industrial energy inputs for aquaculture, and imputed costs

Type of system	GJ /t of protein	GJ/t of whole fish	t diesel equiv/t of protein	t diesel equiv/t whole fish	Equiv. fuel cost USD/ tonne
Mussels, long lines	116	n/a	2.9	n/a	n/a
Carp ponds, feeding and fertilizing	250	11	6.25	0.27	243
Trout ponds feeding	389	28	9.72	0.7	630
Catfish, ponds, feeding only	891	25	22.2	0.625	563
Salmon, intensive, cages	688	56	17.2	1.4	1260
Grouper/sea bass, intensive cages	1311	95	32.77	2.37	2133
Carp, intensive recycle, feed only	3090	56	77.25	1.4	1260

Developed from Muir (2005) - in energy output terms, 1 t of diesel is the equivalent of around 40 GJ

Confirming the link with production systems, LCA (Lifecycle Analysis) assessments carried out by Tyedmers and Pelletier (2007), addressing inputs across the complete process from capital and operating inputs to consumption and waste found that energy dependence correlated strongly with production intensity. This is mainly due to the energy input in the production and delivery of feed (Grönroos et al. 2006). More variable is the energy required for other on-farm activities which can range from virtually zero up to about 3 kWh per kg for highly intensive systems with significant levels of water exchange and quality management. For land-based farms, most of the power is likely to be provided by electricity from the central grid, for which the original energy source and the transmission efficiency can also be a significant factor in total energy accounting. By contrast, cage-based and other immersed/floating farm systems rely mainly on diesel or other fossil fuel. Table 23 shows typical embodied energy levels and ratios for different production systems, with simple unfed seaweed and mussel culture systems requiring much more modest input levels, and having a much greater dependence on solar/renewable energy inputs, primarily through photosynthesis inputs driving food chains.

Table 23: Total embodied energy, for equivalent area

Quantity	Seaweed culture	Mussel culture	Cage salmonid culture
Total inputs (kcal x 10^5)	6.65	1.05-2.40	580-950
Solar/renewable (%) Fossil/non-renewable (%)	95.5% 4.5%	71.4-85.4% 28.6-14.6%	81.0-87.4% 19.0-12.6%
Protein output, kcal	6605	255-440	22420
Input/output ratio	100	410-545	2585-4235

Developed from Muir 2005; Troell *et al.*, 2004 Tyedmers *et al.* 2007

Table 24 demonstrates energy associated with key production inputs for a small sample of aquaculture processes, comparing two intensive systems with a semi-intensive, partially fed system, and with mussel production. Here, feeds account for almost 80% of energy consumption in intensive systems, and almost the entire use in the semi-intensive example, which though not fully dependent

Table 24: Energy allocation in selected aquaculture systems

	Salmon, intensive cages	Grouper/ bass intensive cages	Tilapia, semi-intensive ponds	Mussels, longline
GJ/t edible product	142	262	40	11.6
Contribution to energy expenditure (%)				
Structures	6	2	3	48
Equipment	<1			5
Vehicles	<1			5
Feed	79	78	97	
Stock	3	10		
Fuel & power	4	7		42
Others	6	3		

Source: Stewart, (1995)

on feeds has few other energy inputs. Fuel and power – mainly for vessels and ancillary equipment is much less significant for intensive fish systems, but proportionately represents an important part of the much lower mussel farming energy budget, though not greatly different in absolute terms. The tilapia example has negligible fuel and power inputs, though this could increase where more water exchange is required. These data are broadly consistent with other reviews (eg Troell, et al, 2004,

Feed-based assessments
The largest part of feed-related energy use is associated with the supply of raw materials, including in many cases, inputs of fishmeal and oil, where interactions with capture fisheries are most significant. Further specifications of these inputs are summarised in section 4. Table 25 provides an overview of feed production related to main species groups, projected to 2010. Using average energy consumption figures derived from a major international feed analysis (Nutreco, 200x) – see section 4, total energy estimates are developed. For more accurate estimates, this would require to be adjusted to account for the wide range of raw material sourcing and feed manufacturing practice.

Table 25: World fish feed energy consumption by species groups 2003- 2010.

Species group	Feed production				Total energy consumption)***		
	2003*		2010**		2003	2010	% change/yr
	'000 tonnes	%	'000 tonnes	%	TJ	TJ	
Salmonids	1638	8.4	2300	6.2	802.6	1127.0	4.97
Shrimp	2925	15.0	2450	6.6	1433.3	1200.5	-2.50
Catfish	505	2.6	700	1.9	247.5	343.0	4.77
Tilapia	1578	8.1	2497	6.7	774.0	1223.5	6.76
Marine finfish	1482	7.6	2304	6.2	726.2	1129.0	6.51
Cyprinids (carp)	8775	45.0	27000	72.5	4299.8	13230.0	17.42
Total	19500	100	37226	100	9555.0	18240.7	9.68

* from Tacon *et al.*, 2006** Hardy, 2006. *** Based on Nutreco table: 0.49 GJ/mt feed prod; figures rounded upwards.

However, the table indicates in particular the major feed demands associated with freshwater fish production, primarily carps, for which significant growth is expected, associated with intensification of simpler extensive or semi-intensive systems. Demand associated with shrimp is projected to decrease, while all other species categories are proposed to grow more moderately. An annual growth rate of total energy demand associated with feeds is projected at 9.68%. However, as discussed later, more complex interactions of energy costs, fishing and processing activities and product prices may change these balances. Moreover, these estimates do not take complete account of the relatively unrecorded role of trash fish feeds and their processing and distribution, for which some 5-6 million tonnes were estimated to be used globally (Tacon et al, 2006).

Non-feed energy inputs
Table 26 shows non-feed related energy capacity inputs for a number of systems, (based on a limited number of samples), identifying pumping and aeration as major inputs, with heating/cooling a feature in some recirculation systems. In global terms, aeration associated with pond, tank and recycle systems is likely to be the most significant non-feed input. Although a comprehensive review of installation and use levels is not so far developed, Table 27 summarises some earlier recorded application rates for aeration in aquaculture systems, including a limited amount of data on total energy use per crop or per kg. Thus in the example of pond catfish culture at 2.82 kWhr/kg at a historic power cost of USD 0.05/kWh would yield USD 0.14/kg energy cost, while at current equivalent costs of USD 0.15/kWh would amount to USD 0.42/kg, which is unlikely to be viable.

Table 26 Non-feed energy capacity (kW/tonne output)

Systems	Pumping	Aeration	Heating/ cooling	Vehicle/ vessel fuel	Misc power
Aquatic plant	n/a	n/a	n/a	0.010	neg
Shell fish lines	n/a	n/a	n/a	0.033	neg
Extensive and semi-intensive pond	n/a	n/a	n/a	Neg	Neg
Intensive pond	variable	2*	n/a	Neg	Neg
Intensive cage	n/a	n/a	n/a	0.033	Neg
Intensive flow-through tank/pond	0.66	0.75	n/a	Neg	0.03
Recirculating system	0.33	0.21**	0.4	Neg	0.06

Notes: * Boyd, 1998**Oxygen generator

The balance between the use of aeration and pumping energy for water exchange varies with system and location, though in many installed systems aeration is the most common means of supporting more intensified production. Thus Schuur (2003) estimated that aeration accounted for 68% of total shrimp culture energy demands. In practice, as costs and management pressures increase, the efficiency of aerator use is becoming a more significant issue, and though not as yet fully documented, average energy use per tonne of output is likely to converge towards most efficient levels.

Table 27 : Installed aeration capacity guidelines

System	Function	Capacity	Notes
Tanks	Larvae	0.2 to 1 m^3/hr per m^3	Very short cycle usage
	Broodstock	0.1 to 0.5 m^3/hr per m^3	May only be used periodically
	general use	0.05 to 0.3 m^3/hr per m^3	supplementary aeration
Semi-intensive ponds	shrimp culture	0.44 kW/ha, 1.12 ha ponds	10 t/ha/yr, 2 crops, 20-30% water exchange/day
	shrimp culture	6 kW/ha, 0.49 ha ponds	16.5 t/ha/yr, 2.5 crops, 20% water exchange/day
Ponds	carp culture	4 kW/ha, 0.7 ha ponds	Chinese pond systems
	tilapia,carp	approx 0.5 to 1 kw/ha	approx 0.2 kW per tonne fish/year
	Catfish	34,000 kWhr/ha/crop	2.82 kWhr/kg produced, approx 4 kw installed/ha
Intensive ponds	eel culture	4.5 kW/ha, 0.2 ha ponds	30 t/ha/yr production, Taiwan
	shrimp culture	12 kW/ha,0 .25 ha ponds	yield 13.2 t/ha

Source, Muir, 2000

Where pumping is used for aquaculture, installation and energy costs normally favour the use of very low head, intermittent use applications. Hence the overall energy use effects are limited. The primary exceptions to this are for high intensity and value per biomass systems, such as hatcheries and high market value growout systems near to major markets.

To estimate energy use in specific aquaculture applications, Box 1 summarises calculation methods for water pumping and aeration energy. Note also that for

Box 1 Direct calculation of pumping and aeration energy demand:

For pumping: energy demands are primarily related to water exchange, vertical lift of water, and pump/flow system efficiency. Pump capacity can be calculated from P(kW) = 9.81x lift(m) x flowrate (m^3/sec)/efficiency. An intensive pond system producing 200 tonnes/ha per year, with water exchanged 6 times daily, lifted 2m from source to outlet, with pond depth of 1.5m and pump efficiency of 60% would require per ha:

9.81x2x(10,000 x 1.5 x 6/(24x3600))/0.6 = 34.1kW, or 0.17kW/tonne.

Annually, pumping 100% of the time, would require 34.1x 24x365 = 149200kWh, or 746 kWh/tonne. At USD 0.15/kWh this would be the equivalent of USD 0.11/kg

For aeration: the simplest calculations are based on installed aerator or blower capacity and use per unit of volume or area. Thus with an installed 4kW/ha and a yield of 10 t/ha, with aerators working and average 30% of the time over the production cycle, energy use would be 4 x 30% x 24 x 365kWh/5t = 2102 kWh/tonne, or at USD 0.15/kWh a cost of 0.16/kg.

Where aeration is described in m^3/hr air supply the simplest approach is to check with blower manufacturer's data to define power requirements for the pressure required. Where aeration is defined by kg of O_2 transferred, aerator specifications can be consulted for efficiency in kgO_2/kWh under the expected operating conditions of salinity, temperature and oxygen deficit (difference between saturated and actual concentrations).

recycle systems, pumping energy inefficiencies are commonly transferred as heat into the process water, which may in some cases necessitate cooling, adding further to energy demands. However this is an issue in only a small minority of aquaculture systems. Where energy is supplied locally by generators, or direct engine power, fuel consumption and costs can be assessed based on hours of operation, and local fuel costs.

3.4 Energy use by species groups

Though data is not available for complete overview by species, outline energy profiles for key sectors with relatively standardised production technologies can be set out, described as follows.

Shrimp culture

This sector expanded rapidly in the 1980s, primarily in semi-intensive systems, but in many areas then intensifying, with greater levels of feed input, water exchange and aeration, and associated energy demand. Larsson et al (1994) reviewed resource demands in semi-intensive shrimp farming in Colombia, describing an ecological footprint of some 295 J per J of edible shrimp protein produced, and an industrial energy ratio of 40:1. These were based on aerated and pumped systems, with external feeding. Based on four categories of intensification, energy and direct fuel costs have been estimated (Smith 2008) as shown in Table 28. This suggests that electricity costs are more than those for fuel, though in some cases electricity is generated onsite, adding to fuel use. Total energy costs would range from USD 0.20/kg in extensive production to 0.60/kg in highly intensive production, or some 5 to 15% of first hand sale value. Feeding these values into national production data provides the outputs in Table 29, together with estimated energy costs, and their comparison with first sale value..

Table 28: Cost of energy for shrimp production

Inputs	Energy cost USD/kg shrimp produced			
	Extensive	Semi-intensive	Intensive	Super intensive
Electricity	0.1	0.3	0.4	0.5
Fuel	0.1	0.2	0.1	0.1

Source: Smith, 2008

Table 29: Shrimp culture production/energy cost by country

Country	**Production** (tonnes)	**Value** (USD bn)	**Value/ kg (USD)**	**Estimated energy cost, USD million**	**% of first sale value**
China	2 441 559	9 443	3.87	1220.8	12.9
Thailand	580 315	1 696	2.92	290.2	17.1
Indonesia	346 527	1 405	4.05	173.3	12.3
Vietnam	354 482	1 434	4.05	177.2	12.4
Bangladesh	85 510	385	4.5	42.8	11.1
Ecuador	56 300	270	4.8	28.2	10.4
Others	631 307	2 367	3.75	315.7	13.3
Total	4 496 000	17 000	3.78	2248.0	13.2

Source: Fishstat, 2006; energy costs estimated using Table 26

With a production approaching 4.5 million tonnes in 2006, assuming most production to be at semi-intensive or intensive levels, and with an average energy cost of USD 0.50/kg produced, total energy costs would be some USD 2.5 billion, of which 60-80% would be spent on electricity and 20-40% on fuel. This compares with first sale value of around USD 17 billion. However, this estimate does not include energy involved in feed supply, which as noted earlier would account for a greater input, much more so if the total embodied energy is accounted. In a review of Thai production systems, Tunsutapanich et al (2006) noted that feed and direct energy accounted for some 50% and 20% of production costs respectively, and that aeration accounted for some 80% of direct energy costs. On an LCA basis, operating the aerators contributed almost all the energy inputs involved.

A number of more recent analyses have been carried out of the more intensive shrimp aquaculture sector. Cao et al (2011) surveyed six hatcheries and 18 farms in Hainan Province, China, noting significantly higher impacts per unit production for intensive than semi-intensive farming. Grow-out contributed 96.4 to 99.6% of the cradle-to-farmgate impacts, mainly through feed production, electricity use, and farm effluents. Averaging across intensive (15%) and semi-intensive (85%) farming systems, 38.3 +/- 4.3 GJ of energy and 40.4 +/- 1.7 t of net primary productivity were required per tonne of production. In 2008, estimated total electricity and energy consumption were 1.1 billion kWh and 49 million GJ.

Salmon farming

The salmon farming sector is becoming increasingly concentrated commercially, with major locations in Norway, Chile, Scotland, Canada, Ireland and Tasmania. As the industry has expanded and become more concentrated, systems and production processes are increasingly standardised. Based on 2006 data, key salmon producing countries and the estimated total energy use (including feed related energy) associated with this, based on figures in Table 20 (56 GJ/t) are given in Table 30.

Table 30: Production and industrial energy use of farmed salmon by country

Country	Production (tonnes)	Value USD billion	USD/ kg	Energy input, TJ	Fuel equivalent, '000 tonnes	Fuel cost, USD mill	%age of first sale value
Norway	689 970	2 649	3.84	38638.3	966.0	869.4	32.8
Chile	658 455	3 902	5.93	36873.5	921.8	829.6	21.3
UK	145 433	711	4.89	8144.2	203.6	183.2	25.8
Canada	123 091	679	5.52	6893.1	172.3	155.1	22.8
US	37 312	105	2.81	2089.5	52.2	47.0	44.7
Japan	29 316	198	6.75	1641.7	41.0	36.9	18.6
Other	459 694	1 647	3.58	25742.9	643.6	579.2	35.2
Total	2 143 271	9 891	4.61	120023.2	3000.6	2700.5	27.3

Notes: fuel equivalents at 40 GJ = 1 tonne diesel, costed at USD 900/tonne

These figures, including feed and other inputs suggest that industrial energy inputs to production costs correspond to around 20-30% of first sale value, though reaching almost 45% for the USA for which first sale values are reported as only 61% of the sector average. These sale values are more typical of current (2011) market levels, and suggest that energy related costs are now likely to correspond to a higher proportion of realisable revenue. However, the figures in this table must be considered as very broad initial approximations, and would require to be verified with respect to market conditions, expected feed use and with other demands. Nonetheless, given the significant role of feeds and the extent of embedded energy, these costs are not unexpected. If more accurate feed conversions are known, or average industry standards available, total energy demands can also be estimated by assuming that feed represented 80-90% of the operational energy budget.

Following pioneering work in energy studies by Folke (1988) and others, more recently salmon aquaculture has become the focus of more extensive LCA reviews in which energy consumption is at least an intermediate stage to the definition of other parameters such as GHG impact (see eg Ellingsen et al, 2009, Pelletier et al 2009, Winther et al 2009). These have also compared salmon with other products – eg Ellingsen and Anondsen 2006 comparing farmed salmon and wild cod, comparison with chicken, and assessed different types of production system (Ayer and Tyedmers, 2009, Colt 2010). Assessments have also been made of the impacts of feed choice in salmon aquaculture (Boissy et al, 2011) and of the use of organic farming strategies (Pelletier and Tyedmers, 2010). Reviews have also been made for rainbow trout (Given the prominence of Atlantic

3.5 Global energy use in aquaculture

A number of approaches could be adopted to estimate global and related energy and fuel inputs for aquaculture, though as for capture fisheries, there are few direct sources of data, and estimates require to be extrapolated from partial data sets together with working assumptions. At this stage it also more practical to group systems and species together to avoid highly detailed but not necessarily more accurate estimates based on the complete variety of aquaculture production options currently in use.. Two approaches are shown; one based on a simplified intensification category approach (see Table 20), assigned to different regions and species groups, with fuel equivalents and total energy estimates. The second uses production cost data and the share allocated to energy costs, together with a different species and system categorisation to develop global equivalents.

By system and environment – fuel equivalents
Table 31 is developed from the five-stage intensification categories described in Table 19, with equivalent estimates of energy inputs related to feed, water, aeration and other energy usage. Based on FAO aquaculture production data for 2006, system intensities are allocated to major species groups and regions, separating China from the rest of Asia, due to its dominant influence in global totals. All "Aquatic Plants" are all classified as "extensive" requiring little or no energy inputs and have not been included. This is linked with reported output volumes to produce the regional and global estimates of total equivalent fuel use set out in Table 32.

Table 31 System categories and estimated energy inputs per tonne production

System category	Characterised by	Energy inputs/t production	
		GJ	t fuel equivalent
(A) Extensive	less than 0.5 t/ha/yr for fish, but substantially more for molluscs or algae; use of natural water bodies (eg lagoons, bays, embayments) and of natural, often unspecified, food organisms	0	0
(B) Semi extensive	0.5 – 5 t/ha/yr, possible supplementary feeding with low grade feeds, regular use of organic or inorganic fertilizers, rain or tidal supply, and/or some water exchange; normally traditional or improved ponds: limited cage systems, some enclosures, rope based mollusc culture (energy for vessels/handling).	25	0.5
(C) Semi-intensive	2 to 20 t/ha/yr, dependent largely on natural food, augmented by fertilization or supplementary feed, normally in improved ponds, some enclosures, or simple cage systems.	50	1.0
(D) Intensive	up to 100 t/ha/yr; completely fed,; usually ponds, tanks, raceways with water exchange, or cages	75	1.5
(E) Super-intensive	up to or exceeding 1000 t/ha/yr; completely fed, tanks, raceways with/out recirculation, or cages	100	2

Note that as in the salmon sector example given earlier, these figures represent the full industrial energy use for these systems, incorporating capital items as well as feeds, together with the specific use of fuel – eg for vessels, vehicles, direct drive pumping, power generation. This suggests that the total equivalent oil used in aquaculture would be some 60 million tonnes which at USD 900/tonne would be valued at USD 54 billion. Within this total, more than 50% is accounted for by freshwater fish production. China, as the major producer, would account for more than 36 million tonnes fuel equivalent, valued at some USD 32.4 billion. These figures compare with a total global first sale value of almost USD 78.8 billion, and USD 38.4 billion for China, potentially demonstrating the major role of fully accounted energy in production cost. However as this is based on embodied energy ratios, a substantial part of the energy is unaccounted in market terms, contained in calorific energy of feed components. A more realistic estimate is to be defined using manufactured and operational energy inputs, as follows.

