Food and Agriculture
Organization of the
United Nations

FIRO/ C1080 (En)

FAO
Fisheries and
Aquaculture Circular

ISSN 2070-6065

FUEL AND ENERGY USE IN THE FISHERIES SECTOR

Approaches, inventories and strategic implications

FAO Fisheries and Aquaculture Circular No. C1080 FIRO/ C1080 (En)

FUEL AND ENERGY USE IN THE FISHERIES SECTOR

Approaches, inventories and strategic implications

James F. Muir
FAO Consultant
London, United Kingdom of Great Britain and Northern Ireland

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2015

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

ISBN 978-92-5-108934-7

© FAO, 2015

FAO encourages the use, reproduction and dissemination of material in this information product. Except where otherwise indicated, material may be copied, downloaded and printed for private study, research and teaching purposes, or for use in non-commercial products or services, provided that appropriate acknowledgement of FAO as the source and copyright holder is given and that FAO's endorsement of users' views, products or services is not implied in any way.

All requests for translation and adaptation rights, and for resale and other commercial use rights should be made via www.fao.org/contact-us/licence-request or addressed to copyright@fao.org.

FAO information products are available on the FAO website (www.fao.org/publications) and can be purchased through publications-sales@fao.org.

PREPARATION OF THIS DOCUMENT

The Twenty-ninth Session of the Committee on Fisheries recommended that FAO provide Members with information on fishing industry contributions to climate change, and on ways to reduce the sector's reliance on, and consumption of, fossil fuels, respecting the principles embodied within the United Nations Framework Convention on Climate Change. In 2012, FAO convened an Expert Workshop on Greenhouse Gas Emissions Strategies and Methods in Seafood. It highlighted options for the use of tools and emphasized gaps in information and practice and the need for a basic level of common understanding and for more effective communication.

In 2013, a second workshop on greenhouse gas (GHG) mitigation was held to explore strategies and practical options for reductions in fisheries and aquaculture food production systems.

Following the 2012 workshop, work areas that could support seafood-related GHG emissions efforts were identified, including the need to determine a global figure for GHG emissions in fisheries and aquaculture, using data that can be readily collated and revisited to inform priority setting.

At the second workshop, James Muir presented a background paper that became the basis of this publication. Sadly, Mr Muir passed away during the stages of completion of this publication. Doris Soto and Junning Cai contributed and adapted some of the aquaculture information and discussion building on what was produced by Mr Muir.

This publication has been funded through project GCP/GLO/322/NOR – Climate Change, Fisheries and Aquaculture: Testing a Suite of Methods for Understanding Vulnerability, Improving Adaptability and Enabling Mitigation.

FAO. 2015.
Fuel and energy use in the fisheries sector – approaches, inventories and strategic implications, by J.F. Muir.
FAO Fisheries and Aquaculture Circular No. 1080. Rome, Italy.

ABSTRACT

The role of fuel and energy in the fisheries sector is an important yet 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 rationalization 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 publication addresses the utilization of fuel energy by the global fisheries 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 document, 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.

IN MEMORIAM

James Fraser Muir, 1951–2013

Professor James Muir passed away in the early hours of 1 May 2013 after having suffered from illness for some time.

James was a chemical engineering graduate who later became globally renowned in the field of aquaculture. Shortly after he completed his PhD at the University of Strathclyde, he became instrumental in establishing the University of Stirling's Institute of Aquaculture, where he spent the next 30 years. As a recognized professor, James contributed enormously to the institute's development and status on the international stage. His background was in environmental engineering and economics, with specific expertise in the aquatic sector, including resilient production systems, energy and resources, trade, markets, investment and development policy, climate change mitigation and adaptation, research and education planning and management.

James had great affection for FAO and he was highly respected by FAO in Rome, where he had worked in the Fisheries and Aquaculture Department, as well as by FAO's regional offices. When James retired from Stirling in 2009, he continued his work as an international development and research adviser and evaluator. He advised governments and research and development institutions around the world as well as developing postgraduate programmes and authoring more than 200 papers and publications.

CONTENTS

ABBREVIATION AND ACRONYMS

BTU	British thermal unit
CO_2	carbon dioxide
CSW	chilled seawater
EEZ	exclusive economic zone
FFA	Pacific Islands Forum Fisheries Agency
GDP	gross domestic product
GER	gross energy ratio
GHG	greenhouse gas
GRT	gross registered tonnage
GT	gross tonnage
hp	horsepower
ICL	incandescent light
ICT	information and communications technology
IMO	International Maritime Organization
IQF	individually quick frozen
ISSCFG	International Standard Statistical Classification of Fishing Gear
IUU	illegal, unregulated and unreported (fishing)
J	joule; 1 watt × 1 sec = 4.12 calories; kJ = kilojoule; MJ = megajoule; GJ = gigajoule; TJ = terajoule
LCA	life-cycle assessment
LED	light emitting diode
LNG	liquefied natural gas
MCS	monitoring, control and surveillance
ME	metabolizable energy (in human consumption)
MHL	metal halide light
nm	nautical mile
RAS	recycled aquaculture system
RSW	refrigerated seawater
SFC	specific fuel consumption (of a vessel), expressed in gm/kW/min.
TEU	twenty-foot equivalent unit (transport container)
TOE	tonnes of oil equivalent
UV	ultraviolet
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, litre	10.74 kWh	Joule = 1 watt × 1 sec	0.239 calories
Gasoline, litre	9.63 kWh	kWh = 1 kW × 1 hour	3.6 MJ, 860 kcal
Natural gas, m^3	10.31 kWh		3 413 BTU, 1.35 hp-hour
Light fuel oil, litre	10.40 kWh	BTU = 1 lb H_2O × 1 °F	~ 1055 joules, 0.25 kcal
Bunker C, litre	11.59 kWh	1 hp	~ 0.74 kW

FOREWORD

The role of fuel and energy in the fisheries sector is an important yet 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 rationalization 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 publication addresses the utilization 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 that 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. Global fish output for human consumption grew from some 20 million tonnes in 1950 to more than 136 million tonnes in 2012, (FAO, 2014). 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 percent 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 percent of revenue from landed catch, whereas in 2008, during the first recent period of high oil prices, this increased to about 50 percent. 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 costs.

Although aquaculture is less directly dependent on fuel, 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 fish-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 demand 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, although less so than the catching sector. The great increase in fish trade in recent decades has created significant demands for frozen product, increased export of high-value / low-volume product (e.g. shrimp, lobster, marine fish) to wealthier markets, and trade in lower-value product (e.g. dried and canned fish) around most parts of the world. A greater emphasis on wider distribution of live or 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 postconsumption wastes, of both the fish product and the associated packaging.

Future projections for energy supplies, and for fossil fuel in particular, are challenging, with rising demand, 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 on 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 globalization, 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 Poseidon, 2011; FAO, 2012). It has received particular emphasis most recently owing 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 this publication 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 publication describes future production and cost scenarios and options the fishing industry may need to consider in reducing its reliance on fossil fuels

1.3 Approaches used in the supply/value chain

In the absence of standardized approaches, various practical means have been used to estimate fuel or energy use at a global level, differentiated for different systems where feasible, 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 United States dollar (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, subsector definitions and the fuel utilization of each subsector. 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, owing to lack of data, rather than using the International Standard Statistical 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, although the cumulative impacts of large numbers of small vessels with varying levels of motorization 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, although still have a strong linkage with fossil fuels, especially as most energy-intensive systems owe their dependence to the use of manufactured feeds, in which fishmeals and fish 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 are relatively well documented, and in common with the aquaculture sector, a wider range of energy sources can be accessed. Usage is commonly expressed in kilowatt hours (kWh) per tonne of product, although care is required to determine whether this is 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 refrigerated seawater [RSW]), frozen, canned, dried/cured and reduction to fishmeal. 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 the regional and global levels owing to the lack of reliable data on overall process yields, and on the proportion of output that 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 in order 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 postconsumption wastes) was not attempted, although 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 dependence 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, e.g. 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 by-products. 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 standardization 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, liquefied natural gas [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, e.g. 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, although 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-hour 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 the gross energy ratio (GER). In most fisheries activities, this is well in excess of one (i.e. 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 (e.g. fishing, aquaculture or processing) or to the complete supply chain. They can be applied, most commonly, to the activity carried out a particular time, or the output (e.g. harvested fish or consumer products), or can be compiled more comprehensively to develop more complete life-cycle assessments (LCAs). 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 by-products and wastes (see 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, although 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 – e.g. 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 that 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 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 publication 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 (e.g. in GHGs) are becoming more widely considered. Technology changes at various levels and within both supply and demand areas will also have significant impacts on 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 and 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 power for hauling boats or nets, or carrying product, through to wind power in sailing vessels, has had a long and diverse history. However, 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 onboard 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 (e.g. for electrical supplies). Thus, fuel oil for fishing can have added energy costs related to its transport, and electrically driven pumps in aquaculture systems, although 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 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 a 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, e.g. diesel to biofuels, but significant capital replacement may be needed for other changes, particularly if efficiency of energy use is to be optimized. This has impacts in terms of both time and money.
- Political and consumer acceptability will also have a bearing on future energy options. Fisheries, as 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 that can demonstrate more efficient and protective use of resources. This could have an impact on both the choices of fuels and the efficiency with 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 mechanization, 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 USD40–50 million, well-trained crews and extensive support infrastructure, and they have evolved in response to opportunities to catch and sell substantial global fishery resources. Energy use 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 and structural descriptions

Although a wide range of classifications and definitions can be used for capture fisheries, a simple three-class system is applied here, broadly reflecting the different levels of capital and energy intensification applied. As shown below, 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 and 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 motorized vessels, for outboard or inboard engines, although 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,

---

[1] Definitions vary – ranges from very marginal part-time or seasonal fishing to moderately capitalized full-time occupational activity. See also FAO/World Bank/Worldfish (2008).

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

cool storage, drying and smoking (see below), whose viability will affect sale prices and hence fishing opportunity.

Some 57 percent of vessels in the global fleet are motorized, of which 79 percent (2.1 million vessels) are less than 12 m overall (FAO, 2014). Because of their small size, the area of operation is limited and operations are generally carried out on a daily basis within a coastal or lakeside zone (e.g. 12nm), catching an average of 1–3tonnes of fish per person annually. Based on a global total of 39.4 million people engaged in fishing, and assuming pro rata employment levels across all vessels, some 17.8 million people, plus their dependents, would be associated with this category of fishing. Five countries – 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. However, small-scale fishers are particularly at risk from competition from the increased fishing effort of larger vessels in inshore waters, for which illegal, unregulated and unreported (IUU) 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 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 percent 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 fished, if not overfished, 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, vessels between 12 and 24 m in length are able to fish farther 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 the exclusive economic zones (EEZs) has to some extent curtailed the activities of foreign vessels from nearby fleets and distant-water fishing nations, although access agreements with coastal States have been relatively common in the last 20 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 farther 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 of more than 24 m / 100 tonnes gross registered tonnage [GRT][3]) involves an estimated 500 000 people, each producing about 40 tonnes/year, often operating thousands of

---

[3] GRT – based on usable volume (1tonne = 100ft^3 or 2.83m^3); measurements are now governed by the International Maritime Organization (IMO) International Convention on Tonnage Measurement of Ships, 1969 (London-Rules), applying to all vessels

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 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 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 whitefish and vessels from China and the Republic of Korea fish mainly for tuna. In the Pacific, vessels from Japan, the Republic of Korean and China fish for tuna under agreements with the Pacific Islands 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 monitoring, control and surveillance (MCS) operations and enforcement actions, have opened this category of fishing to persistent concern for damaging stocks through overfishing.

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 rationalization 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.

In most forms of fishing activity, fuel costs 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 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.

---

built after July 1982; the gross tonnage (GT) is a function of the molded volume of all enclosed spaces of the vessel. This class of vessel size is recorded on the Lloyd's Register of Ships.

At the shore side, a decrease in fleet profitability can affect the related economy, particularly in small rural economies, where the 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. Thus, in Scotland, the United Kingdom of Great Britain and Northern Ireland, 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. 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 gear, transportation, marketing, etc. Even with lower multiplier levels, the loss of a fishing port activity can result in very high local unemployment, with workforces that 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 summarize details of the first such analysis, based on five vessel-size classes, and a range of estimates of days at sea, installed power, specific fuel consumption and operational constants (percentage of full activity level while at sea). This included for the first time an analysis of financial viability of the global fishing fleet, but this was 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 more than 20 years in a life cycle of about 30 years. This in turn led to overestimates of related expenditures such as maintenance cost. However, fuel cost, estimated here at USD300/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 consumption, g/kWh**	**Total installed hp**	**Operational constant**	**No. of vessels**	**Fuel consumption (tonnes)**		**Annual fuel costs USD million per vessel class**
						Per vessel	**Per vessel class**	
≥ 1 000	250	160	3 000	0.60	3 010	1 728.00	5 201 280	1 560.4
500–999	250	160	2 000	0.60	2 100	1 152.00	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 undecked	180	200	20	0.20	2 100 000	3.456	7 257 600	2 177.3
Total							46 682 380	14 004.4

Note: Fuel cost estimated at USD300/tonne.
Source: FAO (1993).