Table 32 Estimated total fuel use equivalent and cost by major regions/species groups

Region	‘000 tonnes fuel equivalent					Total fuel million t equivalent	USD million
	Marine fish	Diadromous	Fresh water fish	Crustacean	Molluscs		
Africa	294.5	3.0	633.5	20.0	1.5	0.95	857.2
Americas	10.3	2,098.4	1,228.4	878.9	217.4	4.43	3990.1
Europe	315.1	1,379.7	382.5	0.9	430.9	2.51	2258.1
Asia (-China)	631.5	1,010.4	9,184.6	3,204.4	974.3	15.01	13504.8
China	1,097.8	333.8	23,828.8	4,639.0	7,046.5	36.95	33251.3
Oceania	4.6	77.6	3.8	11.8	71.7	0.17	152.5
Total	2,353.6	4,903.0	35,261.6	8,754.9	8,742.4	60.02	54014.0

1. The crustacean category is dominated by shrimp or prawns with a lesser amount recorded as miscellaneous (misc.); intensive in all areas except super-intensive in Europe and USA
2. Diadromous fish are mainly salmon and trout in all areas except Asia where "misc" dominate and China where eels are dominant; these are super-intensive in all areas except Asia and China..
3. Freshwater fish are dominated by "misc", carps and tilapias, but catfish are the main species in N. America, Total production is > 24 million t mostly from Asia. This section is critical in the overall weighting of global energy demand. Semi-intensive in all areas except Americas and Europe, where intensive
4. Marine fish not reported from South America and Oceania, though some production occurs. The global total is just over 1 million t, about 90% from Asia. . these are intensive in Americas and Europe, semi-intensive elsewhere.
5. Molluscs are dominated by clams, mussels, oyster and scallops, all filter feeders – all semi-extensive.

To estimate the fuel equivalent levels associated with direct consumption of fuel and electricity, two primary components can be considered:

- Direct fuel and electricity involved in production – eg boats, vehicles, pumps, aerators, heating/cooling, miscellaneous inputs – typically 0.5 - 5% of operating costs for all but the most intensive systems (which contribute negligibly to global production)
- Fuel involved in harvesting raw materials, processing them and distributing the manufactured feeds to production locations; feed energy itself accounts for almost 80% of total energy in intensive systems and almost none in extensive systems; of this some 15-25% of the energy might be associated with harvesting, production and distribution.

On this basis, a further set of estimates can be generated to describe more specific energy use, and in particular, those categories which have to purchased by producers at market prices, shown here as an average of 2.5% of total energy for direct fuel/energy, and 20% for combined direct and feed-related energy. This is set out in Table 33, which provides a global total energy cost of some USD10.8 billion, which at 13.7% of reported first hand sale value, corresponding broadly to the sector and other data described earlier.

Table 33 Estimated fuel/energy use for direct and feed-related inputs

	Total embodied energy		Direct fuel/energy use		Direct plus feed related use	
	Million t fuel equiv	Cost, USD billion	‘000 t fuel equiv	USD billion	‘000 t fuel equiv	USD billion
Africa	0.952	0.857	23.8	0.021	190.5	0.17

Americas	4.433	3.990	110.8	0.100	886.7	0.80
Europe	2.509	2.258	62.7	0.056	501.8	0.45
Asia (-China)	15.005	13.505	375.1	0.338	3001.1	2.70
China	36.946	33.251	923.6	0.831	7389.2	6.65
Oceania	0.169	0.152	4.2	0.004	33.9	0.03
Total	60.016	54.014	1500.4	1.35	12003.1	10.80

Energy input could also apply to constructing production facilities, typically no more than 5% of those contained in operating costs, except for extensive shellfish systems for which operating fuel inputs are low, though not all of this would subject to market costing.

By system and species groups
As feed is shown to be the primary determinant of energy use in aquaculture, the second approach uses more specific detail based on two primary categories of aquaculture system – unfed and fed, with several sub-types:

1) Unfed systems ;	2) Fed systems ;
• Extensive pond systems (typically freshwater fish and some marine fish); • Aquatic plant production; • Mollusc production;	• Intensive and semi-intensive pond systems (typically for carp, tilapia, catfish, shrimp); • Intensive cage systems (typically tilapia, salmonids, marine fish); • Intensive flow-through tank/pond system (typically for salmonids, tilapia, catfish); • Recirculating systems (hatchery and high value species)

Examples from the first category are given in Table 34, based on a small number of reported examples for which budgets were developed. The semi-intensive shrimp category shown here may have some fertiliser or feed, but costs are negligible. Annual fuel and electricity costs range from 2.9% to 10.4% of total costs for mollusc systems, approximately USD 20-90 per hectare, and around 35% of total costs in the shrimp systems, corresponding to around USD70 to 140 per hectare

Table 34 Systems without feed/with minimal feed inputs

Item	**Mollusc culture**			**Pond culture**	
Species	*Green Mussel*	*Oyster*	*Bloody cockle*	*Shrimp extensive*	*Shrimp semi-intensive*
Productivity (kg/ha)	3750	8206	8313	104	356
Total cost (USD/ha)	577.2	965.4	956.6	189.8	414.6
Variable cost (% total)	58.8	67.2	90.6	56.3	63.9
Fuel & electricity (% total) [2]	2.9	10.4	8.6	35.9	34.7
Labour (% total)	39.8	48.4	45.1	41.2	25.5
Total revenue (USD/ha)	758.8	1384.2	2989.7	503.6	2170.8
Net profit (USD/ha)	181.3	418.1	2033.1	313.8	1756.1
Average cost (USD/kg)	0.15	0.11	0.11	1.83	1.16
Net profit (USD/kg)	0.05	0.05	0.24	3.03	4.94

Source: STAQ/IPTS 2008

Tables 35 and 36 provide equivalent examples for fed production systems. Total and variable operating costs are significantly higher than for the simpler systems, largely accounting for seed and feed inputs. Fuel and electricity levels vary widely, from less than 1% of total costs for catfish (about USD 80 per hectare), which require very little water exchange and/or aeration, to more than 16% of costs (around USD 2500 per hectare) for intensive shrimp production, for which both aeration and water exchange are critical. For cage and recycle systems, patterns are broadly similar, though for tilapia cages some fuel/electricity is likely to be used, but contained within 'other' costs. It is not clear that the seabass case includes vessel fuel within its fuel/electricity category, as industrial cage systems are more likely to resemble those for salmon, which here correspond to around USD 0.80 per m3, or for an 8m deep cage, the equivalent of USD 64,000 per hectare.. Recycle systems, as noted elsewhere, have much higher relative fuel/electricity costs.

Table 35 Systems with feed inputs – ponds, intensive and flow-through

Item	**Intensive limited water exchange ponds**					**Flowthrough**
Species	*Shrimp*	*Prawn*	*Tilapia*	*Catfish*	*Snakehead*	*Trout*
Productivity (kg/ha)	3953	4000	16875	20545	65640	5850
Total cost (USD /ha)	15159	9545	13869	8286	74148	10700
Fixed cost (% of total cost)	10.4	2.3	7.8	3.2	3.2	25.6
Variable cost (% total)	89.6	97.7	92.2	96.8	96.8	74.4
Feed (% total)	41.8	54.9	71.6	75.7	74.4	43.4
Fuel & electricity (% total)	16.6	8.4	2.2	0.8	3.1	2.5
Labour (% total)	17.8	2.2	7.6	12.7	3.2	8.9
Total revenue (USD/ha)	20792	13078	17189	10703	79271	16205
Net profit (USD/ha)	5633	3534	3320	2417	5123	5558
Average cost (USD/kg)	4.04	2.38	0.74	0.4	1.14	1.82
Net profit (USD/kg)	0.89	0.88	0.28	0.11	0.08	0.95

Source: STAQ/IPTS 2008

Table 36 Systems with feed inputs – cages and recycle systems

Item	**Intensive cages**				**RAS**
Species	*Tilapia* [1]	*Tilapia* [2]	*Sea bass*	*Salmon*	*Various*[3]
Productivity/cycle (kg/m^3)	18.2	43.6	20.5	11	100
Total cost (USD /m^3)	16.99	29.85	23.94	44.23	Various
Fixed cost (% of total cost)	3.8	2	5.9	7.2	Various
Variable cost (% of total cost)	96.2	98	94.1	92.8	Various
Feed (% total cost)	61.9	73	63.1	48.9	36.3
Fuel & electricity (% of total cost)	neg	Neg	0.1	1.8	11.7
Labour (% total)	11.1	1.9	6.2	16.9	8.3
Total revenue (USD/m^3)	19.61	36.35	46.13	49.17	
Net profit (USD/m^3)	2.62	6.50	22.18	4.94	
Average cost (USD/kg)	0.93	0.68	1.16	4.02	
Net profit (USD/kg)	0.15	0.14	1.08	0.45	

Source: STAQ/IPTS 2008 [1] Reservoir site; [2] River site; [3] from EU-CONSENSUS ;

A more specific estimate of fuel use can be developed from data on specific functions within different aquaculture systems (Table 37). By combining species/system categories with recorded outputs and values at global and regional levels, and estimating the relative usage of different system types, a range of energy input totals can be developed. Tables 38 and 39 set out global totals for unfed and less intensive systems, and for more intensive systems and overall totals respectively.

Table 37 Tonnes of fuel equivalent /tonne produced in aquaculture systems

Systems/fuel use category	**Pumping**	**Aeration**	**Heating/ cooling**	**Vehicle/ vessel fuel**	**Misc power**	**Total**
Aquatic plant	0[1]	n/a	n/a	0.0017[2]	0.0017[3]	0.0034
Molluscs	0[1]	n/a	n/a	0.017[4]	0.0085[3]	0.0255

Extensive and semi-intensive pond	0[1]	0.015[5]	n/a	0.026[6]	0.026[7]	0.067
Intensive pond	0[1]	0.036[8]	n/a	0.026[6]	0.026[7]	0.088
Intensive cage	0[1]	n/a	n/a	0.014[9]	0.026[7]	0.040
Intensive flowthrough tank/pond	0.01[11]	0.014[12]	n/a	0.026[6]	0.026[7]	0.76
Recirculating aquaculture	0.29[13]	0.29[13]	0.29[13]	0.026[6]	0.015[7]	1.04

[1]water fed by gravity or natural water current; [2] based on 1 ha unit using 10 hp vessel (consumption: 10km/litre), 4km/day for 3 months with output of 20 t per ha; [3] assume = vessel fuel consumption; [4] 2 ha unit using 80hp vessel (consumption: 3 km/litre); 6 km/day for 3 years with output of 50 t per ha; plus 100 l fuel per 10t crop for vehicle [5] at 0.2 kg O2/kWh and 0.5 kg O2/kg feed fed assuming FCR 0.5 and 15% of oxygen demand is supplied by aeration; [6]300 L fuel per 10t crop for vehicle; [7] assume = fuel consumption for vehicle; [8] as for semi-intensive ponds, but with 0.3 kgO2/kWh, FCR = 1.5 and 30% of oxygen demand supplied by aeration; [9]salmon farm with 750 tonnes production, 500 day crop cycle, using 2 x 200 hp vessel (consumption: 1km/liter) travelling 5km/day; plus 100 l fuel per 10t crop for vehicle; [10] assume average replacement flow of 0.0085 m3/sec per tonne, 2m pump head 65% efficiency [11] as for intensive ponds assuming FCR 1.2 and 15% of oxygen demand supplied by aeration; [12] Based on CONSENSUS Working Group - assuming an equal split of total power consumption between pumping, aeration with oxygen generator and heating/cooling;

The global total developed in this approach, defining direct fuel and power only, is USD 3.48 billion, using % age cost estimates, and USD 2.84 billion when energy demands are built up as per Table 37. These values are more than double the levels defined in Table 31 for the direct use of energy (USD 1.35 billion), but much less than the USD 10.48 billion estimated for use including feed related energy. This compares with the value of total embodied energy use of USD 54.0 billion (Table 33), and direct market-costed fuel use for capture fisheries of USD 40-60 billion, as outlined earlier.

Table 38 Global compilation of system types – unfed/partially fed systems

System	Aquatic plants	Molluscs	Semi-intensive pond[a]	
Fuel/energy values			*Crustacea*	*Freshwater fish*
World total (million tonnes)	15.08	10.47	0.33	20.74
First sale value USD billion	7.19	8.84	1.34	19.49
Estimated input cost, USD billion	2.87	5.30	0.40	12.67
Fuel and power % input cost	3.0	5.0	35.0	15.0
Fuel and power total, U SD million	86.1	265.0	140.0	1900.5
Fuel cost based on Table 35	46.2	243.0	19.7	1250.4

Table 39 Global compilation of fed systems

System	Intensive pond [b]		Intensive cage[c]		Flowthrough tank/pond	RAS[d]	Total all systems
Groups	*Crust-acean*	*Freshwater fish*	*Diadromous*	*Marine fish*	*Diadromous*	*Various*	
Total (million tonnes)	2.94	2.30	1.06	1.09	1.06	0.05	55.12
First sale value USD billion	12.04	2.17	4.87	1.47	4.87	0.11	62.38
Est input cost, USD billion	5.42	1.62	4.14	1.25	4.14	0.10	37.91
Fuel and power % input	15.0	3.0	2.0	2.0	2.5	11.5	9.17
Fuel/power total, USD m	813.0	48.6	82.8	25.0	103.5	11.5	3476.0
Fuel cost based on Table 35	233.1	182.5	38.2	39.2	725.0	46.8	2824.1

They also demonstrate the significance of fuel and power costs in the freshwater pond sector – particularly for semi-intensive freshwater fish (55% of total) and intensive shrimp culture (23% of total). There are however discrepancies between the two methods - % cost estimates give much higher energy costs for aquatic plants and crustacea, lower costs for freshwater fish production, and much lower costs for intensive flow-through systems. The primary cause of these differences is likely to be the limited data in each system category from which reliable representative figures can be drawn. There is clearly a need to develop better data, though as major system types and technologies start to converge under competitive pressure, disparities in performance may reduce.

Though not shown here, the method can also be applied at the regional level, using regional production and value data together with estimated input costs and the relative contributions of fuel and power. Where date is available or where these factors can be estimated, input cost and fuel/power input ratios can also be adjusted to reflect regional variations.

3.6 Scenario development

A number of projections can be developed for the aquaculture sector, based on expected growth rates and species/system composition. The wider range of scenarios is too diverse and complex to present here, though once the features of key systems and output levels are further verified, a range of scenarios can be developed for species groups, systems, national and regional contexts. Thus energy use scenarios have been drawn up for the European aquaculture sector (STAQ/IPTS 2008), based on the extent to which it grows to meet regional demands and/or replaces shortfalls from capture fisheries. For 2025, the most likely range of sectoral annual energy demand – based on current systems and technologies, and using total energy accounting (ie including feed energy), is 200-500 million GJ, or at the equivalent of 50 GJ/t of fuel, 4-10 million t of fuel, valued at 3.6-9 USD billion at USD 900/t.

Similar projections can be drawn for other regions based on expected changes in output over defined periods. If for example aquaculture is anticipated to double in output over the next two decades, energy demands might increase pro rata. However, if yields are to increase through intensification, eg of semi-intensive pond systems, in which much of the world's production is based, energy demand will increase further. Tables 40 and 41, based on the previous tables (using the % cost method) explore implications of increasing production by various amounts for each of the production classes/ systems, targeting an extra 40 million tonnes of output, primarily by expanding intensified pond production.

Table 40 Energy use scenario – unfed/partially fed system

System/ Groups	Aquatic plant	Molluscs	Semi-intensive pond *Crustacea*	Semi-intensive pond *Freshwater fish*
Total (million tonnes)	15.08	10.47	0.33	20.74
Projected increase %	15	20	10	60
Target level, million tonnes	17.34	12.56	0.36	33.18
Energy efficiency gain %	5	10	10	15
Current energy cost (USD m)	86.1	265.0	140.0	1900.5
Target energy cost (USD m)	94.1	286.2	138.6	2584.7

Table 41 Global compilation of fed systems

System/ groups	Intensive pond [b]		Intensive cage [c]		Flowing tank/pond	RAS	Global total
	Crust-acean	*Fresh-water fish*	*Dia-dromous*	*Marine fish*	*Dia-dromous*	*Various*	
Total (million tonnes)	2.94	2.3	1.06	1.09	1.06	0.05	55.12
Projected increase %	30	450	30	150	20	300	
Target level, million tonnes	3.82	12.65	1.38	2.73	1.27	0.2	85.49
Current energy cost (USD billion)	813.0	48.6	82.8	25.0	103.5	11.5	3476.0
Target energy cost (USD billion)	898.4	213.8	96.9	59.4	111.8	39.1	4552.9

The tables also incorporate estimates of energy efficiency gains from current levels, eg with better use of water exchange, aeration, energy costs in feeds and conversion ratios. Respective energy use and cost (here using the value of USD 900/tonne) are also developed, suggesting a target of some USD 4.55 billion for direct energy cost, an increase of slightly more than 30%. On a pro-rata basis this also suggests feed-inclusive energy costs to rise from USD 10.48 to 13.64 billion at current prices.

Clearly these scenarios can be developed in a range of directions depending on the underlying expectations. They can also be developed at a national or regional level to consider resource use and cost implications of the common policy aim of expanding aquaculture. Similarly, species or system-based analysis and/or projections can be developed, and from all of these can be identified the critical areas where energy efficiency gains could be sought. Finally, in a changing context of supply and energy prices, the growth potential for each subsector will be defined by profitability and returns on investment, hence influenced by the relative use and cost of energy.

3.7 Conclusions

Though there are some issues and consequences in common, the role and impact of fuel and energy in the aquaculture sector differ from those for capture fisheries, and these differences are potentially significant for investment, policy and management. Conclusions are as follows:

- Evidence suggests that across a range of aquaculture systems direct fuel inputs and costs are not major components in production and output, but indirectly, fuel and energy associated with feeds and their embodied ecosystem support in particular can be very significant, though not usually subject to market costing. Embodied energy in production facilities is also definable, but generally less critical in energy budgets or related expenditure.

- The most fuel and energy demanding systems are commonly those for intensive fish and crustacean production using complete feeds, and with supplementary energy inputs for water exchange and aeration. Recycled water systems, while reducing water use and waste discharge, have even higher energy demands associated with water treatment and temperature control, but represent only a very small part of global production.
- By contrast, low intensity systems using natural productivity for production of aquatic plants and molluscs have very low energy inputs, usually only associated with limited levels of management input, and with harvesting. Low intensity fish and crustacean systems may also have low energy demands but are often fertilised or partially fed, which raises energy inputs.
- Feed associated inputs have been particularly but not exclusively linked with fishmeal and oil components, where fuel and energy associated with capture and processing can be significant. The levels are linked with the fishery resource, the nature of processing and the transport and distribution costs involved.
- Other feed inputs – eg from conventional agriculture, are becoming increasingly important and also have definable fuel and energy use profiles; in less intensive systems, industrial energy associated with inorganic fertiliser production may also contribute to inputs. Accurate data on energy inputs associated with feeds from all sources require further development.
- In most cases, immediate vulnerability of aquaculture production to direct fuel costs is relatively limited, but increasing levels of competition and tight financial margins in many aquaculture sectors will cause concern for viability and performance – in this, direct fuel costs or feed prices will be key elements.
- Evidence of variation in fuel and energy efficiency within aquaculture subsectors is so far limited, but variation in performance associated with feed use and conversion, and with water exchange and aeration usage, suggest that significant efficiency variations exist. This in turn implies that efficiency changes can be made.
- International competitiveness issues with respect to fuel and energy use are similarly less definable, but good access to efficiently produced feed sources, high dependence on photosynthetically driven food supply and water management systems, and good access to supply chains and markets are all positive elements.
- Across all productive inputs, there are extensive data needs on fuel and energy inputs across the aquaculture sector, and on comparative production efficiency, at enterprise level and in terms of national and global inventories and system transformations.
- An increasing number of LCA (life-cycle assessment) studies have been carried out on energy use and other environmentally-linked issues for aquaculture, and have emphasised the importance of defining system boundaries and allocating inputs or products. These are likely to provide more detailed perspectives on fuel and energy use, and the key sources of variability.

4 Post-harvest functions

4.1 Introduction

It is estimated that in 2008, some 77% of the world catch was used for direct human consumption and 23% for other uses, primarily fishmeal and oil production (FAO, 2010). Of the proportion directly used, some 31% was eaten fresh, 35% was frozen, 16% was dried or smoked and 18% was canned. The balance between product forms varies notably between developed and developing countries, with far greater levels of frozen and canned fish production in the former and reliance on fresh or dried/smoked fish supply in the latter. In developing countries, much of the output is consumed directly, with little infrastructure to do otherwise, while in developed countries, the historical expansion of fisheries capture and trade, had been associated with preservation methods such as drying, salting, canning and curing.

As better transport, freezing and cold storage transport became available, market opportunities for fresh or frozen product have expanded, and over recent decades there has been an increasingly wide provision of fresh fish, an amount now greater than total catches in 1950. Reductions in post harvest loss and spoilage, together with improvements in process recovery have also increased the net amounts available for consumption. Another trend in developed country markets is the increasing role of value added convenience foods, which often incorporate seafood as a component, often the defining and most expensive element, but not necessarily the largest part of the dish. In this sector, processing options may become far more complex, and the attribution of specific energy costs to the seafood element may become difficult to define, and the implications less certain, for example where ingredient mixes, recipes, presentations and market positioning can all be changed in response to process cost changes.

Other uses have also been important, with fish meal and oils, once used in lower value products such as fertiliser, assuming steadily increasing value in animal feeds, including those for aquaculture. Pet foods have also become an increasing valuable market, though the once important direct canning market is increasingly supplied with the offal and offcuts from other fish processing methods. In all of these, energy application is a key factor, the changing cost of which will have widespread implications for products and markets. More widely also, the use of energy in post-harvest and distribution processes is of increasing consumer and policy interest with respect to life-cycle analysis and food footprint. As it is not possible to deal with all the post-harvest and value addition permutations, particularly involving energy and fuel cost attributions for complex food products, this section deals primarily with the main processes used for the sector.

4.2 Systems/structural descriptions,

Product quality, stability, delivery options, reduction of loss and addition of value are key targets in any part of the post-harvest/processing sector, regardless of location and supply chain, and irrespective of whether the focus is on marginal economy food security issues or on high value luxury products. Capitalisation and the role of energy vary across the sector, but energy issues are critical in areas such as raw material and product handling and movement, temperature control, water supply and ice production, and in the manufacture of packaging and presentation materials. An increasing issue in many parts of the sector is the time between harvest and delivery to the customer, and hence the turnover of capital, and particularly for high value/low volume products such as shrimp, shellfish, lobster, tuna etc, post-harvest and transport choices are based on speed and flexibility rather than energy input and costs.

An overview of energy and other features of processing fresh fish or thawed frozen fish is provided in Table 42. This also includes water use, waste and net product yields.

Table 42 : Output and energy costs for fresh fish processing (COWI)

Process element	Water ($m^{3)}$ per tonne)	Energy (kWh per tonne)	Waste (kg/tonne)	Output (kg/tonne)
Thawing (frozen fish)	5	0	20	980-1000
De-icing washing and grading	1	0.8-1.2	0-10	980-1000
Grading	0.3-0.4	0.1-0.3	0-20	980-1000
Scaling	10-15	0.1-0.3	20-40	960-980
Deheading	1	0.3–0.8	270 – 320	680 – 730
Filleting (white fish)	1-3	1.8	200-300	700-800
Filleting (oily fish)	1-2	0.7–2.2	~440	550
Skinning (white fish)	0.2–0.6	0.4-0.9	140	950
Skinning (oily fish)	0.2–0.9	0.2–0.4	140	960
Trimming and cutting	0.1	0.3–3	240-340	660- 760
Packaging freezing, storage	0.2	10-14	0	1000
Average for total process		20		

Here it can be noted that process elements such as filleting (0.7 to 2.2 kWh/tonne) and packaging, freezing and storage (10-14 kWh/tonne) demand the highest energy inputs, though all of the other process elements can be important. The impacts of water use and waste levels on energy use and net demands can also be important in that provision of water and waste treatment or disposal may require fuel and energy, as well as creating input at the overall life-cycle level. However, the relationships are very site dependent and more difficult to specify.

4.3 Key energy elements

Icing/cooling

In global terms, cooling of fish products is the most widespread and important post-harvest process. As outlined in Table 43, fresh fish are commonly cooled by ice or other means to reduce the rate of spoilage. Fresh fish is generally consumed within a week of capture and within a short range of first sale point, though this is extended for highest value products (eg tuna, salmon, shrimp) by using air transport. For fish caught on day-boats, ice might not be used, but unless there are problems with ice supply or fish are to be consumed immediately this is becoming less common, particularly in tropical climates, where impacts of icing are most evident.

Table 43 Fish shelf life (days) under ice

Temperate waters		Tropical waters	
Fish	**Shelf-life**	**Fish**	**Shelf life**
Cod	12–15	Snapper (Brazil)	11–16
Haddock	12–15	Tuna (USA)	29
Whiting	9–12	Synagric japonicus (India)	27
Hake	8–10	Bonga (West Africa)	20
Redfish	13–15	Sea Bream (West Africa)	26
Herring	5–6	Burrito (West Africa)	22
Mackerel	7-9	Tilapia (West Africa)	28

The combination of increased fresh fish consumption and increased quantities of ice being used per unit of output has increased ice use globally. In capture fisheries, freezing fish or producing ice on board, normally only for larger vessels, is generally accounted for in the energy supplied in fuel to the vessel. However, most ice is used on smaller vessels and taken on board prior to fishing, and used on catching or applied to the fish when landed. For aquaculture, ice use is similar, at point of harvest and/or during initial post-harvest grading/packing stages. Thus the cost and energy use associated with ice in most cases is accounted for separately.

Ice has a large cooling capacity per weight, is relatively cheap, prevents drying by keeping the fish moist, is easily portable and maintains a temperature slightly above freezing point of fish without the need for sophisticated temperature control. It can be made from fresh water or sea-water, in block, flake, plate or tube ice format. Clean seawater can be used but produces a soft and wet ice, which due to its salt content can cause partial freezing of the fish, which is not desirable and may need to be monitored. However it is useful where clean fresh water is expensive or in short supply, and can be produced at sea.

Block ice is the most commonly produced in many rural and developing country locations, using simple, accessible technologies. Cooling capacity of different types of ice is similar in weight terms but differs by ice volume due to density differences. The cooling and melting rate varies with type, depending primarily on surface area, which for flake ice is over four times that of tube ice, weight for weight. This is advantageous for rapid cooling of fish but disadvantageous for losses during transport and storage. For this reason also, block ice is normally transported whole, and only at point of application is crushed or chipped to smaller pieces. Finally, the size and shape of ice pieces affects not just the rate of cooling/melting but the surface contact with fish and the quality of the cooled fish with respect to uniform cooling, skin colour and crushing or cutting damage.

There are differences in efficacy of ice use between tropical and temperate regions (Table 44), though to chill fish sufficiently to achieve these gains, more ice is needed per kg of fish in higher ambient temperatures. For bulk and boxed stowage an ice to fish ratio varies between 1:2 to 1:1 depending on climate and intended keeping time. Once landed fish should be kept as near as possible to its chilled temperature through the market, processing and distribution chain, requiring more ice and/or refrigeration, and hence further energy input.

Energy use for ice production depends on ambient conditions and feed water temperatures. Table 44 shows approximate energy use per tonne of ice produced/held refrigerated for temperate and tropical areas, from which estimates can be developed of the energy cost of using ice per tonne of fish. When running to capacity, large plants are more efficient than small plants, though this also depends on the refrigeration technology, refrigerant and the age and maintenance level of the plant. For greatest efficiency, continual ice production is desirable but the demand may fluctuate daily or weekly, and some storage is usually required. For vessels undertaking longer voyages or without convenient access to an ice plant on shore, on board production can be considered, though there are issues of quality and on-board space in the choice between the ice plant or storing large quantities of ice, and whether salt water or fresh water ice is to be used.

Table 44: Energy consumption and costs for manufacture and use of ice

Type of Ice	Temperate			Tropical		
	kWh per tonne ice produced	Ice use per tonne fish	Energy cost USD per tonne fish	kWh per tonne ice produced	Ice use per tonne fish	Energy cost USD per tonne fish
Flake	50–60	1.3	9.8 - 11.7	70–85	1.7	17.9-21.7
Plate	45–55	1.3	8.8 – 10.7	60–75	1.7	15.3-19.1
Tube	45–55	1.4	9.5 – 11.6	60–75	1.9	17.1-21.4
Block	40-50	1.5	6.75	55–70	2.0	16.5-21.0

Source: developed from Smith 2008; assuming less ice required in temperate conditions than in the tropics, and less required if using high surface area ice. Based on ideal use conditions with energy costs of USD0.15 per kWh. These values will vary substantially with the actual conditions of use and subsequent storage

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Refrigerated sea water (RSW) and chilled sea water (CSW)

RSW and CSW are usually used for large catches of small fish, usually ungutted, kept on board for relatively short periods. They allow rapid chilling through efficient heat transfer and can retain fish at or near 0^{o}C. While both are very similar in application, CSW is cooled by adding ice to the water in a tank, while RSW is cooled by on board refrigeration. CSW, generally used in smaller vessels, does not require refrigeration machinery onboard, but its temperature will rise once the ice has melted, whereas RSW can keep the temperature low over an extended period. In both methods, energy required for cooling the catch can be stored prior to the catch being taken on board (as ice or seawater at a reduced temperature.) CSW and RSW techniques are now also being used in aquaculture, particularly for higher-value cage farmed species harvested into well-boats.

These methods have advantages of greater speed of cooling, reduced pressure on the fish, potential for lower holding temperatures, quick handling of large quantities of fish with little delay or labour involved, and extended storage time.. Disadvantages include potential salt uptake by species with a low fat content, loss of protein and some difficulty in controlling anaerobic spoilage bacteria. For larger systems there may also be concerns for vessel stability due to the free surface effect of the liquid volume of the water and fish, and stability guidance needs to be available and understood.

For CSW the amount of ice required will depend on the size of tank, the effectiveness of insulation, the ambient temperatures and the length of trip. A ratio of water: ice: fish of 1:1:4 is commonly used for 3 to 4 days stowage in insulated tanks in temperate climates and 1:2:6 in tropical climates. Chilling in RSW is normally faster than chilling in ice, the refrigeration requirement depending on the initial temperature of the fish and ambient conditions. The initial cooling load is usually the greatest, with much less load during the holding period. As an example 20 tonnes of fish at a temperature of 20 ^{o}C will impose a refrigeration load of about 100 000 kcal to chill to required levels. If the fish are cooled to just below 0 ^{o}C in 6 hours, total energy required will be about 20 kWh, or 1 kWh/tonne. In practice, however, the capacity of the refrigeration system may be limited and the RSW cooling rate will therefore be reduced.

If landed within one or two days of capture, fish intended for fishmeal and oil does not usually need to be chilled, but with increasing focus on the quality of fishmeal and oil depending on raw material quality, chilling allows vessels to undertake longer trips make larger catches and gain better prices.

Freezing and cold storage

Freezing fish lowers its temperature sufficiently to slow down spoilage so that on thawing after cold storage it is almost indistinguishable from fresh fish. Chill preservation may only be suitable for a number of days whereas good freezing and cold storage will enable storage for many months. If grounds are a long way from the port of landing and fishing trips last many days, freezing at sea may be the best option. If the consumer market is distant from sources, freezing may again be necessary to preserve the fish during the period of storage, transportation and distribution.

Typically, high catch periods with low market prices can also make it feasible to freeze and store until supplies drop and prices rise. This can benefit producers, processors and consumers alike as it results in a regular supply, more uniform and better quality and more stable prices. In the absence of reliable and cost-effective means of exporting fresh product, freezing and cold storage also allows access to valuable export markets for higher value products such as frozen shrimp and fish. However, apart from shrimp and the occasional removal of product (eg salmon) during oversupply periods, freezing is relatively rarely used for aquaculture product, which is primarily marketed fresh.

Freezing requires removal of heat, and during the first stage of cooling, temperature falls very rapidly to around 0^{o}C, the freezing point of water. More heat is then extracted to turn the bulk of water to ice - the thermal arrest stage – and temperature changes very little. When about three quarters of the water is turned to ice, temperature falls again as most of the remaining water freezes and the frozen product cools further. A comparatively small amount of heat is removed at this stage. To avoid problems of ice crystallisation in the product, which degrades texture and results in excess water loss on thawing, quick freezing is required – typically reducing temperature of the warmest part of the fish to -20^{o}C in two hours or less. A much more demanding requirement is for frozen tuna for the Japanese *sashimi* market requiring freezers operating at -50 to -60 ^{o} C, and very rapid cooling to reach these levels.

Freezing is carried out at all stages of the distribution chain, with three basic methods applied

a) Blowing a continuous stream of cold air over the fish – blast freezing
b) Direct contact between the fish and a refrigerated surface – contact or plate freezing
c) Immersion in or spraying with a refrigerated liquid – immersion or spray freezing

Normally block or blast freezing is used; the latter is more common for larger, higher-value product, the former for bulk freezing eg for high-quality feed products, 'block' material for filleting, also block fillets; it is also common for smaller product such as shrimp. Modern blast freezers are highly efficient, and give very rapid contact/performance output. These are typically linear in configuration, though spiral belt designs also used. Freezing one tonne of fish, allowing for freezer system efficiency, requires some 120 kWh which at USD 0.15/kWh amounts to USD18/tonne. Subsequent cold storage energy demands depend on storage time, building and insulation specifications, the difference between storage and ambient temperatures, and on the ways in which the store is used.

Curing and drying

Curing fish by drying, salting, smoking and pickling are traditional methods of preservation. Salted and/or dried fish is one of the most common preserved foods, used by peoples of all cultures. The drying of food is the world's oldest known preservation method, and dried fish has a storage life of several years. Drying fish in open air typically reduces water content to 17-18%, sufficient for reasonable product stability, and salting drops this more and further controls bacterial degradation. Stockfish is unsalted fish especially cod, dried by sun and wind on wooden racks. This is cheap and effective in suitable climates, with minimal energy requirements, the product being easily stored, packed and transported to market. Fish to be cured are first cleaned and gutted, and for salting are packed between layers of salt or immersed in brine. For more industrialised applications, energy costs tend to be greater.

A review of energy costs in salting and drying plants in Eastern Canada (CIPEC/NRC, 2005) over 2001/mid 2002, with five plants producing around 7,000 t of salted fish and around 4,500 t of dried fish, with a total energy consumption of over 4 million kWh of electricity, more than 37 000 kg of bottled propane (used exclusively in forklift trucks), and almost 64 000 litres of heating oil (used for space heating of plants and offices). Expenditures for all energy sources totalled more than CAD 400,000 or an average of some USD 36.5/tonne of product. Specific operations included receiving and grading (16.2 to 45.6 kWh/tonne processed), preparation for salting (1.3 to 30.2 kWh/t), salting room operations (0 – 29.5 kWh/t), wet-cooling (31.3 – 108 kWh/t) and drying (69.4-256.7 kWh/t) Packaging (ie the process of putting product into packaging) accounted for 0.4 to 36.8 kW/t, while dry cooling storage post-production accounted for 21.4 to 225.7 kWh/t. For industrial air-drying of fish – mainly cod, in Iceland, (Arason, 2003) evaporative energy requirements were estimated to be 5,400-6,600 kJ/kg (1.52 to 1.69 kWh/kg) for conventional drying cabinets, and 3,800 to 5,000 kJ/kg (1.07 to 1.41 kWh/kg) for improved designs with heat recovery from exhaust air.

Salting is also often used as a preparatory stage for smoking. Cod, herring, mackerel, haddock, salmon, trout and eels are the species commonly smoked, though many others are also used. Many tropical species are also cook-smoked to produce a very hard, dry, robust and highly flavoured product. Smoking preserves fish by drying, by deposition of phenolic and tannic compounds and if near the source of heat, by cooking. Fuel and energy requirements for smoking fish are generally higher than for drying, much depending on the efficiency of the process, particularly for traditional kilns. In tropical zones, artisanal smoking in particular may place high demands on locally available timber, unless improved kiln designs are used. Padilla (2001) notes the use of 6m3 of wood fuel per 500kg of fish using traditional stoves, which are about 16% efficient in energy transfer to drying. At approx 15-20,000 kJ/kg calorific value of fuelwood, and 200kg of wood per m3, this would correspond to around 2.4kg wood per kg of fish and 36,000 to 48,000 kJ/kg (10.0 to 13.3 kWh/kg). Blay and Atikpo (2007) describe the use of an improved smoker design (AFSMO-150) in Ghana, consuming around 0.33kg of fuelwood per kg of fish, or at 15-20,000 kJ/kg fuelwood, some 5-6,700 kJ/kg fish (equivalent to 1.41 -1.89 kWh/kg). Modern smoking processes commonly use electrical or gas fired smoke chambers with much more controllable and efficient smoke flow and temperature management. They are also much more energy efficient. Dried and smoked products in developed country markets are usually transported and held in chilled storage, while in other markets they are normally held in ambient conditions.

Canning

The process of cooking, sterilising and packing fish in steel or aluminium cans is widely used, keeping the final product fit for consumption at ambient temperatures for long periods, with far simpler demands for storage, transport or other aspects of distribution. In fuel and energy terms, primary requirements are for cooking and sterilising, traditionally with steam, together with washing, can handling and other lesser demands. Though the weight of cans will add to distribution costs, this is widely compensated by reduced storage energy demands. Actual energy costs depend substantially on local conditions, and as many installations are relatively old, the efficiency of steam plant and other process elements. A summary of energy and other features of canning is provided in Table 45. Here it should be noted that by far the biggest contributor to energy demand is can sterilisation.

Table 45: Output and energy costs for canning, per tonne (UNEP/COWI)

Process	Water (m^3)	Output (kg/tonne)	Waste (kg/tonne)	Energy (kWh)	
				UNEP	COWI
Unloading	2 – 5	980	20	3	5.7
Packing into cans (grading)	0.2	970-1000	0-30	0.4 - 1.5	0.3
Packing into cans (nobbing and packing)	0.2 – 0.9	700-750	250-300	0.4 - 1.5	1.4
Packing into cans (skinning nobbed fish)	17	940	~55	0	
Precooking	0.03-0.5	850	150	0.3 - 1.1	1.3
(steam, 100kg)					132.4
Draining cans	0	800-900	100-200	0.3	0.3
Sauce filling	0	1100	-100	0	
Can sealing	0	1000	0	5 - 6	5.8
Washing cans	0.04	1000	0	7	7.4
Can sterilization	3-7	920-990	10-80	~230	242.1
Average				250	

Washing cans, and can sealing also represent some energy demand, though substantially less. Note also that as with previous examples, water use and waste treatment, and energy associated with this, may also be relevant. Further, the energy used in manufacturing the cans and in their disposal would be needed for a full life cycle assessment. The form of energy used in canning, for a small range of plant is outlined in Table 46.