The review concluded that, at an average of 15 percent, 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 (< 100 GRT), although 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 1.15 tonne for < 100 tonne undecked vessels, to 28.8 tonne per person for vessels above 500 tonnes GRT.

Table 2

Global fleet operating costs by factor

Operating cost element	Total costs (USD million)	As percentage 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: FAO (1993).

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 percentage of labour cost	Fuel use (tonne) per person employed
≥ 1 000	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: FAO (1993).

Further to this, three studies (Le Rey, Prado and Tietze, 1999; Tietze *et al.*, 2001, 2005) investigated selected fisheries over a period of about ten 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. Gear types were classified as:

- Active demersal gear: 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 with the time going to or from the fishing ground or searching for catch, fuel consumption is relatively higher than for other gear types.
- Active pelagic gear: 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 with 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 gear: including gillnets and trammel nets, tangle nets, longlines, trap nets and pots, and lift nets. These 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 mechanized, but even these have low power consumption compared with the other two categories.

The first analysis (Le Rey, Prado and Tietze, 1999) showed significant overlap between the three categories. However notable differences were found between fisheries in developing and industrialized countries (Table 4) the former spending a far higher share of revenues on fuel (almost twice as much in 2002–03).

Table 4

Cost of fuel as a percentage of landed revenue for different fisheries

	Le Rey *et al*. (1999)		**Tietze *et al*. (2001)**		**Tietze *et al*. (2005)**	
	1995/1997		**1999/2000**		**2002/2003**	
Category	**No. of fishing units**	**Fuel as percentage of gross earnings**	**No. of fishing units**	**Fuel as percentage of gross earnings**	**No. of fishing units**	**Fuel as percentage of gross earnings**
Averages	88	14.83	108	16.70	75	18.53
Developing countries	46	18.52	70	20.65	55	21.63
Industrialized countries	42	11.08	38	9.78	20	10.02
Fishing types						
Developing country / active demersal	20	17.19	25	30.28	22	26.15
Developing country / active pelagic	17	17.33	15	19.35	8	16.99
Developing 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

This suggested that fisheries in developing countries would be far more susceptible to increased fuel prices, although it may also relate to sales prices and earnings being lower. In most cases, particularly in developed countries, active demersal fishing had a higher percentage 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 percentages. The difference between developed and developing countries is most discernible for passive gear, varying by more than a factor of three for all three studies, although there were also substantial differences for active pelagic fishing. The average ratio of fuel cost to landed revenue increased from 14.83 percent to 18.53 percent from 1996 to 2002, a rise of almost 25 percent. 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 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 utilization into an increase in gross domestic product (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 (Le Rey, Prado and Tietze, 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

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

Source: Tietze *et al*. (2005).

Consequent reviews by the European Union (Member Organization)

A detailed series of reports by the European Union (Member Organization), 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 countries of the European Union with substantial fisheries together with Lithuania, Estonia and Latvia (subsequently members of the European Union), 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 percent of the European fishery sector in terms of value and volume. The 2004 study by the European Union (Member Organization) gave an average ratio of fuel cost to landed value of 13 percent (Table 6). However, reporting levels varied, with some countries giving 100 percent coverage and others as low as 3 percent. Comparison with the previous year's figures (2003–04), showed that average fuel costs had increased from 13 percent to 18 percent of landed value.

Table 6

Fuel cost and revenue for European fisheries

Country	Fuel as percentage of revenue	Country	Fuel as percentage of revenue
Faeroe Islands	6.3	Germany	14.0
Denmark	7.3	United Kingdom	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%	

---

[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 Poland, Lithuania, Latvia and Estonia had significantly higher levels of fuel cost to 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 (e.g. 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 7

Comparison of estimates of fuel cost and revenue by FAO and the European Union (Member Organization)

Fleet sector	Data from the European Union (Member Organization)		Data from FAO	
	No. of vessels	**Fuel as percentage of gross earnings**	**No. of vessels**	**Fuel as percentage of gross earnings**
European demersal fleet	8 676	15.42	11	14.37
European pelagic fleet	911	11.15	1	5.48
European passive fleet	16 280	7.43	8	4.61
Baltic demersal fleet	330	29.30	na	na
Baltic passive fleet	144	26.06	na	na

Note: na = not available.

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, Northern European, North Sea and Southern European countries, explained in terms of their characteristic fisheries. However, average output per person in Iceland, Norway and Faeroe Islands was EUR154 500[5], compared with EUR58 800[6] in the EU–15, and EUR31 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 European countries that are not members of the European Union, 48 kW/person in the EU–15, and 36 kW/person in Poland and the three Baltic States. The ratio of annual output value to kilowatts of capacity also varies, at EUR1 644, 1 225 and 875 per kW for northern European, EU-15 and Baltic States, respectively, suggesting that more highly capitalized 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 capitalization may also be a consequence of these factors.

---

[5] Ex-change rate of 1 January 2013: 0.754 Eur 154 500= USD 204 907.

[6] Ex-change rate of 1 January 2013: 0.754 Eur 58 800 = USD 77 984.

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. These 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 these, to generate estimates of fuel cost and use, although care is required to link registered with operational vessels, and to consider the impact of flag of convenience activities. As noted above, fuel use per fish caught will vary with fishing type. Thus, a study by the Institute of Fishery Technology in Trondheim, Norway, indicated that otter trawlers used four times as much fuel per tonne of fish as coastal gillnet and line vessels (Table 8). Coastal vessels also employed more people relative to weight of fish caught.

Table 8

Norwegian data on productivity and fuel use

Fishing method	**Annual catch/person (tonnes)**	**Tonnes fuel used / tonnes fish caught**
Coastal net and line	30–40	0.075
Offshore: longline	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).

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

Much more can be found in closer detail. For example, for Finland (Table 10), the report by the European Union (Member Organization) stated that there were 3 393 registered fishing vessels but not all were active and that 100 percent 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 17 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 kilowatt hours were estimated only based on the prime mover, i.e. engine and propulsion system, excluding power required for freezing, etc. 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 9

European fleet fuel costs – data of the European Union / estimates by FAO

Country	Cost of fuel EUR million (study of the European Union)	Percentage 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
United Kingdom	162.8	52	438	230
Faeroe Islands	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
Total			2 397	2 455

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 consumption (tonnes)	Cost of fuel (USD million)
Trawlers < 24 m	< 12	180	6 000	180	0.20	4	933	0.56
	12–24	200	13 300	190	0.40	47	4 852	2.91
	24	200	800	200	0.50	2	384	0.23
Trawlers ≥ 24 m	24–40	200	14 800	200	0.40	22	5 683	3.41
	≥ 40	250	2 100	180	0.50	2	1 134	0.68
Gillnetters	< 12	180	600	180	0.20	3	93	0.06
	12–24	200	2 700	200	0.40	12	1 037	0.62
Coastal	< 12	180	19 000	180	0.20	227	2 955	1.77
	12–24	200	1 900	200	0.40	11	730	0.44
Total							17 801	10.68

Table 11

FAO fuel consumption methodology applied to the Netherlands fleet

Type of vessel	Size of vessel (m)	Days at sea	Total k W	SFC	Constant	Number of vessels	Fuel consumption (tonnes)	Cost of fuel (USD million)
Shrimp trawler	12–24	200	8 000	200	0.40	54	1 659	1.00
Beam trawler	12–24	200	37 000	200	0.40	171	24 296	14.58
	24–40	250	44 200	180	0.50	32	7 638	4.58
	≥ 40	250	167 000	160	0.60	99	95 230	57.14
Trawlers	24–40	250	9 000	180	0.60	15	875	0.52
Pelagic freezer trawlers	≥ 40	250	98 900	160	0.60	17	9 684	5.81
Total							139 381	84.00

Table 12

Relative fuel consumption in Danish fisheries

Allocation method	Cod	Flatfish	Prawn	Shrimp	Nephrops	Mussels	Herring	Mackerel	Sand-eel
					(litres/kg)				
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
System expanded	0.36	0.97	0.76	1.03	6.05	0.01	0.18	0.06	0.06

Note: Values based on method of allocating fuel use across mixed landings.

Source: Thrane (2004a).

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 (2004a) reported that the Danish fishing sector consumed 197 million litres of diesel in 2000, based on 1 528 firms contributing to more than 99 percent of the total turnover in the sector, representing an average 0.13 litres (0.1 litre kg) per kilogram of caught fish or 0.14 litres (0.12 kg) per kilogram of landed fish. He also noted that, in the previous year, the average had been 0.15 litres/kg of caught fish, the difference arising because of increased landings of industrial fish in 2000. A systematic LCA 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 that for fishing Norway lobster (nephrops), with consumption estimated at up to 6 litres/kg caught, and accounting for almost 16 percent of total Danish fleet consumption. Fisheries targeting shrimp, prawn and flatfish were also relatively energy-intensive at about 1 litre/kg caught. In absolute terms, the last was responsible for 20 percent of the total fuel consumption. By comparison, cod and herring fisheries, which made up some 25 percent of total fuel consumption had much lower relative consumption, respectively, at 0.36 and 0.18 litres/kg, while mussel, mackerel and industrial fisheries are the least energy-intensive – 0.06 litres/kg for the latter two, and as low as 0.012 litres/kg caught mussels (including shells). Although mussels and mackerel are insignificant, industrial fish made up one-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, by value, or by theoretically expanding the system to separate out the species concerned. It was proposed that estimates could vary by 25 percent according to species mix, and 35 percent as a function of vessel size or fishing gear (Thrane, 2004a).

In the United Kingdom of Great Britain and Northern Ireland, the industry support body, the 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 cod recovery plans of the United Kingdom of Great Britain and Northern Ireland noted that in 2009 lower fuel prices (about USD700/tonne) had significantly reduced cost pressures for all segments and compensated for lower fish prices and cuts in days at sea. Demersal boats of more than 24 m were particularly sensitive to fuel price, and had these increased to GBP0.55 per litre (about USD1 000/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 fishing segments the United Kingdom of Great Britain and Northern Ireland, 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 percentage of revenue, United Kingdom segments

Vessel category	**Upper quartile**	**Average**	**Lower quartile**
Demersal trawl, single rig > 24 m	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)

Table 14 summarizes key features of a more detailed assessment of the impact of fuel consumption and costs on European fleet profitability. Based on fuel costs of USD900/tonne, estimates are also developed of fuel costs per kilogram 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, with fuel use ranging from 0.2 to 4.6 litres/kg of catch, and from 0.9 to 8.6 litres/kWday of effort.

Reviewing 32 diverse fishing activities reported over an approximately 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 North Atlantic demersal trawl to 2 300 litres/tonne for flatfish; herring/mixed species seine fishing 100–140 litres/tonne and 1 000 litres/tonne, salmon (range of techniques) 360–830 litres/tonne, tuna/swordfish/billfish 1 400–3 400 litres/tonne; shrimp trawl 920–3 000 litres/tonne, squid jig 1 700 litres/tonne, scallop dredge 350 litres/tonne, crab trap 330 litres/tonne, hand gathering of clams 300 litres/tonne, and nephrops trawl 1 030 litres/tonne. These levels are broadly similar to those shown in the study of the European Union in Table 14, although for the latter, demersal and beam trawl energy consumption levels were higher.

Table 14

Fuel use in European fleet segments, 2005–06

Country & gear	Length (m)	Litres per kg fish	Fuel cost		Litres/ kWday	Target species
			Per kg fish	Percentage 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, cuttlefish, 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%)

Notes: Percentage in parentheses 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.
Source: Scientific, Technical and Economic Committee for Fisheries (STECF)/the Annual Economic Report (AER) 2008 on the Profitability of European Fleets (SGECA 08-02), Copenhagen.

A more specific review of environmental footprints in the fisheries sector of Galicia, Spain (Iribarren, Moreira and Feijoo, 2010a), 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 kilogram, based on a fuel cost of USD900/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 15

Comparison of Galician fishery systems

Fishing system	**tonnes fuel/tonne**	**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, 2004; Ziegler and Hansson, 2003; Ziegler and Valentinsson, 2007; Ziegler *et al*., 2010). 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 kilogram 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 in recent decades, despite technical improvements in localizing fish stocks, potentially due to considerable overfishing of many of the stocks concerned in 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 or to generalize across into other fisheries, although 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, Watson and Pauly (2005) proposed annual fuel use of some 50 million m^3, 1.2 percent of total global oil consumption, or at a fuel density of 0.85, 42.4 million tonnes. With marine fish and invertebrate landings at 80.4 million tonnes, global average fuel-use intensity was 620 litres (527 kg) per live weight tonne, or some 1.9 tonnes of catch per tonne of fuel. Fishing vessels released some 134 million kg of carbon dioxide (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 IUU catches. This average level of fuel use is also considerably lower than many of the fisheries of the European Union reported in Table 13. 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, although significantly inefficient, compared well with a number of other animal-protein production systems.