Table 46 Energy consumption and usage forms in canning

Processing plant	Electricity (kWh per 8 hr)		Steam kg/hr	Fuel oil (litre/hr)	Capacity (t raw fish/hr)
	Equipment	Total			
l. Tuna production	2 000	2 700	5 000	350	20
2. Automatic skipjack line	1 700	2 200	2 000	135	10
3. Sardines in oil	1 500	2 200	3 500	230	15
4. Pre-smoked small fish	600	1 000	1 000	65	5
5. Fish paste products	1 800	2 300	4 500	300	10
6. Salmon	800	1 200	2 500	170	8
7. Shrimp	500	900	750	50	3.6

Source: Warne, in Myrseth, FAO Fish Circ., (784): 1985

In a review of simple retort-based fish canning in Khuzestan Province, Iran, Asakereh et al (2010), reported total input energy of 22681.8 MJ/t of product (6,300 kWh/t), with diesel fuel accounting for up to 98% of total energy, electricity 1.92% and labour 0.08%. Cooking and sterilisation accounted for some 93.5% of energy input, and most other operations less than 1%. Manual operations of fish cleaning and transferring used the least energy but accounted for 43.3% of total human labour. In an LCA analysis of a single plant canning frozen tuna, and based on an input unit of one tonne, Hospido et al (2006) noted the following requirements: reception and thawing 31.5kWh/t (5.1%); cutting 23.6 kWh/t (3.8%); cooking 384.7 kWh/t (62.2%); washing and cleaning 33.9 kWh/t (5.5%), dosing and filling 47.2 kWh/t (7.6%); packaging 33.3 kWh/t (5.4%); storage and ancillaries 58.9 kWh/t (9.5%) and waste treatment 5.6 kWh/t (0.9%). The final yield was 0.66 t and so these figures can be adjusted proportionally to relate energy inputs to final product weight.

In most fish canneries offal from preparatory processes are available for by-products, including canned and frozen pet food, minced frozen fish and fish silage for animal feeding and fish meal. Oil recovered from the canning process is also used for industrial purposes. By-product quality depends on the freshness of raw material, fat content and nutritional value. Fish flesh is generally more valued than viscera, heads, and backbones. The overall energy requirements and costs may be modified to account for byproduct output.

4.4 Fish reduction processes

In 2008, some 27 million t of fish was used for nonfood purposes, approximately 76% of which (20.8 million t) was reduced to fishmeal and fish oil (FAO, 2010). For commercially traded product IFFO (International Fishmeal and Fish Oil Organisation) 2008 data (Jackson, 2011) suggests the use of 16.48 million t of whole fish, plus 5.49 million t of fish process waste, producing 4.94 million t of fishmeal (22.5% overall yield), worth some USD 5.5 billion, and 1.03 million t of fish oil (4.7% yield) worth around USD 1.2 billion. As Table 47 shows, a substantial part of production is used for aquaculture feeds, the remainder going primarily to pig, chicken and other animal feeds. Fish meal and oil are two of the most internationally traded commodities, and it is estimated that each tonne of fishmeal/oil travels an average 5,000 km to reach its end user. Although most is shipped by bulk carrier, a growing share now travels by container, particularly higher quality grades.

Table 47 Production/use of fishmeals and oils

Year	Global production (% aquaculture use)	
	Fishmeal	Fishoil
2005	5877 (45-52)	959 (57-84)
2010	6000 (41-55)	950 (56-87)
2012	6000 (43-60)	950 (70-88)

Source: Jackson, 2006, Tacon, 2006 – higher % uses from IFFO, lower values from FAO

The main producing countries in 2009 were Peru, Chile, Thailand, USA, Japan and Denmark. A certain part of global production is used in national or regional markets, either from specialised industrial fisheries, from lower grade or unmarketed fish from human consumption markets, and increasingly from process offcuts. Jackson (2011) suggests that by 2020 this could supply up to 50% of raw material input. In the US, menhaden is the major fishmeal stock, while in the NE Atlantic major industrial fisheries for sandeel, capelin pout and blue whiting are supplemented by lower grade/surplus catches of pelagics such as herring and mackerel. In 2004 Peru accounted for some 30% of global fishmeal production and about 45% of global trade volume, from some 130 plants with a total capacity of about 9,000 t raw material per hour. Around a third of this was used for Prime and Super-Prime Steam Dried fishmeal. The supply fleet comprised about 600 vessels of which about 550 were smaller wooden artisanal vessels. The industry employed about 23,000 people, of whom 16,000 were in fishing and 7,000 in processing. Indirect economic activity (laboratories, logistics, trading, financing, various services) employed around the same number again. (Smith, 2008).

Industrial processing of fish entails a considerable amount of energy, primarily in cooking, pressing and drying – traditionally with flame-drying, or for better quality products, using more controllable indirect heat (Table 48). Additional energy demands are associated with moving raw materials and products. In some instances some of the fish oil is used to power the cooking systems, but only if otherwise unmarketable. There are widely differing transport costs associated with domestic production of fishmeal in Europe and in the USA and relatively high costs for Peru and Chile where the product has to be shipped to distant markets. Thermal evaporation and drying has been a major focus for energy conservation, and energy used to produce fish meal in Norway has been reduced by 21% since 1990. (Smith 2008). Well selected and sized process components, together with efficient heat recovery is a key issue in effective performance. In terms of overall energy efficiency of production, energy content of fishmeal is directly related to the percentage of protein and oil (fat) in the meal.

Table 48: Output and energy costs for processing fish meal

Process	**Energy (kWh/t)**	**Waste(kg/t)**	**Output (kg/t)**
Unloading	3	0	1000
Cooking	~90	0	1000
Straining and pressing		750 stick water	150 oil 100 press cake
Drying	~340	520 vapour	480 Fishmeal
Average	~400		

Source: UNEP-COWI, 1999

The metabolizable energy (ME) value of fishmeal usually ranges from 2500 to 3200 Kcal ME/kg. The quantity of oil present in fishmeal depends on the species (often with large seasonal variations), on the feeding habits/ opportunities of the fish, and the method of processing. Antioxidants for preserving fishmeal are essential to maintain ME value, which can otherwise be reduced by as much as 20%. Without these also, heat generation in storage needs to be carefully controlled.

Table 49 Energy consumption in fish feed production

Nutreco plants by activity in 2007	**GJ / tonne production**
Nutreco corporate & research*	11.72
Fish feed	
Skretting Northern Europe (Norway/UK/Ireland)	1.05
Skretting Canada	1.39
Skretting Chile	0.7
T&M Species	1.23
Compound feed	
Hendrix	0.23
Nanta	0.19
Meat processing	
Sada	3.26
Premixes and feed specialities	
Trouw Nutrition Americas	0.27
Trouw Nutrition W Europe	0.4
Trouw Nutrition Specialties	7.09
Trouw Nutrition C/E Europe & Asia	0.25
Nutreco Canada (compound feed, premixes and specialities)	0.35
Average GJ/tonne production (kWhr/kg)	0.49 (0.14)

*include pilot-scale plants for production of fish feed, compound feed

Given the particular link between the meal and oil sector and the aquaculture industry, energy use of the subsequent linkage to fish feeds is also useful to consider. Table 49 summarises data from one of the major international feed groups, Nutreco. Andersen (2002) reviewing energy use in Norwegian salmon culture quoted energy inputs into the feed production chain as totalling 5159 kWh/t, of which catch of fish feed raw materials accounted for 30.1%, (1552 kWh/t), production of fish meal 62.2%, (3210 kWh/t), import of fish meal 2.9%, (148 kWh/t) and production of feed-pellets at 4.8% (249 kW h/t).

A further analysis, in Table 50 shows the relative sourcing of energy inputs into the production of fish feeds. This shows the dominance of natural gas, electricity and fuel oil as energy sources. Clearly this depends on the location and history of the production plant, and as the industry has consolidated substantially in the last decade, there can be a variety of installations and energy efficiency.

Table 50: Energy consumption at Nutreco plants in 2007, by source

Energy source	Electricity	Steam	Coal	Natural gas	Fuel oil	Propane	Crude oil	Gasoline petrol	Total
MJoules consumed	1,507.9	162.5	123.9	1,486.9	347.9	165.6	4.9	281.2	4080.9
%total	36.95	3.98	3.04	36.44	8.52	4.06	0.12	6.89	100

Note: figures are based on Global Reporting Initiative conversion factors

Trash fish and drying for other uses

In many countries trash fish are used directly for feeding to aquaculture stock, usually minced and mixed with other ingredients (see eg FAO 2009). The quantities involved are difficult to estimate, though known to be substantial in some areas – eg in SE Asia. Nor is it always clear how much is bycatch from fishing already carried out (and for which fuel/energy is already committed) or is from targeted fishing for the specific purpose. Energy associated with these materials, apart from that associated with capture and transport/distribution is mainly linked with mincing, mixing and pelleting, often done by hand or sometimes with small electrically powered units, rated at typically no more than 1-4kW. Based on simple food pellet machines of capacity 150-180kg/hr, energy use in production is around 0.02 to 0.03 kWh/kg food. If food is air-dried, there is little other energy involved except that involved in screening, bagging and transporting. For more sophisticated medium-scale process lines for extruded floating feeds current manufacturers' data indicates energy demands excluding initial collection and preparation, and final drying and packing of typically 0.1 kWh/kg for 150 kg/hr reducing to 0.066kWh/kg for 2000kg/hr.

Another form of preparation is to spread fish on the beach to dry for animal food or for subsequent preparation for fishmeal. This is common for example n Somalia, Yemen, Oman and Pakistan (Smith 2008). These approaches require little energy apart from significant human inputs in catching, spreading, turning, gathering and bagging the dried fish. Local transport costs may also be involved in collecting and distributing the product, and some energy costs might also be incurred if the resultant dried fish are ground down and enter the national or international markets for fish-meal.

4.5 Multiple plant/process assessments

A number of reviews have been carried out across processing plants which handle a range of species and/or cover a range of products, typically on a seasonal basis. The allocation of specific fuel and energy use to products may be complex (see LCA reviews). Kelleher et al (2001) reviewed energy use in 10 plants in NW USA, producing whole/gutted fish, fillets, canning, fish roe, fresh and frozen crab and shrimp, block surimi and surimi products. The Alaskan plants typically processed halibut, cod, Alaskan pollock, various species of salmon and rockfish, and other species. The Northwest plants typically processed Pacific whiting, bottomfish, crab, and shrimp. In the 10 plants, total costs of energy (electricity, fuel oil, and propane) varied from 1.2 to 3.9% of annual sales, averaging 2.2%, from 1.7% of sales in the Northwest to 2.6% in Alaska. Energy costs/tonne finished product varied between USD 13.2 and 149.6, averaging USD 72.6 for the 10 plants, USD 105.6 in Alaska, and USD 37.4 in the Northwest. Refrigeration equipment operated primarily freezers, cold storage, chillers, and icemakers and used 65 to 85% of the electricity in the processing plants. Recognising the range of processes and the confidentiality of some process data, the wide ranges of energy cost per kg, from USD 0.013 to 0.15, and energy use from 0.45 to 2.71 kWh per kg (electricity and other fuels combined), were partially due to process differences, but also to uncertainty of the production information.

In a comprehensive review of energy inputs of processing in the Vietnamese seafood sector, IFC (2010) assessed 11 shrimp and 10 pangasius (catfish) processing units in the Mekong delta in 2009. Shrimp were block frozen or IQF frozen in raw or cooked form; pangasius were skinned, filleted and block or IQF frozen. In the absence of detailed cost and sales data, energy use was calculated only on a product weight basis, related to tonnes or kg of oil equivalent. More than 41,000 t of finished shrimp goods and nearly 155,000 t of finished basa goods were produced with an annual total energy consumption of more than 17,800 TOE (t of oil equivalent), with an approximate cost of USD 10.19 million. Based on defined efficiency ranges (best 25%, middle 50% and lowest 75%) primary energy inputs/tonne ranged from 0.083, 0.175 to 0.300 TOE/t respectively for shrimp processing and 0.065, 0.076 and 0.083 TOE/t for fish processing. Based on an average of 10kWh per kg OE, these corresponded to 830, 1750 and 3000 kWh/tonne shrimp processed, and 650. 760 and 830 kWh/t fish processed. For shrimp processing there was some connection between energy use and scale, falling from around 0.250 TOE/t at 2500 t/yr to 0.100 TOE/t at 5000 t/yr or more. However there was no link between scale and energy use/employee.

Though there was little difference in technologies used, a wide range in energy use for different functions was observed, on average with freezing requiring 38%, cold storage 16%, ice making 16%, water supply 3%, wastewater treatment 3%, cooking 5%, air conditioning 4%, cooling water 3%, of total energy input. For fish processing units, freezing (45%), cold storage (12%) and icemaking (11%) were also the most significant users of energy. Cooling water (2%), air conditioning (7%), lighting, hot water, water supply (3% each), wastewater (4%) and other uses (10%) accounted for the remainder. Unlike the shrimp units, energy use/labour input rose with the scale of production, from around 0.500 TOE/person at 10,000 t/year to 1.500 TOE/person at 35,000 t/yr, which may be primarily related to the more automated and capital intensive nature of larger plants.

4.6 Summary of findings/emerging work

Fish processing in various forms has a wider range of energy sources than fish capture, typically using mains or locally generated electricity to operate handling machinery, lighting, refrigeration air compressors and cold storage facilities, while thermal energy in the form of steam and hot water, derived from electricity, gas, oil or solid fuels is used for cooking, cleaning and sanitising. Smoking fish uses direct combustion or electrical heating of wood for heat and smoke supply. Overall energy consumption depends on the level of technical input, age and scale of a plant, the level of automation and the range of products being produced. Processes which involve heating, such as the cooking of canned fish and fish meal and oil production, are very energy intensive, whereas simple steps such as gutting, grading, shelling or filleting require much less energy. Typical figures for the energy consumption per tonne of fish intake are 65–87 kWh for filleting, 150–190 kWh for canning and about 32 kWh for fishmeal and oil production, plus 32 litres of fuel oil (UNEP/COWI, 1999).

Substantial savings can be made in many cases with little or no capital investment, through simple housekeeping and through value recovery from process by-products..

In most parts of the world, the cost of water is increasing as supplies of fresh water become scarcer and as the true environmental costs of its supply are taken into consideration. Water is therefore becoming an increasingly valuable commodity and its efficient use is becoming more important. Rates of consumption can vary considerably depending on the scale and age of the plant, the type of processing, the level of automation and the ease with which equipment can be cleaned, as well as operator practices. Typical figures for fresh water consumption per tonne of fish intake are 5–11 m^3 for fish filleting, 15 m^3 for canning and 0.5 m^3 for fish meal and oil production. Fish meal and oil production also consumes about 20 m^3 of seawater per tonne of fish intake.

Considering each of the processing methods and their relative importance in global terms, and estimating their respective energy demands, global energy consumption estimates can then be made. With suitable data this can also be developed at national or regional levels. This calculation is carried out in Table 51. No direct figures are available for processes such as the production of ice, and so significant assumptions would have to be made, with consequent potential for error. Nonetheless it highlights significant effects of canning, and fishmeal/oil production, and in other subsectors, the relative energy cost associated with freezing.

Table 51: Estimated global energy consumption for processing

Process	Landed/ Produced (million t)	Energy consumed, (kWh/t fish)	Energy consumed (GWh)	Cost at USD 0.15/kWh (USD mill)
Aquaculture				
Iced/fresh [1]	40	42 [2]	1680	252.0
Portioned [3]	10	70	700	105.0
Frozen [1]	2	140 [4]	280	42.0
Smoked [1]	0.5	300	150	22.5
Capture fisheries				
Iced/fresh [5]	50	28 [6]	1400	210.0
Portioned	20	70	1400	210.0
Frozen [5]	20	78 [7]	1560	234.0
Canned [5]	13	250	3250	487.5
Dried/cured [5]	12	545	6540	981.0
Fish meal/oil [5]	21	400	8400	1260.0
Total [8]	123		25360	3804.0

Notes: Based primarily on COWI/UNEP energy data and FAO 2008 global totals; [1] excludes molluscs, assumes most raw material is iced; [2] based on 60kWh/t ice, average ice:fish ratio 1:2 , 60% is further processed at average 20kWh/t; [3] assumed 25% of initial input with higher level processing; [4] 120 kWh/t freezing plus 20kWh/t storage; [5] based on FAO 2008 product form data; [6] 60kWh/t ice, average 1:3 ice:fish ratio, 40% further processed at 20 kWh/t; [7] 120 kWh/t freezing plus 20kWh/t storage, 50% frozen at sea, 10% stored at sea – energy already accounted in vessel budgets. [8] total iced/fresh aquaculture and capture fisheries, dried/cured, fishmeal/oil

4.7 Conclusions

- Fuel and energy requirements for the processing sector vary widely, depending on process choice, production stages, storage needs and process efficiency. In most cases, costs of energy in processing are easily recovered within the additional value realised and the wider market options provided.
- Though process energy costs are substantially lower in overall terms than those for fish capture, and usually lower per tonne of product compared with energy associated with capture, there can be considerable savings on fuel costs
- The highest energy use levels are those associated with icing and freezer applications, though these have a strongly positive effect on product quality and hence the economic value of the pre-harvest stocks.

- The amounts of fish frozen at sea, for which energy costs are usually included in fish catching energy totals, has not been possible to quantify in this review, and may result in double counting in some cases. The review assumes that 50% of frozen fish products are frozen at sea, with energy included in catching sector totals, the remainder frozen on shore, for which energy costs can be calculated separately
- Amounts and ratios of landed/processed weight are difficult to estimate, with varying quality levels for data, and significant under-recording. Processing results in differential rates of waste (Which are sometime transformed in to fish meal, fish feed or other foodstuff).
- At artisanal levels, energy use varies widely, and with smoking, can reach significant levels per kg of product, with local energy supplies becoming key production and cost constraints. Though oil products are less used, energy equivalence in fuel wood can be highly critical. Overall use of ice is commonly less than in developed country fisheries, though lower efficiency of production and usage may result in similar energy demands per unit of product.
- Energy costs associated with distribution and storage are considered in section 5. In practice these commonly need to be added to process energy inputs to define the more complete implications of post-harvest strategies, market options and consequences of changing energy costs.

5 Distribution, sales and consumption

5.1 Introduction

Fish is the most widely traded food and agriculture product, with substantial inter-regional exchange, and a major connection between developing country supply and key developed country markets, particularly N America, Europe and Japan, and increasingly a wide range of markets in emerging economies (FAO, 2010). Traditional forms of conserved fish products, dried, salted, smoked and latterly bulk frozen, have increasingly become supplemented with higher added value products, and with fresh chilled or even live product supply. The development of better infrastructure in many sourcing areas, better market and communication links and increasingly diversified and sophisticated transport and distribution systems have increasingly made this possible. Connected in turn with increasingly specialised supply chain approaches for major multiple retailers, these transport and distribution systems have become more highly managed and are now essential components in retaining and adding value in supply to consumers. The specific and growing demands of cold chain integrity, compliance with food safety standards and with traceability specifications place additional demands on transport and distribution. At a less specialised level, and often with simpler products, internal and intra-regional distribution in less wealthy markets is also an essential feature of sector, though this too is changing as major city markets in developing countries become better connected with their hinterlands, and increasing prosperity changes expectations for product quality and other attributes.

There are several fuel and energy issues to consider, including:

- Direct fuel costs in transport and handling
- Energy costs of cold storage and distribution at various stages
- Embedded energy in infrastructure and materials

These will be influenced by the choice of transport and distribution system and the distances involved, which establish the primary energy demands in the supply chain. However, post-delivery fuel and energy costs, such as chiller or freezer storage in distribution centres and retail outlets can also be significant, and can vary widely with location, market characteristics and commercial practice. As noted earlier, post-purchase energy use, in storing, cooking and disposal also need to be considered to form a complete assessment of the supply system.