Using a systematic vessel-based approach, the 1993 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 of less than 100 tonnes. In this case, simplified vessel data are used, with three size categories.

Table 16

Global fuel utilization estimates from vessel power in global fleet

Vessel size classes	No. of vessels	Total installed kW	Days at sea	Operational constant	SFC (g/kWh)	Fuel consumption (tonnes)		Annual fuel cost	
						per vessel	per vessel class	per vessel (thousand USD)	per vessel class (million USD)
≥ 24 m	43 767	27 803 318	180	0.6	180	296.39	12 972 101	266.75	11 674.9
12–24 m	320 997	31 469 963	140	0.4	220	28.99	9 305 703	26.09	8 375.1
< 12 m	2 157 888	33 716 479	100	0.3	240	2.7	5 826 298	2.43	5 243.7
Total	2 522 653	92 989 760					28 104 102		25 293.7

Other factors are as per the 1993 review. An additional specification – a “fleet capacity index” – was considered, estimating the proportion of the vessel category group that 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 fuel (e.g. for lamps), are omitted. At prices of USD900 per tonne, fuel costs of the global fishing fleet were calculated to amount to USD25.3 billion. These results are highly dependent on the accuracy of vessel numbers, as well as on estimates of utilization 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 data from Tietze *et al.* (2005) data for 2002 fuel costs, calculated as 18.5 percent of gross revenue, i.e. USD14 billion out of USD78 billion, and assuming average fuel consumption has not changed, with fuel price in the first six months of 2008 approximately 160 percent 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, although 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 “Sunken billions” study of fishing capacity and subsidies (World Bank and FAO, 2008). Table 17 extrapolates from six countries for which specific data were developed.

Table 17

Global fuel use and cost estimates

	Percentage global catch	No. vessels	MW	GT per vessel	Catch/ GT	Catch/ kW	SFC g/kWh	Fuel use, million tonnes	Fuel cost, billion USD
China	17	509 717	15 506.7	14	2.3	1.04	280	8.68	7.82
EU–15	6	85 480	6 941.1	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	8 184	1 328.9	48.2	7.3	2.18	250	0.66	0.6
Republic of Korea	2	87 203	16 743.1	8.3	2.6	0.11	260	8.71	7.84
Russian Federation	3	2 458	2 111.3	789.2	1.5	1.37	250	1.06	0.95
Total selection	33	693 981	43 094.0	17.6	2.6	0.73		23.09	20.78
Global estimate	100							69.97	60.00

Source: From World Bank and FAO (2008).

A further country in the World Band and FAO study, Japan, was excluded as data on kilowatts were unavailable. At USD900/tonne, these data suggest global costs of USD60 billion. This estimate uses higher specific fuel consumption (SFC) values – potentially better allowing for poorer engine efficiency, but may overstate global use, owing 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 tonnes, worth USD41.76 billion. Overall, balancing the methodologies employed, and assuming higher SFC values for Table 15, global fuel consumption of 30–40 million tonnes, valued at USD27–36 billion could be expected, equivalent to an average of USD0.29–0.39/kg of global landed catch.

2.5 Implications and actions

Although 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 trade-offs e.g. 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 operations 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 percent 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 capitalization, and high fuel costs but relatively low labour costs. 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.

Although 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 kilogram 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-motorized 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 are 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 in an 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 below). 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, although the potential exists for rising fuel prices to result in reduced effort and for catch per effort to stabilize 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. It should also be considered in the wider context of national fuel, energy and currency balances, social impacts, added value, and food security.
- Countries should recognize 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 downturns, but this should not become a structural cause for overfishing.

3. AQUACULTURE

3.1 Introduction

The aquaculture sector has seen considerable growth, from 44.3 million tonnes in 2001 to around 84 million tonnes in 2011 worth USD136 billion and accounting for about 50 percent of the world's fish food supply (Table 18). Asia dominates production, with 91 percent by volume and 79 percent by value, with China by far the largest producer (50.17 million tonnes in 2011).

Table 18
Aquaculture production and value, 2001–2011

Area	**Million tonnes**		**Average annual percentage change**	**USD billion**		**Average annual percentage change**
	2001	**2011**		**2001**	**2011**	
World	44.33	83.73	6.57	51.92	135.99	10.11
Asia	39.85	76.34	6.72	41.58	107.39	9.95
China	29.87	50.17	5.32	24.41	64.27	10.16
Latin America and Caribbean	1.13	2.40	7.79	3.31	11.13	12.88
Europe	2.09	2.68	2.51	4.37	11.19	9.86
North America	0.63	0.56	-1.24	1.27	1.95	4.34
Africa	0.49	1.54	12.15	0.92	3.18	13.16
Egypt	0.34	0.99	11.15	0.76	1.96	10.00
Oceania	0.13	0.21	4.89	0.46	1.16	9.71
New Zealand	0.08	0.12	4.43	0.10	0.28	11.20

Table 19 shows trends in key producing countries, and the higher growth rates associated with particular species in countries such as Viet Nam (*Pangasius* catfish), Indonesia, Myanmar (carps and tilapia), Brazil and Egypt (tilapia).

Table 19
Trends in major producing countries (top 15)

Producer	**Million tonnes**		**Average annual percentage change**	**USD billion**		**Average annual percentage change**
	2001	**2011**		**2001**	**2011**	
China	29.87	50.17	5.32	24.41	64.27	10.16
Indonesia	1.08	7.94	22.11	2.42	7.49	11.96
India	2.12	4.58	8.00	2.39	9.30	14.53
Viet Nam	0.61	3.05	17.51	1.36	5.70	15.44
Philippines	1.22	2.61	7.89	0.72	1.99	10.69
Bangladesh	0.71	1.52	7.90	1.07	3.38	12.23
Republic of Korea	0.67	1.50	8.42	0.61	1.90	11.99
Norway	0.51	1.14	8.35	1.02	5.24	17.78
Thailand	0.81	1.01	2.16	1.75	2.56	3.88
Egypt	0.34	0.99	11.15	0.76	1.96	10.00
Chile	0.63	0.97	4.38	1.75	6.34	13.71
Japan	1.31	0.91	3.63	4.23	4.67	0.99
Myanmar	0.12	0.82	21.02	0.32	1.07	12.83
Brazil	0.21	0.63	11.85	0.32	1.37	15.45
Malaysia	0.18	0.53	11.52	0.32	0.78	9.31

The sector is very diverse, the FAO FishStat database listing more than 500 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 (Tables 20a and 20b), 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 leave small margins in many subsectors, and profitability is also very sensitive to fuel and energy cost changes.

Table 20a
Most significant species (> 1 million tonnes in 2011, excluding aquatic plants), by quantity and value

Species	No. countries	Output, million tonnes	Percentage change		Value billion USD	USD per kg 2011	Percentage change	
			1 year	10 year mean			1 year	10 year mean
Silver carp	41	5.3	30.5	4.4	7.7	1.44	44.0	10.3
Grass carp (= white amur)	44	4.6	4.9	4.2	5.8	1.28	5.0	8.8
Cupped oysters nei[1]	8	3.8	2.6	2.0	2.2	0.59	2.4	-0.4
Common carp	82	3.7	2.8	3.1	5.3	1.42	10.0	6.9
Japanese carpet shell	9	3.7	2.1	7.1	3.4	0.93	2.5	4.5
Whiteleg shrimp	30	2.9	6.2	26.7	12.2	4.23	8.3	23.6
Nile tilapia	69	2.8	9.9	10.4	4.5	1.62	12.5	13.8
Bighead carp	20	2.7	4.6	6.5	3.5	1.28	4.8	10.8
Catla	8	2.4	-19.0	17.4	4.7	1.95	-13.5	26.1
Crucian carp	12	2.3	3.6	5.7	2.5	1.09	3.7	10.4
Atlantic salmon	13	1.7	20.7	5.3	9.7	5.64	24.2	13.4
Roho labeo	9	1.4	27.3	9.1	2.2	1.55	40.1	10.8
Pangasius catfishes nei[1]	5	1.4	8.9	28.7	2.2	1.56	12.2	29.3
Scallops nei[1]	2	1.3	-7.2	4.5	1.9	1.42	-7.2	5.8
Freshwater fishes nei[1]	66	1.3	6.9	-3.8	1.9	1.46	11.6	0.5
Marine molluscs nei	8	1.1	51.3	-1.4	0.7	0.66	45.8	1.6

[1] Including other unclassified stocks in same species grouping.

Table 20b

Most significant aquatic plant species/types

Species	Quantity (million tonne)			Value (billion USD)			Price		
	2001	2010	2011	2001	2010	2011	2001	2010	2011
Japanese kelp	4.03	5.15	5.26	0.42	0.30	0.26	0.10	0.06	0.05
Eucheuma seaweeds nei	0.22	3.49	4.62	0.02	1.14	1.07	0.10	0.33	0.23
Aquatic plants nei[1]	3.17	3.13	2.89	1.30	1.46	1.19	0.41	0.47	0.41
Elkhorn sea moss	0.72	1.87	2.10	0.05	0.27	0.35	0.07	0.14	0.17
Wakame	0.23	1.54	1.75	0.08	0.67	0.73	0.33	0.43	0.42
Warty gracilaria	0.02	1.15	1.52	0.01	0.34	0.47	0.95	0.30	0.31
Nori nei[1]	0.51	1.07	1.03	0.03	0.06	0.06	0.06	0.06	0.06

[1] Including other unclassified stocks in same species grouping.

Unlike capture fisheries, where diesel fuel for propulsion greatly dominates energy demand, fuel and energy inputs in aquaculture 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 categorization 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.

While these trends can be recognized, 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 are rather scattered. However, with increasing competition and converging technologies some species/system configurations (e.g. for cage culture of Atlantic salmon, or of seabass/bream, or for pond culture of shrimp) have tended to become more standardized, and so more generic characterizations 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, although 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 / characterized by
(A) Aquatic plants, mollusc systems, extensive ponds for fish or crustacea	(1) use of natural waterbodies (e.g. 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 – although more in industrialized 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 fertilizer, 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 fertilizers, 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.

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 Troell *et al*., 2004). A wider range of LCA reviews have explored energy and other resource/environment interactions (see Henriksson *et al*., 2011; Parker, 2012). Table 22 summarizes features of a range of production systems, and relates industrial energy input (i.e. 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 USD900/tonne. Compared with capture fisheries, total values of tonnes of fuel equivalent per tonne of product for fed and fertilized systems, at 0.27–2.37 (0.32–2.79 litres/kg), are similar to direct fuel consumption values for capture fisheries, although 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 components. 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/tonne, intensive pork at 595–718 GJ/tonne, closed feedlot beef at 513 GJ/tonne and open feedlot beef production at 1350–3360 GJ/tonne. 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/tonne of protein	GJ/tonne of whole fish	Tonne diesel equivalent / tonne of protein	Tonne diesel equivalent / tonne whole fish	Equivalent fuel cost USD/ tonne
Mussels, longlines	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	1 260
Grouper/seabass, intensive cages	1 311	95	32.77	2.37	2 133
Carp, intensive recycle, feed only	3 090	56	77.25	1.4	1 260

Note: In energy output terms, 1 tonne of diesel is the equivalent of about 40 GJ.
Source: Developed from Muir (2005).

Confirming the link with production systems, LCAs 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 kilogram 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 × 10^5)	6.65	1.05–2.40	580–950
Solar/renewable (%)	95.5	71.4–85.4	81.0–87.4
Fossil/non-renewable (%)	4.5	28.6–14.6	19.0–12.6
Protein output, kcal	6 605	255–440	22 420
Input/output ratio	100	410–545	2 585–4 235

Sources: Developed from Muir (2005), Troell *et al* (2004), Tyedmers and Pelletier (2007).

Table 24

Energy allocation in selected aquaculture systems

	Salmon, intensive cages	**Grouper/ bass intensive cages**	**Tilapia, semi-intensive ponds**	**Mussels, longline**
GJ/tonne 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).

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 percent of energy consumption in intensive systems, and almost the entire use in the semi-intensive example, which although not fully dependent 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, although not greatly different in absolute terms. The tilapia example has negligible fuel and power inputs, although this could increase where more water exchange is required. These data are broadly consistent with other reviews (Troell *et al*., 2004).