5.2 Transport elements

Consignment options

The energy associated with consignment methods depends on the packing format, loading efficiency, and collection/distribution implications. Transport costs and energy/fuel use are usually related to tonne-km of transport, though clearly multiple handling over short distances will significantly add to costs and fuel use. Across the global sector a wide range of shipping and consignment options can be noted, though for commercial markets and longer distances these are increasingly standardized. For larger volumes, steel containers are an essential element in the bulk transport of fish or seafood products in almost any distribution system. These can be carried by road, rail or sea, can be easily and securely transferred from one to the other as required, and are reusable over many transport cycles. Specialised format ''Únit Load Device'' containers, typically 3.4 to 9m^3 volume, can also be used for air transport, and some designs have been specifically configured for fish, ensuring that water and fluids losses are retained securely. Standard containers can be sealed at the point of consignment and the contents untouched until final destination, greatly improving security and port handling efficiency, although net energy efficiency is reduced by the need to ship the container weight.

Containers are in nominal module lengths of 10, 20, 30 and 40 ft, with 20 ft and 40 ft units predominating in sea trade. Width and height are standardised respectively as 8 ft, and 8.5 ft (standard) or 9.5 ft (hicube). Metric equivalents and typical loading levels, which are limited also by container strength and capacity of handling equipment, are given in Table 52. Although most containers are "dry" units, carrying goods that will not spoil under ambient conditions (i.e. canned fish), specialised containers can be used to carry frozen and chilled foods and even fresh food preserved under modified atmospheric conditions. Refrigerated insulated containers are mainly 20 and 40 ft units, and are either:

Table 52: Dimensions of transport containers

Container length and width (m)	Height (m)	Typical operating specifications		
		internal volume	tare wt kg	Payload kg
20 ft (6.06m) x 8ft (2.44m)	8.5ft (2.59 m)	28m3	1,800 to 2,400	22,000
	9.5ft (2.89m)	30m3		
40 ft (12.19m) x 8ft (2.44m)	8.5ft (2.59 m)	58m3	2,800 to 4,200	28,800
	9.5ft (2.89m)	66m3		

Source: Maersk Container Brochure, Maersk Shipping

a) Integral – with self contained refrigeration systems which simply require an external power supply; these have much greater autonomy but a small loss of internal volume and payload, or
b) Directly attached to the ship's refrigeration system – traditionally water-cooled, but increasingly using ventilation, to reduce costs.

In overall terms, energy costs associated with non-ambient transport in containers or other units are directly related to the difference between ambient and storage temperature, together with insulation levels, though there is a tradeoff between insulation thickness, weight and internal volume. Hence frozen transport – commonly -20 to -40^{o}C, is more energy demanding than refrigerated transport, at – 4^{o}C., as is transport in warmer environments. For quality reasons, fish products are more commonly frozen earlier in the supply network, even if subsequent transport energy costs are higher. Consignment options will also have an impact on efficiency of use of transport, as related to intermediate handling, holding delays, and point to point delivery times.

Packaging

The direct containment of fish products also has significance for energy use, both in terms of the energy costs of the packaging materials, and the extent to which they control heat transfer and affect product shelf life and storage needs. Various forms of packaging are used, from traditional, very simple to modern highly sophisticated controlled packaging systems. Functional distinctions can also be made between:

- packaging - to hold/protect/display the product at the level of retail presentation - eg printed bags, cardboard boxes, vacuum packs, tins, pouches;
- packing - in which these packaged products are held - eg for bulk distribution and storage, typically in master packs/cartons,

For iced products, an intermediate type of container can be used, serving both distribution and retail purposes, eg various polystyrene packs/boxes in fishmonger outlets.

Key aspects of material and format selection include: cost/availability of raw materials; cleanliness/hygiene requirements; strength/protection needs; insulation/temperature control; water control - retaining or releasing meltwater, etc depending on circumstances; bulk/distribution cost issues, including costs of moving and storing prior to use. Table 53 summarises key types and characteristics of common packaging options, and Table 54 provides typical energy costs of producing various packaging/container types, though not the costs of preparing/filling them with product, or subsequent handling and storage.

Table 53 Packaging types/characteristics for fish products

Type/form	Characteristics	Energy issues
baskets, leaf wraps	very simple, may hold limited amounts of ice; varying degrees of protection/cleanliness	Low energy source materials, limited levels of insulation,
boxes/cartons;	wood, polystyrene, eg for iced product; also for air transport, with absorbent pads; waxed cardboard boxes increasingly used, also insulation-lined flat-pack boxes for cheaper shipping pre-use.	Varying energy inputs, range of insulating properties, significant effects in chill/frozen transport; may be disposal/reuse issues;
jars, cans;	glass, tin or alloy-plated steel, some synthetic linings; sealed with cooked product;, 100-500g to 10kg; usually packed in cardboard boxes; heavy, simple, reliable, glass may be reusable.	Can be significant manufacturing energy; poor insulation but stable product in ambient conditions; weight adds to transport energy
bags -	normally strong single film polythene bags - for bulk/food service packs of frozen products, also at retail level; also insulated double film bags.	Lower manufacturing energy/unit, limited insulation in most cases
trays;	usually for consumer packs, eg with single fish, fillets, steaks, smoked side, arrays of shellfish, prepared foods; usually overlaid with plastic film;	Various plastics with range of insulating properties; may be manufacturing and disposal issues
controlled atmosphere packs	with heavier grade plastics for vacuum packing; air removed to reduce spoilage access, improve shelf-life, or gas mixes to give similar/better protection without close film of plastic round product.	As above but better storage, shelf life and potential transport energy savings.

Bulk packs are made as appropriate for distribution needs, whether by road, ship, air, train, and depending on handling options and retail or other needs. Typical options include:

- Bulk moulded polythene tubs/ containers – typically 0.5-1.0 m^3; for fresh/iced product, with varying degrees of insulation
- Larger wooden/polystyrene master packs holding smaller packages, usually pallet-based
- Shrink-wrapped packs, using heavier grade films for wrapping individual multi-packs, etc, for moisture protection and physical integrity; often also incorporating pallet bases

Table 54 Energy required to produce food packages

Package	kcal	kWh	Cost*
Styrofoam tray (size 6)	215	0.25	0.04
Moulded paper tray (size 6)	384	0.45	0.07
Polyethylene pouch (16 oz/455 g) *	559	0.65	0.1
Steel can, aluminium top (12 oz)	568	0.66	0.1
Small paper set-up box	722	0.84	0.13
Steel can, steel top (16 oz)	1,006	1.17	0.18
Glass jar (16 oz)	1,023	1.19	0.18
Aluminium TV-dinner container	1,496	1.74	0.26

Source: Pimentel and Pimentel, 1985 * at USD 0.15/kWh

These bulk packs are then shipped in or on road trucks, loaded into containers, etc, and operated as required to meet temperature and other needs. Energy issues have not to date been a primary factor in choice and use of packaging but may be expected to assume greater importance, both in terms of material selection, and in the mode of use (see eg Williams, 2011). There is a growing emphasis on systems which have low manufacturing energy requirements which can provide long shelf-life at ambient conditions, and can be disposed of easily and with minimal additional energy needs.

Surface transport

Traditionally, fish products are carried over long distances in smoked or dried form, using a range of transport methods, often with very little indirect energy or fuel cost for transport. In the case of general cargo on truck or bus carriage, marginal fuel costs may be minimal, though as fuel prices rise, carriage charges are also likely to increase and will reflect actual fuel costs. Fresh or iced fish is often carried in boxes or bags in open or closed truck bodies, in the former case usually covered with a simple tarpaulin or other protective materials. Beyond the energy cost for ice, inputs will relate only to fuel costs of running the truck. In many cases, with old vehicles and older, inefficient and badly tuned engines, fuel efficiency will be low by current standards.

For more developed transport systems, low-temperature road carriage is more common, using specialised truck bodies or articulated trailers. If suitably designed and equipped, vehicles used for transporting iced fish can be used for frozen fish, depending on the length of journey, ambient temperature, insulation and the refrigerating equipment fitted, if any. Internal collection and distribution of frozen fish requires a good deal of planning and foresight, and capital costs can be considerable. Though larger load volumes are generally more efficient, typically up to 40t for larger units, road capacity or local regulation may limit vehicle size, and economics of road transport and hence vehicle choice may also be affected by a local system of taxation or other restrictions. To outline fuel use in typical situations arising from different requirements, such as local and long-distance haulage, three sizes of vehicle are listed in Table 55, which illustrates fuel use per tonne-km at different average speeds, assuming constant driving fuel consumption over the range concerned. Based on 100% load factor, values range from 0.013 to 0.17 litres/t-km (0.14 to 1.83 kWhr/t-km) this shows the significant effect of vehicle size, and the secondary effect of speed, where greater cooling energy required over longer time periods is balanced by reduced fuel consumption for movement.

Table 55: Illustrative fuel costs of road transport

Capacity of transport vehicle	**Fuel consumption**		**Load, tonne**	**Fuel use, litres per tonne-km, at speed**	
	Driving, litres/ 100km	Cooling, litres/hr		50km/hr	100km/hr
1 – 1.5 t	15	1	1	0.17	0.16
3 -3.5 t	20	2	3	0.08	0.073
25 tonne	30	3	25	0.014	0.013

Source: author's compilation of industry data

Anderson (2002) assessing energy costs of fish transport in or from Norway, proposed energy use targets for 2015 of 0.36 kWh/t-km for trucks operating at 60% load factor, and 0.06 kWh/t-km for rail transport, using cooled semi-trailers at 70% load factor. Though significantly more efficient in fuel costs per tonne-km, rail transport is less used for distribution in the fisheries sector, though traditionally, many major fishing ports and entrepots were linked to major population centres by rail, and consignments of boxed iced fish to city markets were common. Reduced investment in rail infrastructure and services, coupled with a shift away from traditional wholesale markets to other supply chains, served with more flexible and competitive road transport options have tended to reinforce this. Nonetheless, often in smaller-scale form, rail transport remains an option, and where connecting links are accessible, is still in use. Anderson (2002) shows results of an analysis of dried cod transport from Alesund, Norway to Foligno, Italy, for which truck and boat transport would require 25,254 kWh per 22t consignment (814km + 10,686 km respectively), taking 438 hrs (1149.3 kWh/t and 0.10 kWhr/t-km), while truck and rail (226 km + 5,274 km) would require only 8752 kWh, and take 166 hrs (397.8 kWh/t and 0.072 kWhr/t-km). This compared with 27, 861 kWh (1266.4 kWhr/t) and 158 hrs for truck and ferry transport. At an electric power equivalent cost of USD 0.15/kWh this would cost USD 172.4, 59.7 and 190.0 per tonne respectively.

Air transport

There has been a substantial increase in transport of fish by air in the last decade as the demand and price of fresh seafood have risen and air cargo capacity has expanded and become more widespread. The more rapid transit time can also potentially improve cashflow and capital turnover. However the unit cost of air transport is still much higher than road or sea transport, and usually only higher value products are transported by air. Nonetheless an increasing quantity of mid-range species products such as Nile Perch fillets from Lake Victoria is also being shipped to developed country markets. So commonplace has air transport become in some markets that in recent periods salmon was being airfreighted from Norway to China for portioning and packing, and then back to European markets, the lower labour costs and high yield and quality control standards justifying the additional transport cost. However, rising fuel costs, and increasing consumer concerns for food miles or the carbon footprint may make this less common in the future. Anderson (2002) estimated energy use for air transport for Norwegian salmon to East Asia/USA from Frankfurt to be 21kWh/kg, together with 0.6 kWh/kg for trucking from Bergen to Frankfurt. This compared with a total of 2.1 kWh/kg for the equivalent transport of frozen fish by truck and boat from Bergen to the destination country. Where energy use for salmon feeds (the largest part of aquaculture energy budgets) were estimated at 9.6kWh/kg, this was less than half the energy cost of the airfreight itself.

Air transport of live fish is also increasingly common, particularly for ornamental fish, broodstock and seedstocks of fish and shrimp for aquaculture, and also for highly prized species such as grouper sold in the live fish restaurant trade, though packing and other costs, such as the costs of insulated oxygenated tanks or bags, commonly used only once. In overall sectoral terms however, these are only very minor levels of use.

Sea transport
Apart from conventional transport of containers by sea, by far the most significant basis for longer distance seafood transport, a number of specialist vessels have been built or adapted specifically for fish carrying. Lloyds Register (2006) lists 533 fish carrier vessels, a number of which have recently been built. This would suggest a continuing demand for some distant water fishing countries to have fish transported most advantageously and potentially more fuel -efficiently, directly from catching grounds to major markets. Most (346) were less than 1,000 t deadweight, 100 between 1,000 and 10,000 t and only eight just over 10,000 t, with a total registered tonnage of just over 1 million t. Larger vessels tend to be registered in Panama, Cyprus and Russia and were built in East Germany in the early 1980s (Table 56)

Table 56: Number of fish carrier vessels by Flag State

Flag state	No of vessels	Flag state	No of vessels
Russia	179	South Korea	36
Panama	65	Ukraine	20
Japan	63	Cyprus	11
China	59	Global total	533

Source: Lloyd's Register, 2006

It is not clear at this stage how much of this capacity is currently in use, though the age of the fleet and the unlikelihood of refitting would make its fuel efficiency questionable by modern standards. Overall efficiency of use would also be linked with the utilisation level and the standby fuel costs while waiting for sufficient supplies. Lloyds database also details:

- Freezer trawlers for catching, processing, freezing and storage at -25°C to -30°C capacity of up to 800 t.
- Refrigerated cargo vessels (reefers), with conventional fully refrigerated holds; capacity about 1,000 - 3,000 t at -20°C.
- General dry cargo vessels with several refrigerated compartments or holds totalling to 500 - 2,000 t (depending on vessel size), temperature controllable to -20°C.
- General cargo container vessels able to accommodate up to about 400 x 20 t insulated containers, each connected to cold air supply and return manifolds which are cooled by a centralized refrigeration system, providing temperatures down to -20°C. "Clip on" units on shore and during long haul transport can also be used to refrigerate the containers.

More recently a number of smaller specialised carrier vessels have been built for the transport of live fish, particularly for fish seed for aquaculture (eg salmon smolts), and for the delivery of aquaculture feeds. In some cases these are multipurpose vessels, allowing for more versatile and efficient use. Where conditions permit – eg long, fjord-like coastlines with poor road transport links, supply costs and fuel efficiencies are at least as good as those for more conventional road transport.

Specific energy use in shipping of raw materials or fisheries products varies widely with vessel type, size and hull condition, fuel, propulsion system, speed, operating routes and sea conditions. Based on a 63 000t container vessel of 4948 TEUs, a normal delivered power of 44 MW and a service speed of 25 knots, using 40-foot (2 TEU) containers with a payload of 26 tonnes, and assuming 50% engine efficiency, energy consumption would be 0.015 kWh/t-km (Mackay, 2009) Maersk (2008) quote values of 0.014 and 0.018 kWh/t-km for 11,000 and 6,600 TEU container vessels respectively. For refrigerated container transport in New Zealand, Fitzgerald et al (2011) quote an average 2.7kW per TEU, and estimated that in 2007, some 19% of sea transport energy was related to refrigeration. Total transport refrigeration energy amounted to 280GWh, corresponding to 61,000 t of fuel.

In reviewing energy use in exporting frozen Norwegian salmon to E Asia and the USA, Andersen (2002) assumed the use of 60,000 dwt. container vessels, carrying 7500 t frozen fish in 300 x 25 t containers. Fuel consumption of heavy oil was assumed at 150 t per 24 h. With an energy content of 11.65 kWh/kg for fuel oil, the energy use per 24 h at full load capacity, including 3.8kWh/t for freezer plant was 32.5 kWh/t fish transported. The average load factor to E Asia was 52.5% (80% outwards and 25% return). Based on average speed, and the time required per trip, energy use per delivered tonne, or energy per t-km could then be estimated.

5.3 Distribution, storage and consumption

The energy costs associated with retail presentation of food and the food service sector can also be very considerable, particularly in modern supply chains. Thus for the UK chilled/frozen food sector, a recent survey (James et al 2009) estimated some 800,000 retail displays across the UK to use a total of between 5,768 and 12,698GWh per year, which at USD 0.15 per kWh, corresponds to between USD 0.79 and 1.90 billion annually. Catering fridges were estimated to account for 3,998 to 4,762GWh/year, compared with refrigerated transport at 4,822GWh/year, with much less significant demand from cold stores (900GWh/year); blast chillers (250-600GWh/year); blast freezing (218-415GWh/year); dairy processing (250GWh/year); milk cooling (99-315GWh/year); potato storage (144-187GWh/year) and meat carcass chilling (115-144GWh/year). While fish related energy use was not differentiated, this illustrates the relative importance of various components in the pre-consumption sector, and would potentially allow more fishery-specific values to be developed. If for example, fish products accounted for some 5% of the chill/frozen stock, this would correspond to a national energy use and costs as estimated in Table 57. Estimates can also be made linking these with per capita consumption levels of aquatic products, and the relative percentage of consumption associated with the retail sector.

Table 57: Estimated fish-related distribution, storage and display energy use and costs – UK

Component	Estimated energy, GWh	Equivalent cost at USD 0.15/kWh, USD million
Blast freezers	10.9 – 20.7	1.7 – 3.2
Blast chillers	12.5 – 30.0	2.0 – 4.5
Cold stores	45	6.8
Refrigerated transport	241	36.2
Catering fridges	200-238	30.0 - 45.7
Retail displays	288-635	43.2 - 95.2
Total	797-1210	119.5 – 181.5

Source: Developed from James et al (2009).

Another survey of the UK retailing sector (Tassou et al, 2011), covering some 30% of retail food stores of 280m2 sales area and above, showed wide variability in energy consumption, from 700 to 2000 kWhr/m2 sales area for hypermarkets and small outlets respectively. Refrigeration accounted for 30-60% of energy use, and lighting 15-25%. No immediate data is available for more traditional retail outlets for fish, but energy costs of cold storage, ice for displays, lighting and cleaning are likely to be incurred, and will vary widely with local conditions and practice.

Following retail presentation, energy use by consumers in travelling to purchase, storing food at home, preparing meals and disposing of wastes is also potentially significant. Little data has been developed for fish products alone, but a number of reviews have explored energy use across normal household food baskets. Pimentel and Pimentel (1985) estimate 5% of total food energy use in refrigeration and food preparation in US households, for an average of 5320 kCal/kg or 6.19 kWh/kg food used. By contrast, in developing country households, they estimated a total annual per capita energy use for food preparation of 1477 kWh, 63.5% of the total food supply energy, largely associated with fuelwood combustion in open stoves. Another area of great diversity is that of energy use in obtaining food for consumption. In developing countries, access to markets on foot, bicycle or public transport adds relatively little to the total energy budget. However in wealthier societies, and increasingly where purchases are made in out of town retail centres, energy inputs can be much more notable. According to Sonesson et al (2010) consumers' home transport can be very energy inefficient, for example using vehicles weighing more than 800kg to carry loads of typically 10-20 kg per trip, even if shared with other functions. However they noted studies in Sweden where more than 60% of shopping trips were made using cars, around 50% of which were for the sole purpose of food shopping. In a more detailed assessment of UK consumption, Pretty et al (2005) estimated that 110.5 trips were made per household per year for food, with an average distance of 6.4 km, or 13.6 km per week. Of these, 7.89 km were by car, 1.09 by bus and 4.49 km by walking and cycling. Total cost for food transport was approximately GBP 0.95 (approx USD 1.50)/household/wk.