The largest part of feed-related energy use is associated with the supply of raw materials, including in many cases, inputs of fishmeal and fish oil, where interactions with capture fisheries are most significant. Further specifications of these inputs are summarized 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. For more accurate estimates, this would need 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**	**Percentage change/year**
	Thousand tonnes	**%**	**Thousand tonnes**	**%**	**TJ**	**TJ**	
Salmonids	1 638	8.4	2 300	6.2	802.6	1 127.0	4.97
Shrimp	2 925	15.0	2 450	6.6	1 433.3	1 200.5	–2.50
Catfish	505	2.6	700	1.9	247.5	343.0	4.77
Tilapia	1 578	8.1	2 497	6.7	774.0	1 223.5	6.76
Marine finfish	1 482	7.6	2 304	6.2	726.2	1 129.0	6.51
Cyprinids (carp)	8 775	45.0	27 000	72.5	4 299.8	13 230.0	17.42
Total	19 500	100	37 226	100	9 555.0	18 240.7	9.68

Note: Based on Nutreco table: 0.49 GJ/tonne feed prod; figures rounded upwards.

However, Table 25 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 percent. However, as discussed below, 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 “low-value fish” feeds and their processing and distribution, for which some 5–6 million tonnes were estimated to be used globally.

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 has yet to be developed, Table 27 summarizes some earlier recorded application rates for aeration in aquaculture systems, including a limited amount of data on total energy use per crop or per kilogram. Thus, in the example of pond catfish culture at 2.82 kWh/kg, a historic power cost of USD0.05/kWh would yield an energy cost of USD0.14/kg, while at current equivalent costs of USD0.15/kWh, it would amount to USD0.42/kg, which is unlikely to be viable.

The balance between the use of aeration and pumping energy for water exchange varies with system and location, although in many installed systems aeration is the most common means of supporting more intensified production. Thus, Schuur (2003) estimated that aeration accounted for 68 percent 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 although not as yet fully documented, average energy use per tonne of output is likely to converge towards more efficient levels.

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
Shellfish 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

Table 27

Installed aeration capacity guidelines

System	Function	Capacity	Notes
Tanks	Larvae	0.2–1 m^3/h per m^3	Very short cycle usage
	Broodstock	0.1–0.5 m^3/h per m^3	May only be used periodically
	General use	0.05–0.3 m^3/h per m^3	Supplementary aeration
Semi-intensive ponds	Shrimp culture	0.44 kW/ha, 1.12 ha ponds	10 tonnes/ha per year, 2 crops, 20–30% water exchange/day
	Shrimp culture	6 kW/ha, 0.49 ha ponds	16.5 tonnes/ha per year, 2.5 crops, 20% water exchange/day
Ponds	Carp culture	4 kW/ha, 0.7 ha ponds	Chinese pond systems
	Tilapia, carp	About 0.5–1 kW/ha	About 0.2 kW per tonne fish/year
	Catfish	34 000 kWh/ha/crop	2.82 kWh/kg produced, about 4 kW installed/ha
Intensive ponds	Eel culture	4.5 kW/ha, 0.2 ha ponds	30 tonnes/ha per year production, Taiwan Province of China
	Shrimp culture	12 kW/ha, 0.25 ha ponds	Yield 13.2 tonnes/ha

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 grow-out systems near to major markets.

To estimate energy use in specific aquaculture applications, Box 1 summarizes calculation methods for water pumping and aeration energy. For 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

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

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) = 9.81 × lift (m) × flow rate (m^3/s)/efficiency. An intensive pond system producing 200 tonnes/ha per year, with water exchanged 6 times daily, lifted 2 m from source to outlet, with pond depth of 1.5 m and pump efficiency of 60 percent would require per hectare:

$$9.81 \times 2 \times (10\,000 \times 1.5 \times 6/(24 \times 3\,600))/0.6 = 34.1 \text{ kW, or } 0.17 \text{ kW/tonne}$$

Annually, pumping 100 percent of the time, would require 34.1 × 24 × 365 = 298 716 kWh, for 200 tonnes.

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 4 kW/ha and a yield of 10 tones/ha, with aerators working an average 30 percent of the time over the production cycle, energy use would be 4 × 30 percent × 24 × 365 kWh/5 tonnes = 2 102 kWh/tonne, or at USD0.15/kWh, a cost of USD0.16/kg.

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

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, Folke and Kautsky (1994) reviewed resource demands in semi-intensive shrimp farming in Colombia, describing an ecological footprint of some 295 J per joule 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.

Table 28

Cost of energy for shrimp production

Inputs	**Energy cost in 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).

This suggests that electricity costs are greater than those for fuel, although in some cases electricity is generated onsite, adding to fuel use. Total energy costs would range from USD0.20/kg in extensive production to USD0.60/kg in highly intensive production, or some 5–15 percent 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.

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 USD0.50/kg produced, total energy costs would be some USD2.5 billion, of which 60–80 percent would be spent on electricity and 20–40 percent on fuel. This compares with a first sale value of about USD17 billion.

Table 29
Shrimp culture production / energy cost by country

Country	Production (tonnes)	Value (USD billion)	Value/kg (USD)	Estimated energy cost (USD million)	% of first sale value
China	2 441 559	9 443	3.87	1 220.8	12.9
Thailand	580 315	1 696	2.92	290.2	17.1
Indonesia	346 527	1 405	4.05	173.3	12.3
Viet Nam	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	2 248.0	13.2

Note: Energy costs estimated using Table 26.
Source: FishStat (2006).

However, this estimate does not include energy involved in feed supply, which as noted above would account for a greater input, much more so if the total embodied energy is accounted for. In a review of Thai production systems, Tunsutapanich, Mungkung and Gheewala (2006) noted that feed and direct energy accounted for some 50 percent and 20 percent of production costs, respectively, and that aeration accounted for some 80 percent 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 6 hatcheries and 18 farms in Hainan Province, China, noting significantly higher impacts per unit of production for intensive than semi-intensive farming. Grow-out contributed 96.4–99.6 percent of the cradle-to-farmgate impacts, mainly through feed production, electricity use, and farm effluents. Averaging across intensive (15 percent) and semi-intensive (85 percent) farming systems, 38.3 +/– 4.3 GJ of energy and 40.4 +/– 1.7 tonnes 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 (the United Kingdom of Great Britain and Northern Ireland), Canada, Ireland and Tasmania (Australia). As the industry has expanded and become more concentrated, systems and production processes are increasingly standardized. 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/tonne), 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 (thousand tonnes)	Fuel cost (USD million)	% of first sale value
Norway	689 970	2 649	3.84	38 638.3	966.0	869.4	32.8
Chile	658 455	3 902	5.93	36 873.5	921.8	829.6	21.3
United Kingdom	145 433	711	4.89	8 144.2	203.6	183.2	25.8
Canada	123 091	679	5.52	6 893.1	172.3	155.1	22.8
United States of America	37 312	105	2.81	2 089.5	52.2	47.0	44.7
Japan	29 316	198	6.75	1 641.7	41.0	36.9	18.6
Other	459 694	1 647	3.58	25 742.9	643.6	579.2	35.2
Total	2 143 271	9 891	4.61	120 023.2	3 000.6	2 700.5	27.3

Notes: Fuel equivalents at 40 GJ = 1 tonne diesel, costed at USD900/tonne.

These figures, including feed and other inputs, suggest that industrial energy inputs to production costs correspond to about 20–30 percent of first sale value, although reaching almost 45 percent for the United State of America, for which first sale values are reported as only 61 percent of the sector average. These sale values are more typical of 2011 market levels, and suggest that energy-related costs are now likely to correspond to a higher proportion of realizable revenue. However, the figures in Table 30 must be considered as very broad initial approximations, and would need 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 percent of the operational energy budget.

Following pioneering work in energy studies by Folke (1988) and others, salmon aquaculture has more recently 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 Ellingsen, Olaussen and Utne, 2009; Pelletier *et al.*, 2009; Winther *et al.*, 2009). These have also compared salmon with other products – e.g. Ellingsen and Aanondsen (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.

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, although as for capture fisheries, there are few direct sources of data, and estimates need 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 categorization 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 2010-2012 system intensities are allocated to major species groups and regions, separating China from the rest of Asia, owing to its dominant influence in global totals. All "aquatic plants" are 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 of production

System category	**Characterized by**	**Energy inputs per tonne of production**	
		GJ	**Tonnes fuel equivalent**
(A) Extensive	Less than 0.5 tonne/ha per year for fish, but substantially more for molluscs or algae; use of natural waterbodies (e.g. lagoons, bays, embayments) and of natural, often unspecified, food organisms.	0	0
(B) Semi-extensive	0.5–5 tonnes/ha per year, 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	2–20 tonnes/ha per year, 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 tonnes/ha per year; completely fed; usually ponds, tanks, raceways with water exchange, or cages.	75	1.5
(E) Super-intensive	Up to or exceeding 1 000 tonnes/ha per year; completely fed, tanks, raceways with/out recirculation, or cages.	100	2

Table 32

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

Region	Thousand tonnes fuel equivalent					Total fuel (million tonnes equivalent)	USD million
	Marine fish	Diadromous	Freshwater 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	3 990.1
Europe	315.1	1 379.7	382.5	0.9	430.9	2.51	2 258.1
Asia (excluding China)	631.5	1 010.4	9 184.6	3 204.4	974.3	15.01	13 504.8
China	1 097.8	333.8	23 828.8	4 639.0	7 046.5	36.95	33 251.3
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	54 014.0

Notes:

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 the United States of America.

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.

Freshwater fish are dominated by “misc.”, carps and tilapias, but catfish are the main species in North America. Total production is > 24 million tonnes, mostly from Asia. This section is critical in the overall weighting of global energy demand. Semi-intensive in all areas except the Americas and Europe, where intensive.

Marine fish not reported from South America and Oceania, although some production occurs. The global total is slightly more than 1 million tonnes, about 90 percent from Asia. These are intensive in the Americas and Europe, semi-intensive elsewhere.

Molluscs are dominated by clams, mussels, oysters and scallops, all filter feeders – all semi-extensive.

As in the salmon sector example given above, 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 – e.g. 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 USD900/tonne would be valued at USD54 billion. Within this total, more than 50 percent 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 USD32.4 billion. These figures compare with a total global first sale value of almost USD78.8 billion, and USD38.4 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.

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 – e.g. boats, vehicles, pumps, aerators, heating/cooling, miscellaneous inputs – typically 0.5–5 percent 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 percent of total energy in intensive systems and almost none in extensive systems; of this, some 15–25 percent 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 that have to be purchased by producers at market prices, shown here as an average of 2.5 percent of total energy for direct fuel/energy, and 20 percent 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 percent of reported first hand sale value corresponds broadly to the sector and other data described above.

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 tonnes fuel equivalent	Cost (USD billion)	Thousand tonnes fuel equivalent	USD billion	Thousand tonnes fuel equivalent	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 (excluding China)	15 005	13 505	375.1	0.338	3 001.1	2.70
China	36 946	33 251	923.6	0.831	7 389.2	6.65
Oceania	0.169	0.152	4.2	0.004	33.9	0.03
Total	60 016	54 014	15 00.4	1.35	12 003.1	10.80

Energy input could also apply to constructing production facilities, typically no more than 5 percent of those contained in operating costs, except for extensive shellfish systems for which operating fuel inputs are low, although not all of this would be 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 systems – unfed and fed, with several subtypes:

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 for 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 fertilizer or feed, but costs are negligible. Annual fuel and electricity costs range from 2.9 percent to 10.4 percent of total costs for mollusc systems, about USD20–90 per hectare, and about 35 percent of total costs in the shrimp systems, corresponding to about USD70–140 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)	3 750	8 206	8 313	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)	2.9	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	1 384.2	2 989.7	503.6	2 170.8
Net profit (USD/ha)	181.3	418.1	2 033.1	313.8	1 756.1
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: Sturrock *et al* (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 one percent of total costs for catfish (about USD80 per hectare), which require very little water exchange and/or aeration, to more than 16 percent of costs (about USD2 500 per hectare) for intensive shrimp production, for which both aeration and water exchange are critical. For cage and recycle systems, patterns are broadly similar, although 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 about USD0.80/m^3, or for an 8 m deep cage, the equivalent of USD64 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**					**Flow-through**
Species	**Shrimp**	**Prawn**	**Tilapia**	**Catfish**	**Snakehead**	**Trout**
Productivity (kg/ha)	3 953	4 000	16 875	20 545	65 640	5 850
Total cost (USD ha)	15 159	9 545	13 869	8 286	74 148	10 700
Fixed cost (% 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)	20 792	13 078	17 189	10 703	79 271	16 205
Net profit (USD/ha)	5 633	3534	3 320	2 417	5 123	5 558
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: Sturrock *et al* (2008)

Table 36

Systems with feed inputs – cages and recycle systems

Item	**Intensive cages**				**RAS**
Species	**Tilapia**[1]	**Tilapia**[2]	**Seabass**	**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 (% total cost)	3.8	2	5.9	7.2	Various
Variable cost (% total cost)	96.2	98	94.1	92.8	Various
Feed (% total cost)	61.9	73	63.1	48.9	36.3
Fuel & electricity (% 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	

[1] Reservoir site.
[2] River site
[3] From EU-CONSENSUS.
Source: Sturrock *et al* (2008).

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 flow-through tank/pond	0.01[10]	0.014[11]	n/a	0.026[6]	0.026[7]	0.76
Recirculating aquaculture	0.29[12]	0.29[12]	0.29[12]	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: 10 km/litre), 4 km/day for 3 months with output of 20 tonnes/ha.

[3] Assume = vessel fuel consumption.

[4] 2 ha unit using 80 hp vessel (consumption: 3 km/litre); 6 km/day for 3 years with output of 50 tonnes/ha; plus 100 litres fuel per 10 crops for vehicle.

[5] At 0.2 kg O_2/kWh and 0.5 kg O_2/kg feed fed assuming an FCR of 0.5 and 15 percent of oxygen demand is supplied by aeration.

[6] 300 litres fuel per 10 tonnes crop for vehicle.

[7] Assume = fuel consumption for vehicle.

[8] As for semi-intensive ponds, but with 0.3 kg O_2/kWh, FCR = 1.5 and 30 percent of oxygen demand supplied by aeration.

[9] Salmon farm with 750 tonnes production, 500 day crop cycle, using 2 × 200 hp vessel (consumption: 1 km/litre) travelling 5 km/day; plus 100 litres fuel per 10 tonnes crop for vehicle.

[10] Assume average replacement flow of 0.0085 m^3/s per tonne, 2 m pump head, 65 percent efficiency.

[11] As for intensive ponds assuming FCR 1.2 and 15 percent 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.

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.

The global total developed in this approach, defining direct fuel and power only, is USD3.48 billion, using percentage cost estimates, and USD2.84 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 (USD1.35 billion), but much less than the USD10.48 billion estimated for use including feed-related energy. This compares with the value of total embodied energy use of USD54.0 billion (Table 33), and direct market-costed fuel use for capture fisheries of USD40–60 billion, as outlined above.

Table 38

Global compilation of system types – unfed / partially fed systems

System	Aquatic plants	Molluscs	Semi-intensive pond	
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, USD million	86.1	265.0	140.0	1 900.5
Fuel cost based on Table 35	46.2	243.0	19.7	1 250.4

Table 39

Global compilation of fed systems

System	Intensive pond		Intensive cage		Flow-through tank/pond	RAS	Total all systems
Groups	**Crustacean**	**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
Estimated 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 million	813.0	48.6	82.8	25.0	103.5	11.5	3 476.0
Fuel cost based on Table 35	233.1	182.5	38.2	39.2	725.0	46.8	2 824.1

They also demonstrate the significance of fuel and power costs in the freshwater pond sector – particularly for semi-intensive freshwater fish (55 percent of total) and intensive shrimp culture (23 percent of total). However, there are discrepancies between the two methods – percentage 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 a need to develop better data, although as major system types and technologies start to converge under competitive pressure, disparities in performance may reduce.

Although 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 are 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, although once the features of key systems and output levels are further verified, a range of scenarios can be developed for species groups, systems, and national and regional contexts. Thus, energy-use scenarios have been drawn up for the European aquaculture sector, 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 (i.e. including feed energy) – is 200–500 million GJ, or at the equivalent of 50 GJ/tonne of fuel, 4–10 million tonnes of fuel, valued at USD3.6–9.0 billion at USD900/tonne.

Similar projections can be made 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, e.g. 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 percentage 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	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 million	86.1	265.0	140.0	1 900.5
Target energy cost, USD million	94.1	286.2	138.6	2 584.7

Table 41

Global compilation of fed systems

System/groups	Intensive pond		Intensive cage		Flowing tank/pond	RAS	Global total
	Crustacean	*Freshwater fish*	*Diadromous*	*Marine fish*	*Diadromous*	*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	3 476.0
Target energy cost, USD billion	898.4	213.8	96.9	59.4	111.8	39.1	4 552.9

Tables 40 and 41 also incorporate estimates of energy efficiency gains from current levels, e.g. with better use of water exchange, aeration, energy costs in feeds and conversion ratios. Respective energy use and cost (here using the value of USD900/tonne) are also developed, suggesting a target of some USD4.55 billion for direct energy cost, an increase of slightly more than 30 percent. On a pro rata basis, this also suggests feed-inclusive energy costs to rise from USD10.48 billion to USD13.64 billion at current prices.

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

Although 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. However, indirectly, fuel and energy associated with feeds and their embodied ecosystem support in particular can be very significant, although 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 demanding systems in terms of fuel and energy 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 fertilized or partially fed, which raises energy inputs.
- Feed-associated inputs have been particularly but not exclusively linked with fishmeal and fish-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 – e.g. 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 fertilizer production may also contribute to inputs. Accurate data on energy inputs associated with feeds from all sources require further development.
- In most cases, the 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 has so far been limited, but variations 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 studies have been carried out on energy use and other environmentally linked issues for aquaculture, and have emphasized 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 2012, some 76 percent of the world catch was used for direct human consumption and 24 percent for other uses, primarily fishmeal and fish oil production (FAO, 2014). 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 have become available, market opportunities for fresh or frozen product have expanded, and in 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 fishmeal and fish oils, once used in lower-value products such as fertilizer, assuming steadily increasing value in animal feeds, including those for aquaculture. Pet foods have also become an increasing valuable market, although 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 LCAs and food footprints. 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. Capitalization 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. 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.

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

Here it can be noted that process elements such as filleting (0.7–2.2 kWh/tonne) and packaging, freezing and storage (10–14 kWh/tonne) demand the highest energy inputs, although 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.

Table 42
Output and energy costs for fresh fish processing (Danish Environmental Protection Agency)

Process element	Water (m^3 per tonne)	Energy (kWh per tonne)	Waste (kg/tonne)	Output (kg/tonne)
Thawing (frozen fish)	5	0	20	980–1 000
De-icing washing and grading	1	0.8–1.2	0–10	980–1 000
Grading	0.3–0.4	0.1–0.3	0–20	980–1 000
Scaling	10–15	0.1–0.3	20–40	960–980
Deheading	1	0.3–0.8	270–320	680–730
Filleting (whitefish)	1–3	1.8	200–300	700–800
Filleting (oily fish)	1–2	0.7–2.2	~440	550
Skinning (whitefish)	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	1 000
Average for total process		20		

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 is 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, although this is extended for highest-value products (e.g. 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 (United States of America)	29
Whiting	9–12	*Synagris 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, in most cases, the cost and energy use associated with ice are 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 freshwater or seawater, in block, flake, plate or tube ice format. Clean seawater can be used but produces a soft and wet ice, which owing 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 freshwater is expensive or in short supply, and it can be produced at sea.

Block ice is the type 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 owing 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 it 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), although to chill fish sufficiently to achieve these gains, more ice is needed per kilogram of fish in higher ambient temperatures. For bulk and boxed stowage, an ice to fish ratio varies between 1:2 and 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 approximately 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, although 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, although there are issues of quality and onboard space in the choice between the ice plant or storing large quantities of ice, and whether saltwater or freshwater 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

Notes: 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.
Source: Developed from Smith (2008).

Refrigerated seawater (RSW) and chilled seawater (CSW)

Both 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 °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. Generally used in smaller vessels, CSW does not require refrigeration machinery on board, but its temperature will rise once the ice has melted, whereas RSW can keep the temperature low for an extended period. In both methods, the 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). Both CSW and RSW techniques are also 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 owing 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 3–4 days stowage in insulated tanks in temperate climates, with one of 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 °C will impose a refrigeration load of about 100 000 kcal in order to chill to required levels. If the fish are cooled to just below 0 °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 fish oil does not usually need to be chilled, but with increasing focus on the quality of fishmeal and fish 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 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 allow 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 (e.g. 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 °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 crystallization 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 °C in two hours or less. A much more demanding requirement is for frozen tuna for the Japanese sashimi market requiring freezers operating at from –50 to –60 °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:

- Blowing a continuous stream of cold air over the fish – blast freezing.
- Direct contact between the fish and a refrigerated surface – contact or plate freezing.
- 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, e.g. 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, although spiral belt designs also used. Freezing one tonne of fish, allowing for freezer system efficiency, requires some 120 kWh, which at USD0.15/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 percent, 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 industrialized applications, energy costs tend to be greater.

A review of energy costs in salting and drying plants in eastern Canada for the period from 2001 to mid-2002 identified 5 plants producing about 7 000 tonnes of salted fish and about 4 500 tonnes of dried fish. Their total energy consumption was more than 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 CAD400 000, or an average of some USD36.5/tonne of product. Specific operations included receiving and grading (16.2–45.6 kWh/tonne processed), preparation for salting (1.3–30.2 kWh/tonne), salting room operations (0–29.5 kWh/tonne), wet-cooling (31.3–108 kWh/tonne) and drying (69.4–256.7 kWh/tonne). Packaging (i.e. the process of putting product into packaging) accounted for 0.4–36.8 kW/tonne, while dry cooling storage post-production accounted for 21.4–225.7 kWh/tonne. 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 (1.52–1.69 kWh/kg) for conventional drying cabinets, and 3 800–5 000 kJ/kg (1.07–1.41 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, although 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. The use of 6 m^3 of wood fuel per 500 kg of fish using traditional stoves, which are about 16 percent efficient in energy transfer to drying, at approximately 15 000–20 000 kJ/kg calorific value of fuelwood, and 200 kg of wood per cubic metre would correspond to about 2.4 kg wood per kilogram of fish and 36 000–48 000 kJ/kg (10.0–13.3 kWh/kg). An improved smoker design (AFSMO–150) in Ghana, consuming about 0.33 kg of fuelwood per kilogram of fish, or at 15 000–20 000 kJ/kg fuelwood, uses some 5 000–6 700 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, sterilizing 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 sterilizing, traditionally with steam, together with washing, can handling and other lesser demands. Although 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. Table 45 provides a summary of energy and other features of canning. By far the largest contributor to energy demand is can sterilization.

Table 45
Output and energy costs for canning, per tonne (UNEP/Danish Environmental Protection Agency)

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	970–1 000	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, 100 kg)					132.4
Draining cans	0	800–900	100–200	0.3	0.3
Sauce filling	0	1 100	0–100	0	
Can sealing	0	1 000	0	5–6	5.8
Washing cans	0.04	1 000	0	7	7.4
Can sterilization	3–7	920–990	10–80	~230	242.1
Average				250	

Source: UNEP/Danish Enviornmental Protection Agency, 1999. Cleaner Production Assessment on Fish Processing. Denmark, COWI Consulting Engineers and Planners AS.

Washing cans and can sealing also represent some energy demand, although substantially less. As with previous examples, water use and waste treatment, and energy associated with this, may also be relevant. Moreover, the energy used in manufacturing the cans and in their disposal would be needed for a full LCA. 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 h)		Steam (kg/h)	Fuel oil (litres/h)	Capacity (tonnes raw fish/h)
	Equipment	Total			
Tuna production	2 000	2 700	5 000	350	20
Automatic skipjack line	1 700	2 200	2 000	135	10
Sardines in oil	1 500	2 200	3 500	230	15
Pre-smoked small fish	600	1 000	1 000	65	5
Fish paste products	1 800	2 300	4 500	300	10
Salmon	800	1 200	2 500	170	8
Shrimp	500	900	750	50	3.6

Source: Myrseth (1985).

In a review of simple retort-based fish canning in Khuzestan Province, Iran (Islamic Republic of), Asakereh *et al*. (2010), reported total input energy of 22 681.8 MJ/tonnes of product (6 300 kWh/tonne), with diesel fuel accounting for up to 98 percent of total energy, electricity 1.92 percent, and labour 0.08 percent. Cooking and sterilization accounted for some 93.5 percent of energy input, and most other operations less than 1 percent. Manual operations of fish cleaning and transferring used the least energy but accounted for 43.3 percent of total human labour. In an LCA 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 31.5 kWh/tonne (5.1 percent); cutting 23.6 kWh/tonne (3.8 percent); cooking 384.7 kWh/tonne (62.2 percent); washing and cleaning 33.9 kWh/tonne (5.5 percent), dosing and filling 47.2 kWh/tonne (7.6 percent); packaging 33.3 kWh/tonne (5.4 percent); storage and ancillaries 58.9 kWh/tonne (9.5 percent); and waste treatment 5.6 kWh/tonne (0.9 percent). The final yield was 0.66 tonne, and so these figures can be adjusted proportionally to relate energy inputs to final product weight.

In most fish canneries, offal from preparatory processes is available for by-products, including canned and frozen pet food, minced frozen fish, and fish silage for animal feeding and fishmeal. 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 by-product output.