The use of energy in the seafood-related parts of the food service sector (ie commercial and institutional catering) has been little documented so far, not least because the sector is so diverse and fast changing, particularly in commercial food service, and also as with limited exceptions, seafood products form only a relatively small part of the overall volume and value of transactions. Nonetheless some approximate estimates can be made. Davies and Konisky (2000) noted that in the US, total energy use in commercial foodservice and food retail sectors accounted for less than 1% of total domestic energy consumption, with food service using some 349,000 TJ in 1995, accounting for some 6.2% of total commercial building energy consumption, the most significant uses of energy being for cooking (31.7%) and refrigeration (13%) of food, water heating (11.2%) together with staff and customer provision of heating, cooling and ventilation (22.7%) and lighting (15.1%). The foodservice industry spent over USD 4.8 billion on major fuels (electricity, natural gas, fuel oil, and district heat) in 1995, costing an average of 4.5% of total sales for restaurants. They also note a study by Kobliner (1994) examining energy costs of school meal provision, ranging from 0.3 kWh per meal for central provision, chilling and reheating on site, to 1.1 kWh per meal for on-site production.

5.4 Wastes

According to Stuart (2009), significant levels of food waste can be defined within the global system, with a greater emphasis on primary stage spoilage and loss in less developed economies and markets, and on process, retail, food service and household waste in modern consumer markets. Waste levels were estimated to amount to some 33% of global food supply, significant parts of which could be reduced relatively simply. In UK households Ventour (2008) noted large differences between product groups, with 45% of purchased salad greens being wasted, 31% of bread, 26% of fruits, with 13% waste levels for meat- and seafood, and only 3% for dairy products. In energy terms, waste levels carry two major implications:

- Increased energy levels per kg, tonne or unit value of consumed product, with impacts at various points in the supply chain, eg from capture or aquaculture – spoiled raw materials; transport, processing and storage – yield and quality losses, spoiled product; retail and final consumption – unusable product.
- Energy costs of disposal of waste materials (including raw materials, product, process materials, associated packaging), including collection and transport to disposal/treatment, waste

treatment capital and operating costs, energy related externalities of final disposal options – eg BOD in aquatic systems, landfill impacts.

Data on energy related to fish and aquatic product waste is as yet very limited, but using data on loss/spoilage levels estimates can be made of the effects in specific supply chains, while disposal implications can be drawn from generic food waste data, either on a pro rata basis for consumption per capita, or using more focused data allowing for waste differentials between food products and their disposal impacts.

5.5 Integrated perspectives

With respect to the financial boundaries in which energy and fuel costs would be placed, transport and distribution, particularly with widening markets and expanding trade, becomes an essential element in building value from primary product to final consumption, and so rising fuel costs will have an impact through transport not just on the costs of supply, but also potentially in the wider opportunities for consumer access and for economic output. While this process may be seen to restrict demand and further reduce margins available to primary producers, potentially reducing pressure on resources, considerable disbenefits could arise over the whole supply chain. For international trade, most imported seafood has already undergone initial process stages, after which there may well be further processing and then distribution through retail, food service and indeed further exports. Impacts and benefits along the supply and value chain will vary widely, with significant economic and social consequences.

Analysing the entire production chain from fisheries to fish consumption, most analyses confirm that the fishing phase accounts for the greatest share of total energy utilisation through onboard fuel combustion during fishing in modern, industrialised fisheries (see eg Thrane 2004, 2006; Ziegler et al. 2003, Ziegler and Valentinsson 2008; Ziegler et al. 2009). By contrast, the added value is often substantially greater than the cost of the primary imported material. Thus Gudmundsson et. al. (2006), studying four different fisheries products and countries found between 54% and 75% of value addition to be in the secondary processing, wholesale and retail sectors. KPMG (2004) studied cod, haddock and nephrops supplies in Europe, finding value additions in processing and distribution over first sale value to be 69%, 75% and 74 % respectively. Removing the primary stage of processing reduced these values slightly to 66%, 71% and 74% respectively.

Table 58: Overall distribution of fuel/energy costs in supply chains

	Middle water		**Near water**		**Middle water**		**Near water**			
	MJ/Kg	**%**	**MJ/Kg**	**%**	**MJ/Kg**	**%**	**MJ/Kg**	**%**	**MJ/Kg**	**%**
Fishing	85	76	50	65	25	48	17	38	9	25
Processing	13	12	13	17	13	25	13	29	13	36
Transport	10	9	10	13	10	19	10	23	10	38
Distribution	4	3	4	5	4	8	8	4	4	11
Total	112	100	77	100	52	100	44	100	36	100

Source: Smith 2008/KPMG

In overall terms this suggests that unless these later stage components have significant energy inputs they are much less likely to be affected by energy prices. However, their efficiency and output would be affected by supply reductions consequent on energy cost impacts on the capture or aquaculture sectors. Whether this would result in changing margins at each level and/or shifts in supply patterns would remain to be seen.

Assessing the energy use and carbon footprint of a range of Norwegian production and distribution options in global supply chains, Winther et al (2009) noted the primary importance of fossil fuel use in fishing, followed by refrigerants in CO2 equivalent outputs, except for cases such as cod processing in China, where transport was the largest component. For pelagic fishing, where fishing fuel energy use is relatively low, other aspects of the supply chain are usually more significant. They also noted that processing in Norway was relatively efficient in spite of high labour costs due to reduced transport and greater potential for developing value from byproducts. Although super-cooling or freezing product required more energy in the first instance, this could often be recouped over longer distances through more energy-efficient transport options, including better load levels by avoiding the use of ice.

Across the complete supply and value chain, Canning et al (2010) reviewed the US food system, calculating per capita energy demands for fish products in 2002 as 305,000 BTU (89.5 kWh) /capita, with production, processing and wholesale/retail functions contributing the main energy demands (see Table 59). These patterns were broadly similar to those for other food categories. Heller and Keoleian (2003) assessing the US food system, estimated that 20.8% of total energy use related to agricultural production, 15.8 processing, 13.9 transport, 6.9 packaging, 6.9 food service, 4% retail and 31.7% home refrigeration and preparation.

Table 59 Energy use distribution, US

Supply stage	kWh	%
Production	26.1	29.2
Processing	23.7	26.5
Packaging	2.7	3
Freight services	4.3	4.8
Wholesale/retail	32.6	36.4
Total	89.5	100

Assessing a range of seafood products in the Danish market, Thrane (2004) noted the range of fuel and electrical energy inputs and the relative importance of processing, distribution and consumption (Table 60). Across 6 frozen products, 1 in jars and 1 canned, energy used in catching ranged from 5 to 941 MJ/kg (7.2 to 90.9%), use in processing 1.5 to 15.1 %, while that used in consumption ranged from 5.5 to 43.1%.

Table 60 Energy use in Danish seafood supply

	Demersal fillet				Shellfish boiled peeled						Pickled/canned			
	Cod block		Flatfish IQF		Shrimp		Nephrops		Mussel		Herring		Mackerel	
	MJ/kg	%	MJ/kg	%	MJ/kg	%	MJ/kg	%	MJ/kg	%	MJ/kg	%	MJ/kg	%
Fishery	41	49.3	110	67.8	119	64.6	941	90.9	5	7.2	16	35	5	18.7
Landing	1.3	1.6	1.3	0.8	1.4	0.8	0.1	0	5.3	7.6	0	0	0	0
Process	4.8	5.8	7.2	4.4	15.1	8.2	15.1	1.5	10.5	15.1	4.2	9.2	3.7	13.9
Transport	5	6	6	3.7	6	3.3	8	0.8	10	14.4	6	13.1	4	15
Wholes	0.2	0.2	0.9	0.6	0.9	0.5	0.9	0.1	0.9	1.3	0.1	0.2	0	0
Retail	8.4	10.1	12.9	8	12.9	7	12.9	1.2	12.9	18.6	5.2	11.4	2.5	9.4
Consumer	22.4	27	23.9	14.7	28.9	15.7	56.9	5.5	24.9	35.8	14.2	31.1	11.5	43.1
Total	83.1	100	162.2	100	184.2	100	1034.9	100	69.5	100	45.7	100	26.7	100

Notes: developed from Thrane, 2004, based on weight of consumed product. Shrimp data is average of shrimp and prawn categories – very small differences in fishing energy only. Herring in jars, mackerel in cans

In a major LCA review of UK food products, Foster et al (2006) assessed energy use for the supply of cod fish fingers to households, estimating a total input of 24 MJ/400g pack, of which production accounted for 69%, primary and second stage processing 7% and 11% respectively, retail 8%, and in a 'low energy' household, consumption 5%. However, with a 'high energy' consumption variant, in which fish fingers are fried rather than microwaved, consumption energy rises from 1.3 to 10.6 MJ/pack, 32% of the increased total of 33 MJ/pack. For a 400g fresh/chill pack of salmon fillets, the same authors calculate a total input of 23 MJ, of which 89% is in production, less than 0.5% in processing, 4% in retail and 7% in home consumption.

5.6 Conclusions

- Although energy costs are a significant component in many transport operations, and such costs in transport and distribution are definable, in many cases they are not a major part of the overall fisheries chain value, or the total cross-sectoral energy input.
- There is a wide variability in transport and distribution energy costs, and in modern markets relatively similar products may have widely differing characteristics.
- Some product and supply forms are more energy demanding than others, and long distances using highly energy demanding transport options can add significantly to energy costs of capture or culture and those of processing.
- There are options of reducing energy consumption, or adapting to higher energy costs, ranging from improving technical efficiency of components (road, rail, sea or air transport technologies, shipping units), better supply chain management, and reducing supply distances
- In some cases, marginal costs may be more important determinants of transport and distribution choice than average costs – eg with partial loads in air transport, shipping or road transport. Much depends on the specific conditions of the distribution decisions; these may vary.
- Transport choices also affect market options and potential for prices at first sale; depending on the scale of market access and supply substitution options, other things being equal, reduced transport choice arising from higher energy costs will tend to lower first sale prices.
- Retail and food consumption factors can have a particularly significant impact, and the storage, preparation and use of fish products can be a large part of the overall supply chain energy budget. Travel to purchase food can also be a significant component.
- In developing country contexts, energy use in cooking food, including fish, can be significant, and a major household burden as well as impacting local environments. Fish are likely to play their share in this, though products such as dried/smoked fish and fish sauces may have less impact.
- Wastes in the supply chain are also potentially important, and there can be notable tradeoffs between higher energy investment and reduction in waste. However, domestic and food service food waste, particularly for fishery products, is relatively little measured.
- There is limited data on the relative impact of the disposal of fish-related waste materials on the energy demands associated with solid or liquid waste treatment. However, with very few exceptions such wastes are of low-toxicity nature and their impact could be estimated on a mass flow basis, pro rata in wider food waste energy budgets.
- There are potentially important linkage effects, which could make changes in transport or distribution costs have a disproportionate effect on supply or market options in certain locations or within specific sectors

6 Strategies for mitigating energy costs

6.1 Introduction

There have been substantial real term price fluctuations in fuel oil prices, and while broader energy prices, deriving from a wider range of sources and subject to longer term supply contracts, have been less volatile, they have also varied substantially. High fuel prices in the 1980s were protracted over several years. Compounded by poor demand and high interest rates, this forced many vessels into laying up or going bankrupt, and contributed to the loss of function or closure of some fishing ports. However in Europe at least, the inshore fleet remained intact, as it was relatively new and decommissioning was unfeasible, though repossessions and deep write-downs of capital value of vessels occurred. The aquaculture sector and other parts of the supply chain had been less directly affected by earlier energy price changes, due to their lower levels of dependence and their more recent development, but had also been increasingly impacted.

The first part of 2008 had seen dramatic rises in the price of oil and retail fuel prices. For the fishery sector, effects were profound, with fuel prices often more than doubling, and many forms of fishing becoming increasingly unviable. Since this period, fuel prices had dropped, but this had also accompanied an economic downturn, with negative impacts on market confidence, purchasing power, and potentially on first sale prices for fish. Both conditions have re-emphasised the focus on costs and margins, and the prospect of longer term shortages. These have most recently been reflected in further price rises, with current forecasts for continued real term increases (WRI 2011).

6.2 Strategic issues

The catching sector in particular is heavily dependent on diesel fuel, and its characteristics are such that it would take time to adapt to new conditions. Hence in this sector the first emphasis has to be placed on mitigating the effects of fuel price rises. Building from this, longer-term strategies could be considered. As evidenced in the recent history of fuel prices, short-term instability may simply mean interruptions in activity; and major investment in adaptation might not be justifiable, or accessible unless fuel and energy cost remain higher. Thus the issue of price expectations, and the probability of longer term change is also important. The issues of fuel subsidies have received considerable attention in recent years, and the net costs, particularly to the catching sector have been widely noted, as has their potential to create and maintain incentives for overfishing (see eg Sumaila et al 2006, 2008, WB/FAO, 2008). The specific details are not addressed in this review, save to note that fuel subsidies are still widely applied in the food sector as a whole (eg in for agricultural fuel, fertilisers) as well as in the fishery sector, and that policy issues very often extend to the support of affordable foods, and sometimes to national food self-sufficiency, as well as more direct measures aimed to maintain otherwise poorly sustainable fishing activity.

Clearly however, fuel and energy subsidies are becoming less politically defensible, particularly when undesirable consequences such as overfishing may result. At owner, fishery sector and national level, steps will need to be taken to adjust to changes in energy access and cost, and structural and operational changes may be expected as a consequence. There are also particular implications for fishing capacity and effort, and for the stocks being fished. More widely, thought has to be given both to the measures that could be taken, and where necessary, the processes of validating them and communicating the options within the sector. Thus education/training in energy use/misuse and energy saving within various fishery sector activities is needed, together with capacity building in sectoral agencies to provide the appropriate support.

With respect to addressing the use and cost of energy and fuel in the fisheries sector, and to determining ways to mitigate these, distinctions can be made concerning:

- Strategic and specific actions to reduce the use of fuel or energy, of whatever kind, within the constraints of the system employed, recognising other tradeoffs which may be involved (eg energy vs labour use in fishing or post-harvest, water exchange in aquaculture vs use of land, etc, transport distance vs market access)
- At the specific level, the versatility or dependence of a fisheries sector element on specific fuel sources, and hence their practical options for change and the rate at which they could do so

These are also potentially important for the resilience of the production system, and for the livelihoods of those involved, where activities with a high degree of dependence on specific energy sources (particularly fishing, with its reliance on hydrocarbons) will be more easily disrupted or disabled by price instabilities than those which have a more diverse range of options and can more easily switch between them.

Though some responses during previous periods of high fuel/energy price can be useful in defining practical options at enterprise or national level, the wider environment has changed substantially in recent years, and this has had important impacts on current options and their practicality. In particular, in many areas, the capture sector has moved significantly to a position of overcapacity and excess fishing effort, with declining resource rents, while aquaculture has expanded widely, with increasing energy content in its material inputs and production processes. In both sectors, market chain developments with wider sourcing options and greater dominance by multiple retailers have tended to decrease market power for producers, limiting their margins, and their scope for adjusting to higher fuel or energy costs. Higher production and distribution costs may also act to reduce market access and scale, and in turn reduce sectoral output and turnover. These complex interactions can at this stage only be outlined, but serve to demonstrate that impacts and responses to energy costs will occur within a far more interconnected system, with more economic and policy consequences than might have occurred in previous decades.

In some cases, price rises and the inability to improve technical efficiency sufficiently may simply make some fishery subsectors unviable. The drop in fishing capacity and effort could also have important effects on resource pressures, stock condition and fish supplies, with significant implications for industry strategy and expectations, as well as for wider issues of national or global food supply and security. Some types of aquaculture system may become unviable, and processing, package and distribution options may be changed, with trading opportunities for lower value/margin products less likely to be feasible. Linked with and consequent on these potential impacts are the potentially sensitive policy issues of supporting output, employment and enterprise profitability by subsidising fuel and energy costs or other interventions. These will be discussed in the last part of this review.

6.3 Mitigation in the capture fisheries sector

Vessel and propulsion options

In response to successive rounds of fuel price rises, a number of practical guides to energy reduction have been produced by FAO and its partners (FAO/SIDA 1986, FAO, 1999), the latest of which (Gulbrandsson, 2012) provides a very clear practical guideline for fuel and energy saving in small fishing vessels, recognising the common constraints faced by many owners and operators, with limits to significant capital investment, or major change in fishing targets or practice. This emphasises the primary importance of fuel-efficient speed, hull length and propulsion system, and offers practical guidance for specifying and installing more efficient inboard engines and gearboxes and for selecting propeller size and pitch. It also provides recommendations for hull and engine maintenance, and for further options such as the use of sails.

A more detailed set of analyses and recommendations for the Australian fishing industry has been developed by Sterling and Goldsworthy (2007) and Sterling and Klaka (2007) respectively addressing fuel choice and propulsion options, and hull design. In India, the Central Institute of Fisheries Technology (CIFT), developed an energy efficient design. Sagarkripa, a medium class fishing vessel, with a narrower hull and an asymmetric nozzle propeller system. The outcome of commercial trials conducted by the fishing boat operators showed 17 % savings in fuel cost (Infofish, 2007) Rihan et al (2010) describe the design concept of a green trawler, showing that savings of 30% or more on fuel consumption could be achieved with relatively modest length increases. Additional savings of 10 to 20% could be achieved by reducing the drag of hull appendages, eg better aligning bilge keels. They also suggest that within the EU fisheries management regime, green trawler new builds or rebuilds could be permitted at any size provided capacity limits were respected. Enerhaug and Pedersen (2010) reported concepts of new designs for stern trawlers – amending hull form and propulsion systems, and disposition of hauling blocks, saving some 25% in energy demand when towing in rough weather. Friis et al (2010) described a range of theoretical, model scale and practical field trials in Newfoundland, to explore vessel-based energy reduction in local fleets of 10-20 m length range, with 250-660 installed HP, demonstrating positive effects of hull design, including bulbous bows, stability management, propulsion, and the use of ongoing energy audits. However specific cost and benefit characteristics were not defined..

The potential for reduction of drag in fishing vessel transom sterns using flaps and interception devices had been noted by Pelaez et al, (2010). Collazo and Fernandez (2010) noted the potential for improving common rudder designs, suggesting that for a 74m tuna purse seiner, with a beam of 14.2 m and displacement of 4200 t, working for 5000h/yr at an average velocity of 15.5 kn, annual fuel savings of at least 52 t/year could be achieved (approx 2.3%) , paying back rudder change costs within around two years. The potential fuel saving advantages of using ducted propellers had also been noted (Haimov at al, 2010), suggesting rapid recovery of costs of propeller replacement.

The potential for energy savings in vessel propulsion systems has also been noted, and depending on the duty cycles (use periods and load levels) diesel-electric installations (Fernandez et al 2010) could potentially reduce energy use by some 15%. However, these were only likely to be cost–effective, if at all, for new builds. Notti and Sala (2012) estimated similar savings by optimizing diesel-electric systems in the Italian fleet. Sola (2012) reported on the Shymgen system for optimizing propulsion and generator function, with estimated power reductions of 12.2%, 7.4% and 16.7% respectively for trawling, setting and hauling with a 36m trial vessel. Over a one year period, savings of 9.1% were made, which at EU 53,150 gave a payback of 1.2 years for the power control modifications made. A more complex prototype small vessel energy system comprising hydrogen power, lithium batteries and a diesel generator set driving an electric motor for propulsion was described by Montenegro and Rodriguez (2010) for potential application in the Galician fleet, but practical performance gains were yet to be described.