4.4 Fish reduction processes

In 2012, some 21.7 million tonnes of fish was used for non-food purposes, about 75 percent of which (16.3 million tonnes) was reduced to fishmeal and fish oil (FAO, 2014). For commercially traded product, 2008 data from the International Fishmeal and Fish Oil Organisation (Jackson, 2011) suggest the use of 16.48 million tonnes of whole fish, plus 5.49 million tonnes of fish process waste, producing 4.94 million tonnes of fishmeal (22.5 percent overall yield), worth some USD5.5 billion, and 1.03 million tonnes of fish oil (4.7 percent yield) worth about USD1.2 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. Fishmeal and fish oil are two of the most internationally traded commodities, and it is estimated that each tonne of fishmeal / fish oil travels an average of 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 fishmeal and fish oil

Year	**Global production (%aquaculture use)**	
	Fishmeal	**Fish oil**
2005	5 877 (45–52)	959 (57–84)
2010	6 000 (41–55)	950 (56–87)
2012	6 000 (43–60)	950 (70–88)

Source: Jackson (2006) and Tacon (2006) – higher percentage uses from the International Fishmeal and Fish Oil Organisation, lower values from FAO.

A certain part of global production is used in national or regional markets, either from specialized 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 percent of raw material input. In the United States of America, menhaden is the major fishmeal stock, while in the Northeast Atlantic major industrial fisheries for sand eel, capelin pout and blue whiting are supplemented by lower-grade and/or surplus catches of pelagics such as herring and mackerel. In 2004, Peru accounted for some 30 percent of global fishmeal production and about 45 percent of global trade volume, from some 130 plants with a total capacity of about 9 000 tonnes of raw material per hour. About one-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 about 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 United States of America, 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 fishmeal in Norway has been reduced by 21 percent 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 fishmeal

Process	**Energy (kWh/tonne)**	**Waste (kg/tonne)**	**Output (kg/tonne)**
Unloading	3	0	1 000
Cooking	~90	0	1 000
Straining and pressing		750 stick water	150 oil 100 press cake
Drying	~340	520 vapour	480 Fishmeal
Average	~400		

Source: UNEP Danish Environmental Protection Agency (1999).

Table 49
Energy consumption in fish feed production

Nutreco plants by activity in 2007	**GJ/tonne production**
Nutreco corporate & research[1]	11.72
Fish feed	
Skretting Northern Europe (Norway, United Kingdom, 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 (kWh/kg)	0.49 (0.14)

[1] Includes pilot-scale plants for production of fish feed, compound feed.

The metabolizable energy (ME) value of fishmeal usually ranges from 2 500 to 3 200 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 percent. Without these, also heat generation in storage needs to be carefully controlled.

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 summarizes 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 5 159 kWh/tonne, of which catch of fish feed raw materials accounted for 30.1 percent (1 552 kWh/tonne), production of fishmeal 62.2 percent, (3 210 kWh/tonne), import of fishmeal 2.9 percent (148 kWh/tonne), and production of feed pellets at 4.8 percent (249 kW h/tonne).

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. 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
MJ consumed	1 507.9	162.5	123.9	1 486.9	347.9	165.6	4.9	281.2	4 080.9
Percentage 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

Low-value fish and drying for other uses

In many countries, low-value fish are used directly for feeding to aquaculture stock, usually minced and mixed with other ingredients. The quantities involved are difficult to estimate, although known to be substantial in some areas – e.g. in Southeast Asia. It is not 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 1–4 kW. Based on simple food pellet machines with a capacity of 150–180 kg/h, energy use in production is about 0.02–0.03 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 indicate energy demands excluding initial collection and preparation, and final drying and packing, of typically 0.1 kWh/kg for 150 kg/h, declining to 0.066 kWh/kg for 2 000 kg/h.

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, in 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 fishmeal.

4.5 Multiple plant/process assessments

A number of reviews have been carried out across processing plants that 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, Kolbe and Wheeler (2001) reviewed energy use in ten plants in the northwest of the United States of America – 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 percent of annual sales, averaging 2.2 percent, from 1.7 percent of sales in the northwest to 2.6 percent in Alaska. Energy costs per tonne of finished product varied between USD13.2 and USD149.6, averaging USD72.6 for the 10 plants, USD105.6 in Alaska, and USD37.4 in the northwest. Refrigeration equipment operated primarily freezers, cold storage, chillers, and icemakers, and used 65–85 percent of the electricity in the processing plants. Recognizing the range of processes and the confidentiality of some process data, the wide ranges of energy cost per kilogram, from USD0.013 to USD0.15, and energy use from 0.45 to 2.71 kWh per kilogram (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 individually quick frozen (IQF) in raw or cooked form; *Pangasius* were skinned, filleted and block frozen or IQF. In the absence of detailed cost and sales data, energy use was calculated only on a product weight basis, related to tonnes or kilograms of oil equivalent. More than 41 000 tonnes of finished shrimp goods and nearly 155 000 tonnes of finished basa goods were produced with an annual total energy consumption of more than 17 800 tonnes of oil equivalent (TOE), with an approximate cost of USD10.19 million. Based on defined efficiency ranges (best 25 percent, middle 50 percent and lowest 75 percent), primary energy inputs per tonne ranged from 0.083 to 0.175 to 0.300 TOE/tonne, respectively, for shrimp processing, and from 0.065 to 0.076 and 0.083 TOE/tonne for fish processing. Based on an average of 10 kWh per kilogram of oil equivalent, these corresponded to 830, 1 750 and 3 000 kWh/tonne shrimp processed, and 650, 760 and 830 kWh/tonne fish processed. For shrimp processing, there was some connection between energy use and scale, falling from about 0.250 TOE/tonne at 2 500 tonnes/year to 0.100 TOE/tonne at 5 000 tonnes/year or more. However, there was no link between scale and energy use per employee.

Although there was little difference in technologies used, a wide range in energy use for different functions was observed, with, on average, freezing requiring 38 percent of total energy input, cold storage 16 percent, ice making 16 percent, water supply 3 percent, wastewater treatment 3 percent, cooking 5 percent, air conditioning 4 percent, and cooling water 3 percent. For fish processing units, freezing (45 percent), cold storage (12 percent) and ice making (11 percent) were also the most significant users of energy. Cooling water (2 percent), air conditioning (7 percent), lighting, hot water, water supply (3 percent each), wastewater (4 percent) and other uses (10 percent) accounted for the remainder. Unlike the shrimp units, energy use per labour input rose with the scale of production, from about 0.500 TOE/person at 10 000 tonnes/year to 1 500 TOE/person at 35 000 tonnes/year, 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. It typically uses 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 sanitizing. 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 that involve heating, such as the cooking of canned fish and fishmeal and fish 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 fish oil production, plus 32 litres of fuel oil (UNEP/Danish Environmental Protection Agency, 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 freshwater become scarcer and as the true environmental costs of its supply are taken into consideration. Thus, water is 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 freshwater 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 fishmeal and fish oil production. Fishmeal and fish 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 the significant effects of canning, and fishmeal and fish 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 tonnes)	Energy consumed (kWh/tonne fish)	Energy consumed (GWh)	Cost at USD0.15/kWh (USD million)
Aquaculture				
Iced/fresh[1]	40	42[2]	1 680	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]	1 400	210.0
Portioned	20	70	1 400	210.0
Frozen[5]	20	78[7]	1 560	234.0
Canned[5]	13	250	3 250	487.5
Dried/cured[5]	12	545	6 540	981.0
Fishmeal / fish oil[5]	21	400	8 400	1 260.0
Total[8]	123		25 360	3 804.0

Note: Based primarily on COWI/UNEP energy data and FAO 2008 global totals.

[1] Excludes molluscs, assumes most raw material is iced.

[2] Based on 60 kWh/tonne ice, average ice:fish ratio 1:2, 60 percent is further processed at average 20 kWh/tonne

[3] Assumed 25 percent of initial input with higher level processing.

[4] 120 kWh/tonne freezing plus 20 kWh/tonne storage.

[5] Based on FAO 2008 product form data.

[6] 60 kWh/tonne ice, average 1:3 ice:fish ratio, 40 percent further processed at 20 kWh/tonne.

[7] 120 kWh/tonne freezing plus 20 kWh/tonne storage, 50 percent frozen at sea, 10 percent stored at sea – energy already accounted in vessel budgets.

[8] Total iced/fresh aquaculture and capture fisheries, dried/cured, fishmeal / fish 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 realized and the wider market options provided.
- Although 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, although these have a strongly positive effect on product quality and, hence, the economic value of the pre-harvest stocks.
- In this review, it has not been possible to quantify the amounts of fish frozen at sea, for which energy costs are usually included in fish catching energy totals, and this may result in double counting in some cases. The review assumes that 50 percent of frozen fish products are frozen at sea, with energy included in catching sector totals; with 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 fishmeal, fish feed or other foodstuffs).
- At artisanal levels, energy use varies widely, and with smoking, can reach significant levels per kilogram of product, with local energy supplies becoming key production and cost constraints. Although oil products are less used, energy equivalence in fuelwood can be highly critical. Overall, the use of ice in developing country fisheries is commonly less than in developed country fisheries, although 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 in order 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 North 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 specialized 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, and compliance with food safety standards and with traceability specifications, place additional demands on transport and distribution. At a less specialized level, and often with simpler products, internal and intraregional distribution in less wealthy markets is also an essential feature of the sector. However, 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 above, post-purchase energy use in storing, cooking and disposal also need to be considered in order 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 weight and distance (in tonne-km) of transport, although 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, although 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. Specialized format “unit load device” containers, typically of 3.4–9 m^3 in 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 (1 ft = 30.48 cm). Width and height are standardized 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), specialized 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:

- 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
- directly attached to the ship’s refrigeration system – traditionally water-cooled, but increasingly using ventilation, to reduce costs.

Table 52

Dimensions of transport containers

Container length and width	Height	Typical operating specifications		
		Internal volume	Tare weight (kg)	Payload kg
20 ft (6.06 m) × 8 ft (2.44 m)	8.5 ft (2.59 m)	28 m^3	1 800 to 2 400	22 000
	9.5 ft (2.89 m)	30 m^3		
40 ft (12.19 m) × 8 ft (2.44 m)	8.5 ft (2.59 m)	58 m^3	2 800 to 4 200	28 800
	9.5 ft (2.89 m)	66 m^3		

Source: Maersk Container Brochure, Maersk Shipping.

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, although there is a trade-off between insulation thickness, weight and internal volume. Hence, frozen transport – commonly from –20 °C to –40 °C is more energy-demanding than refrigerated transport, at 4 °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, in terms of both 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, e.g. printed bags, cardboard boxes, vacuum packs, tins, pouches;
- packing – in which these packaged products are held, e.g. 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, e.g. 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; and bulk/distribution cost issues, including costs of moving and storing prior to use. Table 53 summarizes key types and characteristics of common packaging options, and Table 54 provides typical energy costs of producing various packaging/container types, although 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, e.g. 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; possible disposal/reuse issues.
Jars, cans	Glass, tin or alloy-plated steel, some synthetic linings; sealed with cooked product; 100–500 g to 10 kg; 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, e.g. with single fish, fillets, steaks, smoked side, arrays of shellfish, prepared foods; usually overlaid with plastic film.	Various plastics with range of insulating properties; possible 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 multipacks, etc., for moisture protection and physical integrity; often also incorporating pallet bases.

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 Williams, 2011). There is a growing emphasis on systems that have low manufacturing energy requirements that can provide long shelf-life at ambient conditions, and can be disposed of easily and with minimal additional energy needs.

Table 54

Energy required to produce food packages

Package	kcal	kWh	Cost[1]
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

[1] At USD0.15/kWh.

Source: Pimentel and Pimentel, 1985

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, although 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 specialized 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 planning and foresight, and capital costs can be considerable. Although larger load volumes are generally more efficient, typically up to 40 tonnes 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 load factor of 100 percent, values range from 0.013 to 0.17 litres/tonne-km (0.14–1.83 kWh/tonne-km). This shows the significant effect of vehicle size, and the secondary effect of speed,

Table 55

Illustrative fuel costs of road transport

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

Source: Author’s compilation of industry data.

where greater cooling energy required over longer time periods is balanced by reduced fuel consumption for movement.

Assessing energy costs of fish transport in or from Norway, Anderson (2002) proposed energy-use targets for 2015 of 0.36 kWh/tonne-km for trucks operating at 60 percent load factor, and 0.06 kWh/tonne-km for rail transport, using cooled semi-trailers at 70 percent load factor. While significantly more efficient in fuel costs per tonne-km, rail transport is less used for distribution in the fisheries sector, although, traditionally, many major fishing ports and entrepôts 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, has tended to reinforce this. Nonetheless, often in smaller-scale form, rail transport remains an option, and where connecting links are accessible, it 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 22 tonne consignment (814 km + 10 686 km, respectively), taking 438 hours (1 149.3 kWh/tonne and 0.10 kWh/tonne–km), while truck and rail (226 km + 5 274 km) would require only 8 752 kWh, and take 166 hours (397.8 kWh/tonne and 0.072 kWh/tonne-km). This compared with 27 861 kWh (1 266.4 kWh/tonne) and 158 hours for truck and ferry transport. At an electric power equivalent cost of USD0.15/kWh, this would cost USD172.4, 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 / the United States of America from Frankfurt, Germany, to be 21 kWh/kg, together with 0.6 kWh/kg for trucking from Bergen, Norway, 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) was estimated at 9.6 kWh/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, although packing and other costs, such as the costs of insulated oxygenated tanks or bags (commonly used only once). However, in overall sectoral terms, 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, specialist vessels have been built or adapted specifically for fish carrying. In 2006, 533 fish carrier vessels were listed, 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 of these vessels (346) were less than 1 000 tonnes deadweight, with 100 between 1 000 and 10 000 tonnes, and only 8 slightly more than 10 000 tonnes, with a total registered tonnage of slightly more than 1 million tonnes. Larger vessels tend to be registered in Panama, Cyprus and the Russian Federations 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
Russian Federation	179	Republic of Korea	36
Panama	65	Ukraine	20
Japan	63	Cyprus	11
China	59	Global total	533

Source: Lloyd’s Register, 2006.