As earlier noted, the capture fishing sector is specifically dependent on fuel oil for its operations, and the availability and high energy density of conventional fuels has been a fundamental driver of vessel design, fleet investment and practical operation. Options for energy choice have been examined in a number of cases. Regentec (2008) reviewed the potential use of biofuels in the fishing sector, noting that for diesel propulsion in particular, use of biofuels would be a practical option. Though the shift to renewable sourcing might be welcome, if the net life-cycle energy gains were positive, and there were no other undesirable implications (eg competition for food production in agriculture), costs are unlikely to be reduced (see eg OECD-FAO, 2011). For small vessels in particular, the use of sails, even as an adjunct to motorised power, could yield significant energy savings, though issues of trip time, catch value and safety at sea would have to be satisfactorily addressed. More recently, Buglioni et al (2010) Compared MDO (marine diesel oil) with LNG (liquefied natural gas), and the use of variable vs fixed pitch propellers for pelagic 'volante' trawls for anchovies and sardines in the Italian Adriatic. This showed a 2.4% cost reduction with variable pitch propellers while dual fuel LNG offered a 26% cost reduction. Though there were considerable extra costs for a replacement dual fuel engine and extra fuel storage required for LNG – significant benefits were also noted in in reduced CO2 and NO2 emissions.

Walton (2010) described the potential use of copra oil as partial replacement for diesel fuel in Pacific Island fishing fleets, also providing local income to compensate for potential closure of beche de mer (sea cucumber) fishery. Initial evidence suggested positive potential, with byproducts of oilcake for animal feed, and an overall reduction of around 30% compared with local diesel costs. The fuel could be readily used in a range of local engine types, though depending on injector characteristics, preheating and microfiltration could also improve performance.

Fishing method and gear modification

A great diversity of methods exists for harvesting from the aquatic environment, the choice depending on location and behaviour of target species, as well as local traditions, skills and resources. For sessile or sedentary organisms such as seaweeds or molluscs direct harvest by hand is often possible in tidal zones, while for fish species, factors such as feeding, migration (food, spawning, winter) and swimming behaviour, position in the water column (bottom demersal, pelagic) and social behaviour (schooling or non-schooling) determine the choice of fishing method. Other factors are hydrographic conditions (currents, bottom condition etc.), utilisation of the catch (direct human consumption or reduction to meal and oil), and the social and economic contexts which determine common practice, access to resource and the financial resources available for carrying out fishing. More strategically, as discussed later, fisheries management will also affect choice of method. As noted earlier, fishing methods can be categorised with regard to fuel usage. Changing from a method using a high level to a lower level of energy has been suggested as a primary response to conserve fuel and preserve profitability.

Suggested changes of fishing gear vary with the stocks and other fishing conditions, but common examples include shifting from beam trawls to twin trawls, and from single boat to pair trawling, as well as shifting from trawling to less active and energy demanding methods, and moving where possible to less distant grounds. However, the size, design of vessel and the machinery on board may limit possibilities of changing from one fishing method to another. Fishing gear has broadly evolved in any location to catch fish in a manner that offers the best technical/ economic solution to harvest the target species However, the shift in balance created by rising fuel costs may change the viability of competing methods. Even for example if catches are reduced because of lower gear impact or reduced time at sea, the net return after fuel costs may increase. This may particularly be the case if vessels can target more precisely on higher value species.

Modifications to fishing gear can also be considered. For active pelagic fishing gears and passive gears, fuel use during fishing is relatively small and so the focus here is on active demersal fishing gears. It is estimated that measures to reduce the drag of fishing gear can reduce fuel consumption by 20 – 25%, without resulting in any decrease of the catch of the target species. According to Richard and Tait (1997) new designs of trawls can reduce engine power and fuel consumption by a factor of 33 %. Several means can be considered for gear modification:

- Allowing unwanted fish to escape (e.g. using square meshes, or escape panels). Towed fishing gear tends to be non-selective and traditionally, the less valuable part of the catch is discarded. There are now significant efforts to reduce discards, due to concerns for the recruitment or viability of other fish stocks, and for resource waste. Selectivity devices allow unwanted species or sizes of fish to escape, reducing the load on the fishing gear, and hence fuel consumption.

- Smaller or multiple nets; drag of fishing gear is determined by the size of the net towed. In many fisheries, multiple nets can reduce drag considerably for the same amount of catch. This is particularly true for species that do not react very strongly to the presence of the fishing gear (e.g. shrimp or flatfish)
- Use of more hydrodynamic or stronger twine (eg Dyneema). Stronger materials allow smaller diameter twine to be used for similar loads, with less drag, and can also allow an increase in mesh size in the wings and mouth of the net to reduce drag. Use of twine with hydrodynamic properties (i.e. an oval section whose long axis aligns parallel to the flow of water through the net) can reduce gear drag by 15 – 25%. This can also provide lift or spread to netting if rigged properly, using smaller otter boards or fewer floats, reducing the overall drag of the fishing gear.
- Use of platelets instead of kites or floats. The hydrodynamic shape of weights and floats on the nets can be used to generate forces to keep the net open thereby reducing the need for floats and otterboards to spread the gear, reduce drag and improve fuel utilisation
- Electrical stimulation In shrimp and beam trawls can be used to force the target species to swim clear of the bottom, reducing the need for the footrope of the net to dig into the sandy sea bottom to reach the target species

Priour (2012) describes modelling and sea trial work on bottom trawls in the Northern French fleet, and simple net modifications resulting in fuel savings of some 17%, readily taken up by 15 vessels, with estimated annual savings of EU 800,000. In the NE US groundfish fleet, Eayrs (2012) describes four initiatives, including development and use of large-mesh, fine-diameter trawls, acoustic codend catch sensors to optimise net hauling decisions, use of semi-pelagic otter boards, and vessel energy audits, demonstrating very good returns on investment and rapid uptake of key savings in parts of the fleet. Trawl modifications offered up to 23% in fuel savings with no differences in catch levels or composition, up to 50% fuel savings with cod-end sensors, 12% savings with otter board redesign, and significantly less seabed impact. Sala et al (2010) applied Danish high lift otterboard design to Mediterranean demersal trawl fishing, demonstrating up to 15-20% less fuel consumption and up to 40% more door spread, with a reduction from 0.41 to 0.33 kg fuel per 1000m2 fishing area. They also noted potential interactions with net drag and the possibility to reduce this further with different net aspect and towing speed. No significant decrease in total catch was found between traditional and the alternative doors, and latter decreased total discards. Though the new doors were double the cost of traditional doors, fuel savings give a payback time of less than four months.

As part of a broad industry-wide initiative to reduce fuel costs and improve environmental performance and market effectiveness, Taal and Hoefnagel (2010) describe the potential impact of pulse trawl cf beam trawls, with up to 40-45% reduction in energy consumption, also providing benefits to benthic ecosystems, and less damage to undersize fish. However, comparative performance in species targeting were uncertain and capital costs were relatively high (typically 400,000 EU),

Sterling and Eayrs (2010) describe potential modifications to Australian prawn trawl rigs, including; a five-net trawling system, improving swept area performance by 12% compared to the normal quad-rig, correct size-matching of otter boards to nets, a newly designed Batwing otter board, which conceivably can reduce drag by as much as 70%; and the concept of a double-tongue, square-mesh trawl. Gaston et al (2012) noted the potential to reduce energy costs by some 5% in Australian prawn trawling using light-based bycatch reduction devices, attributing gains both to reduced cod-end drag and slightly greater yields of target species. Balash and Sterling (2012), comparing drag properties in modeled Australian prawn trawls noted that twine diameter itself is not the only determinant of drag, and that twine surface, layup configuration and knotting could also be critical.

van Vugt and van Marlen (2010) describe a generalised approach to analysing energy absorption in various vessel and gear combinations in the European beam/demersal trawl fleet, modelling component energy dissipation in various operating conditions, suggesting energy savings of 5-30% across a range of fleets. The analytical and modelling technique is potentially applicable to any arrangement of hull, propulsion system and gear assembly

Thomsen at al 2010 assessed fuel and energy use in the Faroese fleet in 2006, noting a wide range of values of fuel use/tonne of output, and that most fuel and energy savings were to be realized by speed management, for which direct fuel use indicators and the attitude of skippers was critical. Engine capacity and fishing duties were not always well matched, resulting in further losses. Fuel use ranged from an average 0.36 tonnes fuel/tonne fish (range 0.21 – 0.70) for pair trawlers, 0.78 (0. 47 – 1.10) for large single trawlers, 0.24 (0.17 – 0.60) for large longliners, 0.50 for small single trawlers, 0.63 for factory trawlers (1.5 l/kg fillets) and 0.08 (0.07 – 0.09) for pelagic vessels. One result of earlier fuel price rises was that vessels targeting saithe converted from single to pair trawls, with the same catch quantity, 40-45 % savings on fuel, and by eliminating trawl doors reduced fishing gear expenses by around 15 %. Toring and Hansen (2012) also describe significant savings in three vessels, fishing cod, roundfish, sandeel in the North and Baltic Seas, with reductions of up to 40% through optimizing trawl and otterboard designs and configurations, with potential returns of some 300% on the investments involved.

A very specific area of interest for energy reduction occurs in the wide range of light-attractant fisheries, eg in the W Pacific. In Japan, major light-based fisheries include the stick-held lift-net for Pacific saury *Cololabis saira*, purse seine for mackerels *Pneumatophorus japonicus*, jack mackerel *Trachurus japonicus* , and squid jigging for Japanese common squid *Todarodes pacificus* and neon flying squid *Ommastrephis bartrami* (Inada et al 2010). Here, steadily growing fishing pressure has lead to significant increases in installed lighting power as vessels compete to attract fish. Takayama et al (2010) reviewed energy use in squid-jigging, from inshore dayboats to offshore and open seas fleets; coastal boats (25m) typically consuming 287 kL of fuel annually, 58% for propulsion, and 37% for lights; offshore boats (40m) using 431kL, 27% for propulsion, 34% for lights and 22% for freezing; open seas vessels (80m) using 828 kL, with propulsion accounting for 32%, lights 23%, freezing 30%. Based on 250-260 fishing days/year. However, though it was noted that most vessels were financially viable, energy use relative to catches or values was not recorded.

Katsuya et al (2010) describe the use of LED (light emitting diode) lights to replace metal halide lights (MHL) or incandescent lights (ICL) for a range of fisheries, noting that in suitable cases the light frequency can be tuned for the visual response of the target species. They also note the avoidance of UV emissions from MHL systems which can be harmful for crew, the reduction of generator noise and avoiding the safety issues of replacing ICL bulbs while fishing. LED lights are also lighter and improve vessel stability. Katsuya et al (2010) demonstrated 47% reduction in light energy use in typical squid-jigging system over a fishing season (69 kJ). Total consumption including vessel movement was reduced by 30%, and though there was a small reduction in catch from the previous year, its value was higher. They noted considerable further scope for managing light periodicity and intensity to optimise attraction, collection and harvesting efficiency, and an associated need to assist skippers and crews to use LED systems to best effect.

Management and operating improvements

A range of options could be considered within fleets to reduce fishing effort and costs. Uchida and Watanobe (2010) describe an effort pooling arrangement for Pollack longline fishing. The share of fuel cost in total fishing costs for the 10-20 tonne vessel category, the majority in this fishery, increased from 20.1% in 2004 to 22.8% in 2005, an additional 264 thousand (USD2,700) yen in fuel cost for vessels making on average 4.6 million yen (USD46,000). Under pooling arrangements fuel consumption and cost in 2007 decreased by 23.8% and 8.7%, respectively for five-crew vessels, while fuel price increased by 22.6%. However, these conservation efforts were not without cost: profit decreased by 34.4% for five-crew vessels; 28.4% reduction for three-crew vessels.

Driscoll and Tyedmers (2010) explored the implications of fisheries management approaches on fuel use in herring fisheries in New England, demonstrating substantial differences in fuel use from 20 to 120litres/tonne with fishing method and potential for reallocating seasonal access to reduce total energy use. Driscoll et al (2010) carried out a similar review of Maine and Nova Scotia lobster fisheries, highlighting potential impacts of bait use, gear use per vessel and trip length.

Bastardie et al (2010) demonstrated that by using VMS and logbook data analysis in the Danish fleet, modelling of spatial allocation could result in strategies providing significant energy efficiency improvements, for example by restricting fuel use or trip length, or limiting fishing to areas with highest marketable yields. These models did not however extend to reallocation of effort between vessels, and in some cases, energy reduction choices would result in reduced landings and value, hence requiring more specific tradeoffs, and better determination of marginal returns to fuel use. Palenzuela et al (2010) explored the potential for using oceanographic and remote sensing data to plot optimal longer distance routes to fishing grounds, saving energy by avoiding adverse win d and sea conditions, yet maintaining comparable travel times.

For more distant water fisheries, Mayorga and Jones (2010) describe the potential for multiple component ocean information systems in contributing to fishing efficiency, locating stocks, avoiding weather downtime, logistics of vessel deployment, landing and marketing arrangements. Paige (2010) noted the potential use of the Marine Exchange Program in Alaska information, communications and services to ensure safe, secure, efficient and environmentally responsible maritime operations – vessel tracking systems, data sharing to authorised users.

Strategic and fleet level responses
Although a number of options can be proposed, the key issues in practical terms include the cost of making changes and the uncertainties associated with the effectiveness of these changes. Unless direct measures of fuel use (eg fuel meters or regular record-keeping) are employed it may also be difficult to generate the feedback required to create the incentives for changing gear or practice. To address these at industry level a number of actions have already been taken. Seafish (2006) described a range of options explored directly with UK fishing fleet, considering fleet operations, gear type and fishing patterns, With fleet fuel costs then estimated at some USD 160 million annually, small percentage change could have valuable impact. The study showed specific awareness and responses by many industry participants and a shift in attitude towards specific fuel cost saving. The most common strategic changes reported were: diverting fishing effort to fishing grounds closer to the mainland; changing the landing port to nearest port to fishing grounds to reduce steaming time; replacing the engine with a more fuel efficient engine; and changing the fishing method and target species. Operationally, changes were noted in: changing towing patterns to minimise fuel use; reconsidering going to sea in bad weather; modifying gear to reduce fuel use, including: switching from single to pair trawling, reducing length of trawls, size of the trawl and changing the size and type of trawl doors; reducing steaming and towing speeds.

Abernethy et al (2010) described the response of the small-scale Cornish fleet to fuel cost rises, identifying links with ownership and age of vessels. Responses included better use of tides, limiting fishing trip length, reducing bad weather trips, and gear experimentation/ innovation. Over 4 species and three catch sizes, there was no evidence that increased costs could be passed through to market price. Based on case of the Gulf of Maine Sustainable Fisheries Program, involving community support fisheries, supply chain collaboration, partnerships, and the development of positive media relationships, Levin (2010) noted the importance of market recognition of fisheries meeting specific sustainability criteria, and the need for producers to build and develop this Taal (2010) described a process of developing study groups and knowledge circles to engage the Netherlands fleet in reducing fuel costs and improve returns. These showed 10-30% fuel savings and up to 45-60% in individual cases based on gear development and other fishing options. Further profitability potential was also evident from fishing or market co-operation but was not reported. Energy audits in fleets or fleet sectors are also now being adopted with potentially promising results (Eayrs, 2012, Basurko et al, 2012), and these are likely to become more commonplace in routine practice.

A small number of recent studies have explored mitigation responses across international dimensions. Emanuelsson, et al (2010) described an environmental comparison of Senegalese shrimp production in industrial and artisanal fisheries using life cycle assessment methodology, focusing on carbon footprint and biological impacts and showing significantly lower GHG (energy use) in artisanal fishing (stow and drift nets vs demersal trawl), which were also lower than processing energy use. However significant levels of undersized catch were also recorded. Abernethy and Kebede (2010) explored comparative interactions of fuel and energy use in tropical and temperate fisheries, with potentially greater fuel dependence in the latter, together with higher fuel intensity. They also noted the range of capacity to respond – including technical ability, access to investment, etc. Across a range of datasets, short-run responses to fuel price rises in most fleets were slow but there was evidence of longer-term positive elasticity, and hence a fall in consumption.
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On the closely related issue of GHG estimations in the capture sector, primarily linked to fuel use, Ziegler et al (2010) note the potentially significant role of on board refrigerant leakage from fishing vessels, and much greater impact arising from the current generation of HCFC replacements, arguing for a further shift towards ammonia, carbon dioxide and other systems, which although requiring additional investment, can usually demonstrate very short payback periods.

6.4 Mitigation in the aquaculture sector

As earlier described, a large part of aquaculture related energy consumption is related to feeds, and strategies to reduce their impact will all contribute to improving energy efficiency. These range across the supply and management system, and include:

- Shifting towards better formulated, more stable and manageable compound feeds, with more reliable performance and less waste; where appropriate (eg in semi-intensive pond systems), optimising fertiliser and feed based strategies
- Diversifying raw material sources and reducing the embodied energy and other energy inputs associated with these.
- Improving processing systems to reduce energy consumption, optimise feed quality, reduce production and handling waste
- Improving distribution options to reduce transport and handling energy costs
- Managing feeding systems and husbandry interactions to optimise food conversion levels and yields, based also on
- Improving biological performance through selection of species and strains with better feed conversion and product yields, and reducing underperformance and mortality losses through better disease diagnosis and control, and better disease resistance.

The potential of wider feed bases is of particular significance given potential constraints of availability of fish meal and oil (see eg Tacon and Metian, 2008). However, based on an LCA analysis, Papatryphon et al (2004) reviewed four feed strategies for Atlantic salmon production, concluding that lower fish based diets did not necessarily improve energy performance, particularly if additional processing was required to remove anti-nutritional components or supplement deficiencies in alternative feed sources. Nonetheless, the energy implications of a wider range of dietary options across the more complete range of aquaculture species deserves further attention. For carp culture in Hungary and India, Olah and Sinha (1986) noted a wide variation of embodied and direct energy costs, depending on the role of fertilisation and feeding, and on the degree of water management and circulation. Colt and Cooper (2010) assessed energy budgets and global warming potential (GWP) for three large scale salmon netpen farming options in NW Pacific, comparing inshore with offshore locations for a functional output of 2500t annually. These demonstrated the significant role of feeds The energy demand/kg fish ranged from 18.1-19.3 MJ/kg fish, dominated by energy needed for feed, which ranged from 92-94% for the three facilities. The next largest contributors were typically ice production and fixed capital. Smolt production, feed generator operation, and transport were in the range of 0- 1%. There were no major differences between inshore and offshore locations.

Opportunities to reduce fuel and energy inputs and costs in other aspects of aquaculture production vary with the system employed. As evidenced by wide variation in practice and in system efficiency. There is a considerable need to clarify power application rates for common purposes in aquaculture, to avoid oversizing or inefficient use; Bankston and Baker (1995) provide practical guidance for sizing aquaculture equipment, and guidance on installed application of aerators and other equipment is also increasingly common in key sectors for which it is becoming important. As a recent example of a more specifically designed comparison, with optimised equipment selection, Colt et al (2010) assessed six options for salmon smolt production, based on an output of 2 million annually ranging from 42 TJ (flow-through with gravity supply), 53 TJ (partial reuse), 55 TJ (reuse), to 81 TJ (pure oxygen), to 126 TJ (partial reuse with temperature control), to a maximum value of 151 TJ (flow-through with pumped supply). This equated to 117, 186, 197, 324, 567 and 680 MJ/kg output.

The specific case of recycled aquaculture systems (RAS) may need further exploration; these are widely advocated in some contexts as alternatives to open-flow systems, particularly caged based aquaculture, to reduce impacts on external environments and ecosystems, and where they can be suitably located, to reduce energy costs of transport to process and market centres (Martins et al, 2010). However, as outlined here and elsewhere, direct energy use per output is significantly higher than for other aquaculture systems, and would have to be matched by substantial efficiencies in other respects, or specific environmental gains such as reduced ecosystem/biodiversity impact. Colt (2010) evaluated energy use and a range of other attributes for alternative for intensive salmon aquaculture, concluding that RAS technologies were unlikely to be able to compare positively on most energy, environmental and footprint parameters.