It is not clear how much of this capacity is currently in use, although 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 utilization level and the standby fuel costs while waiting for sufficient supplies. Lloyd’s database also details:

- Freezer trawlers for catching, processing, freezing and storage at –25 °C to –30 °C capacity of up to 800 tonnes.
- Refrigerated cargo vessels (reefers), with conventional fully refrigerated holds; capacity about 1 000–3 000 tonnes at –20 °C.
- General dry cargo vessels with several refrigerated compartments or holds totalling 500–2 000 tonnes (depending on vessel size), temperature controllable to –20 °C.
- General cargo container vessels able to accommodate up to about 400 × 20 tonnes insulated containers, each connected to cold air supply and return manifolds that 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 specialized carrier vessels have been built for the transport of live fish, particularly for fish seed for aquaculture (e.g. 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 – e.g. 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 63 000 tonne container vessel of 4 948 twenty-foot equivalent units (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 percent engine efficiency, energy consumption would be 0.015 kWh/tonne–km (Mackay, 2009; Maersk, 2008) with quote values of 0.014 and 0.018 kWh/tonne-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 of 2.7 kW per TEU, and estimated that in 2007 some 19 percent of sea transport energy was related to refrigeration. Total transport refrigeration energy amounted to 280 GWh, corresponding to 61 000 tonnes of fuel.

In reviewing energy use in exporting frozen Norwegian salmon to East Asia and the United States of America, Andersen (2002) assumed the use of 60 000 deadweight tonnage container vessels, carrying 7 500 tonnes frozen fish in containers of 300 × 25 tonnes. Fuel consumption of heavy oil was assumed at 150 tonnes 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 3.8 kWh/tonne for freezer plant, was 32.5 kWh/tonne fish transported. The average load factor to East Asia was 52.5 percent (80 percent outwards and 25 percent return). Based on average speed, and the time required per trip, energy use per delivered tonne, or energy per tonne-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 chilled/frozen food sector in the United Kingdom of Great Britain and Northern Ireland, one survey (James *et al.*, 2009) estimated some 800 000 retail displays across the country used a total of between 5 768 and 12 698 GWh per year, which at USD0.15/kWh, corresponds to between USD0.79 billion and USD1.90 billion annually. Catering fridges were estimated to account for 3 998–4 762 GWh/year, compared with refrigerated transport at 4 822 GWh/year, with much less significant demand from cold stores (900 GWh/year), blast chillers (250–600 GWh/year), blast freezing (218–415 GWh/year), dairy processing (250 GWh/year), milk cooling (99–315 GWh/year), potato storage (144–187 GWh/year) and meat carcass chilling (115–144 GWh/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 percent 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 fish 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 – United Kingdom

Component	Estimated energy GWh	Equivalent cost at USD0.15/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 retailing sector in United Kingdom of Great Britain and Northern Ireland (Tassou *et al.*, 2011), covering some 30 percent of retail food stores of 280 m^2 sales area and above, showed wide variability in energy consumption, from 700 to 2 000 kWh/m^2 sales area for hypermarkets and small outlets, respectively. Refrigeration accounted for 30–60 percent of energy use, and lighting 15–25 percent. No immediate data are 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. Few data have 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 percent of total food energy use in refrigeration and food preparation in households in the United States of America, for an average of 5 320 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 1 477 kWh, 63.5 percent 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, Davis and Ziegler (2010), consumers' home transport can be very energy inefficient, for example, using vehicles weighing more than 800 kg 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 percent of shopping trips were made using cars, about 50 percent of which were for the sole purpose of food shopping. In a more detailed assessment of consumption in the United Kingdom of Great Britain and Northern Ireland, 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 km by bus and 4.49 km by walking and cycling. Total cost per week for food transport was about USD1.50/household.

The use of energy in the seafood-related parts of the food service sector (i.e. 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 United States of America, total energy use in commercial foodservice and food retail sectors accounted for less than 1 percent of total domestic energy consumption, with food service using some 349 000 TJ in 1995, accounting for some 6.2 percent of total commercial building energy consumption; the most significant uses of energy being for cooking (31.7 percent) and refrigeration (13 percent) of food, water heating (11.2 percent) together with staff and customer provision of heating, cooling and ventilation (22.7 percent) and lighting (15.1 percent). The foodservice industry spent more than USD4.8 billion on major fuels (electricity, natural gas, fuel oil, and district heat) in 1995, costing an average of 4.5 percent 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 percent of global food supply, significant parts of which could be reduced relatively simply. In households the United Kingdom of Great Britain and Northern Ireland, Ventour (2008) noted large differences between product groups, with 45 percent of purchased salad greens being wasted, 31 percent of bread, 26 percent of fruits, with 13 percent waste levels for meat and seafood, and only 3 percent for dairy products. In energy terms, waste levels carry two major implications:

- Increased energy levels per kilogram, tonne or unit value of consumed product, with impacts at various points in the supply chain, e.g. 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 – e.g. biochemical oxygen demand in aquatic systems, landfill impacts.

Data on energy related to fish and aquatic product waste are as yet very limited. However, 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, become essential elements 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 processing 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.

Table 58 provides an overview of the overall distribution of fuel/energy costs in supply chains.

Analyzing the entire production chain from fisheries to fish consumption, most analyses confirm that the fishing phase accounts for the greatest share of total energy utilization through onboard fuel combustion during fishing in modern industrialized fisheries (see Thrane, 2004b, 2006; Ziegler and Hansson 2003, Ziegler and Valentinsson, 2007; Ziegler 2009). By contrast, the added value is often substantially greater than the cost of the primary imported material. Thus, Gudmundsson, Asche and Nielsen (2006), studying four different fisheries products and countries, found between 54 percent and 75 percent of value addition to be in the secondary processing, wholesale and retail sectors. They 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 percent, respectively. Removing the primary stage of processing reduced these values slightly to 66, 71 and 74 percent, 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).

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 CO_2 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 owing to reduced transport and greater potential for developing value from by-products. 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 food system in the United States of America, calculating per capita energy demands for fish products in 2002 as 305 000 BTU (89.5 kWh) per capita, with production, processing and wholesale/retail functions contributing the main energy demands (Table 59). These patterns were broadly similar to those for other food categories. Heller and Keoleian (2003), also assessing that country’s food system, estimated that 20.8 percent of total energy use related to agricultural production, 15.8 percent processing, 13.9 percent transport, 6.9 percent packaging, 6.9 percent food service, 4 percent retail and 31.7 percent home refrigeration and preparation.

Table 59

Energy use distribution, United States of America

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 (2004b) 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 MJ/kg to 941 MJ/kg (7.2–90.9 percent), use in processing from 1.5 to 15.1 percent, while that used in consumption ranged from 5.5 to 43.1 percent.

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: Based on weight of consumed product. Shrimp data are average of shrimp and prawn categories – very small differences in fishing energy only. Herring in jars, mackerel in cans.
Source: Developed from Thrane (2004).

In a major LCA review of food products in the United Kingdom of Great Britain and Northern Ireland, Foster *et al.* (2006) assessed energy use for the supply of cod fish fingers to households, estimating a total input of 24 MJ per 400 g pack, of which production accounted for 69 percent, primary and second stage processing 7 and 11 percent, respectively, retail 8 percent, and, in a “low energy” household, consumption 5 percent. 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 percent of the increased total of 33 MJ/pack. For a 400 g fresh/chill pack of salmon fillets, the same authors calculate a total input of 23 MJ, of which 89 percent is in production, less than 0.5 percent in processing, 4 percent in retail, and 7 percent 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 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 – e.g. 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 affecting local environments. Fish are likely to play their share in this, although 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 trade-offs between higher energy investment and reduction in waste. However, domestic and food service food waste, particularly for fishery products, is relatively little measured.
- There are 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. 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, although 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, owing to their lower levels of dependence and their more recent development, but had also been increasingly affected.

The first part of 2008 saw 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 have dropped, but this has also been accompanied by an economic downturn, with negative impacts on market confidence, purchasing power, and potentially on first sale prices for fish. Both conditions have re-emphasized 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 Sumaila *et al.*, 2006, 2008; World Bank and 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 (e.g. for agricultural fuel, fertilizers) 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 at maintaining otherwise poorly sustainable fishing activity.

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 to both 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, recognizing other trade-offs that may be involved (e.g. energy vs labour use in fishing or post-harvest; water exchange in aquaculture vs use of land; transport distance vs market access).
- At the specific level, the versatility or dependence of a fisheries sector element on specific fuel sources, and hence its practical options for change and the rate at which it 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 that have a more diverse range of options and can more easily switch between them.

Although some responses during previous periods of high fuel/energy prices can be useful in defining practical options at the enterprise or national level, the wider environment has changed substantially in recent years. 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 they 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 subsidizing 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; Wilson, 1999). The latest of these (Gulbrandsen, 2012) provides a clear practical guidance on fuel and energy saving in small fishing vessels, recognizing the common constraints faced by many owners and operators, with limits to significant capital investment, or major change in fishing targets or practice. This emphasizes 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) addressing fuel choice and propulsion options, and hull design, respectively. In India, the Central Institute of Fisheries Technology developed an energy-efficient design – the *Sagarkripa* is 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 a 17 percent saving in fuel cost (Infofish, 2007). Rihan, O'Reagan and Deakin (2010) describe the design concept of a green trawler, showing that savings of 30 percent or more on fuel consumption could be achieved with relatively modest length increases. Additional savings of 10–20 percent could be achieved by reducing the drag of hull appendages, e.g. better aligning bilge keels. They also suggest that, within the fisheries management regime of the European Union (Member Organization), 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 percent in energy demand when towing in rough weather. Friis *et al.* (2010a, 2010b) described a range of theoretical, model-scale and practical field trials in Newfoundland, Canada, to explore vessel-based energy reduction in local fleets of 10–20 m length range, with 250–660 installed horsepower, 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.

Pelaez *et al.* (2010) noted the potential for reduction of drag in fishing vessel transom sterns using flaps and interception devices. Collazo and Fernández (2010) noted the potential for improving common rudder designs. They suggested that for a 74 m tuna purse seiner, with a beam of 14.2 m and displacement of 4 200 tonnes, working for 5 000 h/year at an average velocity of 15.5 kn, annual fuel savings of at least 52 tonnes/year could be achieved (about 2.3 percent), paying back rudder change costs within about two years. The potential fuel saving advantages of using ducted propellers had also been noted (Haimov *et 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 (Fernández *et al.*, 2010) could potentially reduce energy use by some 15 percent. 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. Solla (2012) reported on the Shymgen system for optimizing propulsion and generator function, with estimated power reductions for trawling, setting and hauling with a 36 m trial vessel of 12.2, 7.4 and 16.7 percent, respectively. Over a one-year period, savings of 9.1 percent were made, which at EUR53 150[7] gave a payback of 1.2 years for the power control modifications made. Montenegro and Rodriguez (2010) described a more-complex prototype small-vessel energy system comprising hydrogen power, lithium batteries and a diesel generator set driving an electric motor for propulsion for potential application in the Galician fleet, but practical performance gains were yet to be described.

As noted above, 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. Regenatec (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. Although the shift to renewable sourcing might be welcome, if the net life-cycle energy gains were positive and there were no other undesirable implications (e.g. competition for food production in agriculture), costs are unlikely to be reduced (e.g. OECD/FAO, 2011). For small vessels in particular, the use of sails, even as an adjunct to motorized power, could yield significant energy savings, although issues of trip time, catch value and safety at sea would have to be satisfactorily addressed. More recently, Buglioni, Altosole and Figari (2010) compared marine diesel oil with LNG, 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 percent cost

---

[7] [7] Ex-change rate of 1 January 2013: 0.754 Eur 53 150 = USD 70 490.

reduction with variable pitch propellers, while dual-fuel LNG offered a 26 percent cost reduction. Although there were considerable extra costs for a replacement dual-fuel engine and extra fuel storage required for LNG – significant benefits were also noted in reduced CO_2 and nitrogen dioxide 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 the sea-cucumber fishery. Initial evidence suggested positive potential, with by-products of oilcake for animal feed, and an overall reduction of about 30 percent compared with local diesel costs. The fuel could be readily used in a range of local engine types, although 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.), utilization of the catch (direct human consumption or reduction to meal and oil), and the social and economic contexts that determine common practice, access to the resource and the financial resources available for carrying out fishing. More strategically, as discussed below, fisheries management will also affect choice of method. As noted above, fishing methods can be categorized with regard to fuel usage. Changing from a method using a high level of energy to one using lower level has been suggested as a primary response to conserve fuel and preserve profitability.