6.5 Mitigation in post-harvest systems

Surveying across a range of processing units in NW USA, Kelleher et al (2001) projected total energy cost savings from recommendations at USD 1.4 million per year, averaging USD261,500 per year per plant in Alaska and USD 19,000 in the Northwest, primary differences being due to opportunities for direct power generation in Alaska. Changes included; improving power factor, self-generation, premium efficiency motors, compressor adjustments on refrigeration; adjusting boilers, lighting efficiency. Annual savings associated with productivity recommendations totalled USD 2.7 million, averaging USD 419,000 per year per plant in Alaska and USD161,000 in the Northwest. Options included automating and modifying processes, machine vision sorting, replacing a cryogenic freezer, automating packaging, and modifying waste drains. Simple payback rates on modifications were typically around 1 year or less.

A number of energy saving initiatives are under way in a range of contexts, as post-harvest sectors become increasingly competitive and subject to environmental performance compliance, as illustrated in Table 61 for seafood performance targets for Thailand. At an operational level, UNEP/COWI (1999) noted that in many operations, substantial savings could be made quickly, with little or no capital investment, through simple housekeeping efforts, including: implementing switch-off programs and installing sensors to turn off or power down lights and equipment when not in use; improving insulation on heating or cooling systems and pipework.; favouring more efficient equipment; improving maintenance to optimise energy efficiency of equipment; maintaining optimal combustion efficiencies in steam and hot water boilers; eliminating steam leaks; capturing low-grade energy to use elsewhere in the operation. Brandsson and Benediktsson (2010) assessed the sometimes overlooked issue of matching electrical loads with phase outputs in onboard and onshore electrical power systems, controlling voltage irregularities and harmonics, and the potentially significant savings of energy and equipment life which can result. The benefits of installing an electronic power load adjustment device were noted, initially for onshore processing plant with energy savings of up to 7%, with further options being explored for fishing vessels.

Table 61 Performance targets for seafood processing, Thailand

Parameter	Typical Performance	Target
Power consumption (kWh/ton of fish)	22 – 279	36.7
Furnace oil grade B (L/ton of fish)	71 – 174	174
Water consumption (m3/ton of fish)	9 – 16	8.5
Yield (%)	40 – 53	41.9
BOD loading (kg/ton of fish)	8 - 29	7.5

Source: Dept of Industrial Works. (2005). Industrial Sector codes of practice for

In a review of channel catfish processing energy use, Boyd al (2010) describe a unit assessed in 2009, which used 4.682 GWh of electricity and 523 MBtu of natural gas to produce 8,277 t of processed fish, from approximately 17,234 t of live fish, shipping 7,358 t of processed fish using its truck fleet. This used 863,533 L of diesel fuel of which 175,200 L were used by the refrigeration units. It was also estimated that a further 50,386 L of fuel was used for transporting process wastes to a rendering plant. While it was recognised that efficiency improvements could be made, primarily through yield recovery gains, investments in plant efficiency within a very competitive, low-margin market would be difficult to support.

In addition to reducing a plant's demand for energy, there are also potential opportunities for using more environmentally benign sources of energy, including replacing fuel oil or coal with cleaner fuels, such as natural gas, purchasing electricity produced from renewable sources, or co-generation of electricity and heat on site. In some cases it may also be feasible to supplement fuel supplies by recovering methane from anaerobic digestion of high-strength effluent streams.

As noted above, an important waste reduction strategy for waste reduction and energy efficiency at any level is the recovery of marketable by-products from process wastes. Using meat and bone separators, products such as surimi and flaked fish can be created from previously underutilised materials. Products such as chitin can be recovered from shellfish wastes, and hydrolysed fish wastes can also be used for fish meal or fertilisers. Assuming a broader perspective of energy transfers from ecological to economic systems, Ichien et al (2010) assess options for Alaskan Pollack processing, comparing the discharge of untreated process wastes (1610.7 kJ/tonne of fish processed), and its positive effects on marine wildlife populations, with waste treatment to produce fishmeal and oil (1474.1 kJ/tonne), noting the value of multicriteria analyses to refine options. However, costs and returns under various regulatory and operational conditions were not determined.

More strategic approaches for reengineering process plant are exemplified by the Enerfish project in Thailand, based on the Hiep Thanh Seafood processing unit using some 414 kWh per t of fish input, or 1400 kWh per t of product**.** Together with higher efficiency cooling and freezing units, external energy demands are proposed to be reduced by converting process wastes into biofuel and process energy needs, possibly also raising external sales on the biofuel market. A range of process options are described, including daily use of 80 t of process waste to produce 17t of fish oil, producing 13 t of biodiesel equivalent to 126 MWh/day energy output. This can be fed into the processing unit, producing 57 MWh/day of power and 77 MWh/day of heat, or if demands are less, biodiesel can be sold externally. (Enerfish, 2008)

6.6 Mitigation in distribution systems

Hill et al (2010) note the potential for energy reduction in retail outlets, based primarily on N American and UK experience, pointing to a range of options for balancing building heat management with product display and temperature control, reducing lighting energy demands – proposing realistic targets of 400kWh/m2 of retail space from current averages of around double this level. Weber and Matthews (2008) reviewing energy use and GHG emissions for retail food supply in the US note that although food is transported long distances (average 1640 km delivery and 6760 km life-cycle supply chain) food associated emissions were dominated by production phase, contributing 83% of the average household's food consumption footprint, transportation only 11% and final delivery from producer to retail only 4%. They also noted that on average, red meat is around 150% more GHG intensive than chicken or fish, suggesting that dietary shifts can be more effective in lowering food-related energy use and climate footprint than buying local. Shifting less than one day per week's worth of calories from red meat and dairy products to chicken, fish, eggs, or a vegetable-based diet would achieve more GHG reduction than buying all locally sourced food.

In the EU, a range of initiatives is currently underway to improve environmental performance in the retail sector (see EU/JRC/IPTS, 2011) – including new designs, building modifications, HVAC improvements, layout improvement and design/operation of key refrigerated units, integrated heat/cooling systems. Examples fitting lids on cabinets, vertical displays can reduce energy consumption by 40%. More generically, the issue of supply chain sustainability (Ambler-Edwards et al, 2009) is also receiving attention – reducing potential energy losses by ensuring reliable and efficient delivery of the range of products required to meet consumer demands.

Another element with increasing impact on the food industry transport and distribution sector is that of access and quality of information. This applies at least as significantly in the fisheries sector, where catch opportunities, harvest decisions and product perishability make timing and location very critical, and where market information can link with transport decisions with great effect on efficiency and profitability within the whole supply and value chain. Here the role of ICT (information and communications technology) is becoming increasingly significant, whether for mobile phones providing access to market intelligence in artisanal fishing or aquaculture communities, or sophisticated logistics modelling and planning in modern high-added value markets. While ICT components do not in themselves have a high energy demand, their impact on energy efficiency in other parts of the supply system can be potentially very positive.

6.7 Conclusions

- Mitigation measures against rising fuel and energy costs can defined across the fisheries supply and value chain; a wide range of these have already been identified and a number have been demonstrated, though uptake may be variable without practical incentives.

- Mitigation responses can be defined at both strategic and operational levels, and apart from reducing net energy and fuel use may bring about differing mixes of consequences, both within and beyond the fishery sector itself.
- The removal of more energy-inefficient forms of production and/or value addition may have negative effects on supply availability, social and economic welfare, and on consumer options. However, they may also bring about other benefits such as reduced stock pressure and a greater focus on understanding ecosystem and other interactions.
- Strategically, the key issues concern energy and fuel pricing policy, and the extent to which support for energy and fuel costs can be justified in the food sector and in fisheries. In most cases the sector is likely to become less protected against rising energy prices, but this may justify arguments for adjustment support for better energy efficiency.
- Options to shift from non-renewable to renewable energy sources exist for the sector in some contexts, though much depends on the national and regional level energy options and policy choices. The high level of dependence of the capture sector on safely transportable high energy density fuels is likely to continue, though options are wider for other parts of the supply chain.
- With fluctuating energy prices, operational adjustments have so far been more practical than those involving capital expenditure as temporarily falling fuel prices allow resumption of less efficient practices. However, low profitability in many parts of the supply system make significant capital investment a challenge.
- Practical levels of mitigation response can be identified across the fisheries sector; those related to capture fisheries are the most significant in terms of potential effects on fuel and energy costs, though energy use at the retail and consumption end of the supply chain are also potentially significant. At this stage there is little documented information available on consequences of actions taken, nor of the potential for lesson-learning across the sector.
- In the commercial retail and food service sectors in developed markets however, significant changes in energy efficiency are already underway, driven by cost and competitive pressures. In many cases these have specific relevance to the aquatic food sector. However, the extent of effect in less developed markets is less evident.
- Logistics and the use of ICT can have a significant effect on energy efficiency, as can infrastructure quality. While rail transport can offer significant gains for terrestrial distribution, only some markets are conveniently accessible without multiple handling.
- Generic improvements in energy efficiency can also be gained through better product utilisation and reduced wastes, ensuring that quantities and value of product per energy input are improved. However while some gains can be made in operational practice, capacity building and capital investment may also be required to improve performance.
- At present, the primary incentives for mitigation within the supply chain relate to reducing the direct cost of fuel and energy, in some cases recovering from loss-making conditions. Apart from market-led pressures for more responsible fishing and for reduced GHG or other footprints there are no other direct incentives for action. However, future potential may exist for financial incentives related to GHG reduction.
- In the absence of an extensive body of case studies, there is no clear evidence at this stage that mitigation opportunities are related to operating scale, though it is likely that larger integrated enterprises competing in large national, regional or global marketplaces will be more able and committed to invest in mitigation.
- For smaller-scale activities it may be necessary to find ways to support change, avoiding competitive disadvantages in more widely traded markets. There is also a need to build better experience, and develop good practice in mitigation approaches.

7 Conclusions and recommendations

7.1 Overview

This review has attempted to provide a perspective on fuel and energy use across the fisheries sector, based on recent and emerging assessments and procedures. Its original focus had been on estimating fuel use in fishing vessels, but as the importance of other fuel and energy related issues across the aquatic food supply system became evident, the scope was extended. The work has presented a range of methodologies, directly or indirectly linking specific cases and examples with generic larger scale assessments, leading to potential global estimates of fuel and energy demand. Although data is limited in scope and detail across most sectors, there is sufficient available either from empirical studies or through technical relationships to identify key characteristics and trends.

The review has confirmed that the capture fishing sector has at this stage the strongest dependence on fuel inputs in particular, and given low profitability levels in a range of fisheries, vulnerability to rising prices is high and could result in reductions in effective fishing capacity. In the absence of specific measures to reduce fuel use, and with greater pressure on reducing fuel subsidies, options in some fleets may become very limited. However, more balanced relationships between fish resources and fleet effort may improve prospects of coping with higher fuel prices. Better supply management may also assist in sustaining and increasing first sale prices for some species.

Though the aquaculture sector has the potential of complementing capture fisheries supplies, and meeting future increases in global demand, it also has a notable degree of energy dependency, related primarily with feed supplies, linkages with capture fisheries for key ingredients, and energy inputs into terrestrially derived feed materials. Feed processing and transport costs are also involved, as are energy inputs into water exchange, treatment and waste management. Many if not most forms of aquaculture can however access a wider range of energy sources, primarily through electricity supply. There is considerable scope for feed efficiency improvement across the sector, with wider scope for expanding production of lower trophic level species, though more information is required on the energy and related footprint characteristics of feed input and management strategies. Recent trends towards intensification in aquaculture may be tempered in the future by the need for higher energy efficiency, and for better integration in other systems.

Post-harvest functions and activities also have important energy use interactions, in turn interlinking with and impacting on choices for distribution and final sales, whether through retail or food service outlets. A wider range of energy sources is usually accessible, though there may be wide geographic variations, and for developing economy markets in particular, fuel access can be critical constraint. Though energy costs are rarely a major element in most processes, they are significant enough to affect future choices for investment and operation, and to stimulate change. Technical innovations, higher levels of utilisation and reduction of wastes will all be critical in improving energy efficiency. Many of these, as in the food sector more widely, are already underway, particularly in modern market chains where significant investment has been committed in the last decade. However, such technical gains are not necessarily accessible to all sectors, and there is potentially a need to make these more widely available.

The issue of consumer and household level energy use and waste in food consumption is a generic issue with similar implications for the fisheries sector. In markets where chilled or frozen meal presentations are increasingly common, there may be less consumption waste, but energy associated with travelling to purchase, with food storage and with packaging use and disposal can be significant. Fresh fish consumption bought in daily purchases from traditional markets, or from local travelling vendors is potentially less energy demanding, but urban habitation trends, work demands and transport planning make this a steadily less common option in many societies.

Impacts on trade of rising energy prices will be variable; though current advances in transport and distribution technology are addressing critical energy issues, and improving efficiencies, there are likely to be real term increases in costs of moving aquatic products into major markets. There may be particular impacts on trade of lower-value materials meeting demands of poorer markets, for example in Sub-Saharan Africa, as transport costs relative to product costs may be relatively high. Access to more prosperous markets by less geographically favoured producers may also be negatively affected, as smaller-scale transport options and poor infrastructure will tend to create adverse trade conditions in higher energy cost environments.

Investment by public and private sectors will important particularly in the downstream stages of the supply chain, and in developed food markets there is already significant competitive drive to improve energy efficiency in processing, transport, distribution and final purchase options. However, primary producers and those in poorer economies, unprotected from energy and fuel price rises, may have fewer options and limited investment potential. The need for effective mechanisms for responding to rising fuel and energy costs will therefore be increasingly important.

Across the sector, though key features can be highlighted and some aspects of fuel and energy use can be quantified, there are considerable constraints in understanding and gaps in data, whether within and across specific sectors, or in developing national profiles, competitive cross-sectoral analyses, or in scenario analyses addressing potential outcomes of changing access and cost of fuel and energy. Some of the issues and connections are outlined below.

7.2 Links with other issues and themes

The use of fuel and energy in the fishery sector is closely related to a range of other economic and environmental performance attributes. A strongly emerging concern in the global climate change agenda is the role of the fisheries sector in GHG emissions, the potential for reducing these, and possible tradeoffs which might result. Because of the importance of fuel use intensity to GHG emissions of fishery-derived products, fishing vessel fuel consumption has been the particular focus of a number of studies and sensitivity analyses (eg Thrane, 2004, Hospido and Tyedmers, 2005; Ziegler and Valentinsson, 2008; Fulton, 2010; Parker, 2011). In most cases, fuel use intensity has marked effects on overall performance of fisheries; irrespective of the methodology used, GHG emissions are very closely linked with fuel use.

For aquaculture, definable GHG emissions are closely linked with two feed-related variables; feed conversion ratio (eg Pelletier and Tyedmers, 2007; d'Orbcastel et al., 2009; Cao et al., 2011) and feed ingredient mix (Ellingsen and Aanondsen, 2006; Boissy et al., 2011; Bosma et al., 2011). However, results of analyses vary and will require to be further elucidated across a wider range of aquaculture systems and species. There are also potentially important issues of methane and nitrous oxide emissions which will be less easily captured by feed efficiency analyses.

Because of the relative importance of primary energy sources in resource efficiency and GHG impacts, a number of studies have also explored the implications of electricity mixes (eg Ellingsen and Aanondsen, 2006; Schmidt and Thrane, 2007; Ayer and Tyedmers, 2009; Ziegler et al., 2011), mainly for aquaculture production. However the importance of energy sources in processing, storage and retail options may also be significant, and has the potential to create substantial geographical variation in direct energy pricing and in potential GHG impact. Here also, variations in fuel sourcing and pricing will have significant effects in competition between national fleets, landing options and access to raw materials for onwards value addition and potential food security.

Links with fuel and energy use and other thematic aims are also potentially significant, including connections and tradeoffs along the supply and value chain, GHG mitigation options and consequences, employment and profitability effects of energy decisions, development implications of energy costs and mitigation opportunities, capacity building needs and potential. Specific connections can also be assessed across the wider range of environmental attributes (eg Mungkung et al 2005 exploring LCA in shrimp culture) – LCA environmental elements, and could be extended to social and other attributes, links of fuel and energy options with food security, poverty and vulnerability, issues of equity of options and outcomes, etc.

7.3 Policy implications

Regardless of the policy environment, rising fuel and energy prices are likely create a range of changes across the fisheries sector, at a global and cross-sectoral level. Fuel and energy supply and access will be amongst the most significant drivers of global economies and societies over the coming decades. Though in GDP terms the fisheries sector is in most cases a relatively small part of national economies, it has well documented significance beyond these measures and will be subject to important interactions in fuel and energy. Significant policy implications include:

- Strategic issues of fisheries management, resource protection, and their consequences for capacity, fishing effort and returns to fuel expenditure; specific issues of management effects for more vulnerable groups, potential differentials of opportunity and impact across the sector
- Energy policy issues, fuel subsidies and links with wider food supply perspectives – in energy terms, food, habitat and transport have the closest policy connections in most national economies, but are likely to have increasingly competing policy positions which will require clearer and more effective articulation.
- Links of energy and fuel use in the sector with its role in wider climate change and development themes, including climate change adaptation, food security, and trade development
- The need to create an environment for a mix of public, private and market driven incentives for change towards strategic goals; the need to position the fisheries sector effectively in this context, to understand where and how effective change can be brought about.
- Identifying and promoting options for public and private partnerships, particularly along the supply chain, to build capacity, provide effective investment environments
- The need to connect and integrate with wider themes of development knowledge, local empowerment, vulnerability issues, resilience of communities and food supply systems to increasingly stressed resource, energy and economic systems.

7.4 Future work;

A number of areas of future work can be identified. In many if not all cases these need to be seen as part of an integrated approach to sustainable food supply, interlinking with other resource and economic systems, responding effectively to climate change needs, meeting food security objectives, and delivering practical and cost effective solutions to meet the needs of the sector and its dependent communities and populations:

- As noted in Parker (2011), LCA reviews in the seafood sector, within which fuel and energy assessments are normally conducted, are predominantly oriented towards Northern hemisphere demersal species – cod and flatfish, together with salmon and shrimp aquaculture. Most reviews to date had been done in Europe or N America, and much more would be required to clarify regional and global characteristics.

- Regardless of location, better data is required across the sector, with improved links with GHG and other analyses of potential policy significance; strategically there is also a need to develop tools such as integrated product flow mapping at local or national levels (see eg Thrane, 2004) to define how resource flows and efficiencies link together, and to provide a framework for description, comparative scenario building and policy development.
- Common approaches need to be developed to deal with energy use allocation between multiple or by-products. To date, capture fisheries LCA studies commonly used mass-based allocation methods, while aquaculture and feed studies used economic- or energy-based allocation. Across the sector, in some studies multiple allocation methods were applied for different processes. As allocation method can have a significant bearing on results (see eg Thrane 2004) some means of reliable comparison across systems and food sectors needs to be available, particularly if these are to be scaled up for national, regional or global inventories.
- Better perspectives of energy and fuel use in integrated systems, and in other sectors such as fisheries enhancement (see eg Lorenzen, 2008), need to be developed. These can also be connected with wider LCA environmental and social definitions.
- In the capture sector, the close connections between fuel price and use, fisheries management options and impacts, social aspects of fishing employment and value addition, varying sector dependence levels will justify wider explorations of interactions with policy, scenarios of response and consequences of change.
- Wider comparisons across food sector will also be important in clarifying the resource competitive issues, complementary implications for food security, and investment options and implications for various components in the aquatic food value chain.
- Based on data compilations, measures of effectiveness and other criteria, and on comparative analyses, particularly for less resourced regions and communities, there is an important need to develop good practice in sectoral perspectives, effective approaches to fuel and energy mitigation, and better longer-term indicators of performance.

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