Suggested changes in 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 and design of the vessel and the machinery on board may limit the 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 gear types and passive gear types, fuel use during fishing is relatively small and so the focus here is on active demersal fishing gear types. It is estimated that measures to reduce the drag of fishing gear can reduce fuel consumption by 20–25 percent, without resulting in any decrease in the catch of the target species. According to Richard and Tait (2007), new designs of trawls can reduce engine power and fuel consumption by a factor of 33 percent. 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, owing to concerns about the recruitment or viability of other fish stocks, and about 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. The 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 (e.g. 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 percent. 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 otter boards to spread the gear, reduce drag and improve fuel utilization.
- 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 percent, readily taken up by 15 vessels, with estimated annual savings of EUR800 000. In the groundfish fleet of New England, the United States of America, Eayrs (2012) describes four initiatives, including development and use of large-mesh fine-diameter trawls, acoustic codend catch sensors to optimize 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 percent in fuel savings with no differences in catch levels or composition, up to 50 percent fuel savings with cod-end sensors, 12 percent savings with otter board redesign, and significantly less seabed impact. Sala, Buglioni and Lucchetti (2010) applied Danish high-lift otter board design to Mediterranean demersal trawl fishing, demonstrating up to 15–20 percent less fuel consumption and up to 40 percent more door spread, with a reduction from 0.41 to 0.33 kg fuel per 1 000 m^2 of 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 the traditional and the alternative doors, and the latter decreased total discards. Although 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 trawls compare with beam trawls, with up to 40–45 percent 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 EUR400 000).

Sterling and Eayrs (2010) describe potential modifications to Australian prawn trawl rigs, including: a five-net trawling system, improving swept area performance by 12 percent compared with 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 percent; and the concept of a double-tongue, square-mesh trawl. Gaston *et al.* (2012) noted the potential to reduce energy costs by some five percent in Australian prawn trawling using light-based bycatch reduction devices, attributing gains both to reduced codend drag and slightly greater yields of target species. Balash and Sterling (2012), comparing drag properties in modelled 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 generalized 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 percent across a range of fleets. The analytical and modelling technique is potentially applicable to any arrangement of hull, propulsion system and gear assembly.

Thomsen *et al.* (2010) assessed fuel and energy use in the Faroese fleet in 2006, noting a wide range of values of fuel use per 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 of 0.36 tonnes/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 litres/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 percent savings on fuel, and, by eliminating trawl doors, reduced fishing gear expenses by about 15 percent. Torring 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 percent through optimizing trawl and otter board designs and configurations, with potential returns of some 300 percent on the investments involved.

A very specific area of interest for energy reduction occurs in the wide range of light-attractant fisheries, e.g. in the Western Pacific. In Japan, major light-based fisheries include the stick-held lift-net for Pacific saury (*Cololabis saira*), purse seine for mackerel (*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 (25 m) typically consuming 287 kL of fuel annually, 58 percent for propulsion, and 37 percent for lights; offshore boats (40 m) using 431 kL, 27 percent for propulsion, 34 percent for lights and 22 percent for freezing; and open seas vessels (80 m) using 828 kL, with propulsion accounting for 32 percent, lights 23 percent, freezing 30 percent (based on 250–260 fishing days per year). However, although 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 light emitting diode (LED) 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 ultraviolet (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. The LED lights are also lighter and improve vessel stability. Katsuya *et al.* (2010) demonstrated a 47 percent reduction in light energy use in a typical squid-jigging system over a fishing season (69 kJ). Total consumption of energy including vessel movement was reduced by 30 percent, and although 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 optimize 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 Watanabe (2010) describe an effort pooling arrangement for pollack longline fishing. The share of fuel cost in total fishing costs for the 10–20 tonnes vessel category, the majority in this fishery, increased from 20.1 percent in 2004 to 22.8 percent in 2005, an additional JPY264 000 (USD2 700) in fuel cost for vessels making on average JPY4.6 million (USD46 000). Under pooling arrangements, fuel consumption and cost in 2007 decreased by 23.8 percent and 8.7 percent, respectively, for five-crew vessels, while fuel price increased by 22.6 percent. However, these conservation efforts were not without cost: profit decreased by 34.4 percent for five-crew vessels, with a 28.4 percent 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 120 litres/tonne with fishing method and potential for reallocating seasonal access to reduce total energy use. Driscoll, Boyd and Tyedmers (2010) carried out a similar review of Maine and Nova Scotia lobster fisheries in the United States of America, highlighting potential impacts of bait use, gear use per vessel and trip length.

Bastardie *et al.* (2010) demonstrated that by using a vessel monitoring system 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. However, these models did not extend to reallocation of effort among vessels, and in some cases, energy reduction choices would result in reduced landings and value, hence requiring more specific trade-offs, and better determination of marginal returns to fuel use. Palenzuela, Vilas and Spyrakos Dominguez (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 wind 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 authorized 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 (e.g. 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 the United Kingdom fishing fleet, considering fleet operations, gear type and fishing patterns. With fleet fuel costs then estimated at some USD160 million annually, a small percentage change could have a 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 the nearest port to the 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 minimize 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; and reducing steaming and towing speeds.

Abernethy *et al.* (2010) described the response of the small-scale fleet based in Cornwall, the United Kingdom of Great Britain and Northern Ireland, 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 four species and three catch sizes, there was no evidence that increased costs could be passed through to market price. Based on the 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 fuel savings of 10–30 percent (up to 45–60 percent in individual cases) based on gear development and other fishing options. Further profitability potential was also evident from fishing or market cooperation but was not reported. Energy audits in fleets or fleet sectors are also being adopted with potentially promising results (Eayrs, 2012; Basurko, Gabiña and Uriondo, 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 LCA 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.

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 hydrochlorofluorocarbon 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 described above, a large part of aquaculture-related energy consumption is related to feeds, and strategies to reduce their impact will 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 (e.g. in semi-intensive pond systems), optimizing fertilizer- 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, optimize feed quality, reduce production and handling waste.
- Improving distribution options to reduce transport and handling energy costs.
- Managing feeding systems and husbandry interactions to optimize food conversion levels and yields.
- 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 fishmeal and fish oil (see Tacon and Metian, 2008). However, based on an LCA analysis, Papatryphon *et al.* (2004) reviewed four feed strategies for Atlantic salmon production. They concluded that lower fish-based diets did not necessarily improve energy performance, particularly if additional processing was required to remove antinutritional 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 in embodied and direct energy costs, depending on the role of fertilization and feeding, and on the degree of water management and circulation. Colt and Cooper (2010) assessed energy budgets and global warming potential for three large-scale salmon netpen farming options in the North West Pacific, comparing inshore with offshore locations for a functional output of 2 500 tonnes annually. These demonstrated the significant role of feeds, the energy demand per kilogram of fish ranged from 18.1 to 19.3 MJ/kg fish, dominated by energy needed for feed, which ranged from 92 to 94 percent 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 percent. 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 in order 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 optimized equipment selection, Colt *et al.* (2010) assessed six options for salmon smolt production, based on an output of two million annually ranging from 42 TJ (flow-through with gravity supply), to 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, respectively.

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, in order 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 it 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 the northwest of the United States of America, Kelleher, Kolbe and Wheeler (2001) projected total energy cost savings from recommendations at USD1.4 million per year, averaging USD261 500 per year per plant in Alaska and USD19 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; and lighting efficiency. Annual savings associated with productivity recommendations totalled USD2.7 million, averaging USD419 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 one 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/Danish Environmental Protection Agency (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 programmes 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 optimize 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 that 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 percent, with further options being explored for fishing vessels.

Table 61

Performance targets for seafood processing, Thailand

Parameter	**Typical performance**	**Target**
Power consumption (kWh/tonne of fish)	22–279	36.7
Furnace oil grade B (litres/tonne of fish)	71–174	174
Water consumption (m^3/tonne of fish)	9–16	8.5
Yield (%)	40–53	41.9
BOD loading (kg/tonne of fish)	8–29	7.5

Source: Department of Industrial Works (2005). Industrial Sector codes of practice for pollution prevention (cleaner technology) for canned fish industry, ministry of Industry, Thailand.

In a review of energy use in the processing of channel catfish, Boyd, Polioudakis and Viriyatum (2010) describe a unit assessed in 2009 that used 4 682 GWh of electricity and 523 MBTU of natural gas to produce 8 277 tonnes of processed fish, from about 17 234 tonnes of live fish, shipping 7 358 tonnes of processed fish using its truck fleet. This used 863 533 litres of diesel fuel, of which 175 200 litres was used by the refrigeration units. It was also estimated that a further 50 386 litres of fuel was used for transporting process wastes to a rendering plant. While it was recognized 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 (e.g. natural gas), purchasing electricity produced from renewable sources, or cogeneration 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 underutilized materials. Products such as chitin can be recovered from shellfish wastes, and hydrolysed fish wastes can also be used for fishmeal or fertilizers. Assuming a broader perspective of energy transfers from ecological to economic systems, Ichien, Harte and Egna (2010) assessed 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 fish 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 re-engineering process plant are exemplified by the Enerfish project in Thailand, based on the Hiep Thanh Seafood processing unit using some 414 kWh per tonne of fish input, or 1 400 kWh per tonne 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 tonnes of process waste to produce 17 tonnes of fish oil, producing 13 tonnes 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 lower, biodiesel can be sold externally (Enerfish, 2008).

6.6 Mitigation in distribution systems

Hill, Courtney and Levermore (2010) note the potential for energy reduction in retail outlets, based primarily on experience in North America and in the United Kingdom of Great Britain and Northern Ireland, 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 400 kWh/m^2 of retail space from current averages of about double this level. Reviewing energy use and GHG emissions for retail food supply in the United States of America, Weber and Matthews (2008) note that, although food is transported long distances (average 1 640 km delivery and 6 760 km life-cycle supply chain), food-associated emissions are dominated by the production phase, contributing 83 percent of the average household’s food consumption footprint, with transportation contributing 11 percent and final delivery from producer to retail 4 percent. They also noted that, on average, red meat is about 150 percent 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 European Union (Member Organization), various initiatives are under way to improve environmental performance in the retail sector (see EU/JRC/IPTS, 2011), including: new designs; building modifications; improvements in heating, ventilation, and air conditioning; layout improvement and design/operation of key refrigerated units; and integrated heat/cooling systems. For example, fitting lids on cabinets, or vertical displays can reduce energy consumption by 40 percent. 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 to 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 information and communications technology (ICT) 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 be defined across the fisheries supply and value chain. A wide range of these have already been identified and a number have been demonstrated, although uptake may be variable without practical incentives.
- Mitigation responses can be defined at both strategic and operational levels. Apart from reducing net energy and fuel use, they 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 consumer options. However, it 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, although 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, although 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 makes 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, although energy use at the retail and consumption end of the supply chain is also potentially significant. 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, significant changes in energy efficiency are under way, driven by cost and competitive pressures. In many cases, these have specific relevance to the aquatic food sector. However, the extent of effects 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 utilization and reduced wastes, ensuring that quantities and the 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 that mitigation opportunities are related to operating scale, although 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 to 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 are limited in scope and detail across most sectors, sufficient data are 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 the greatest 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.

Although the aquaculture sector has the potential to complement capture fisheries supplies, and meet future increases in global demand, it also has a notable degree of energy dependence. This is 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. However, many forms of aquaculture can 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, although 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 affecting choices for distribution and final sales, whether through retail or food service outlets. A wider range of energy sources is usually accessible, although there may be wide geographic variations. For developing economy markets in particular, fuel access can be critical constraint. Although 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 utilization and reduction of wastes will all be critical in improving energy efficiency. Many of these, as in the food sector more widely, are already under way, 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. However, the energy associated with travelling to purchase, with food storage and with packaging use and disposal can be significant. Fresh fish consumption – with fish 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. Although 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 the trade of lower-value materials in meeting demands of poorer markets, e.g. 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. 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. Therefore, the need for effective mechanisms for responding to rising fuel and energy costs will be increasingly important.

Across the sector, key features can be highlighted and some aspects of fuel and energy use can be quantified. However, 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 to 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 trade-offs that 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 (Thrane, 2004a; Hospido and Tyedmers, 2005; Ziegler and Valentinsson, 2007; Parker, 2012). 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: the feed conversion ratio (Pelletier and Tyedmers, 2007; Roque d'Orbcastel, Blancheton and Aubin, 2009; Cao *et al.*, 2011); and the feed ingredient mix (Ellingsen and Aanondsen, 2006; Boissy *et al.*, 2011; Bosma, Thi Anh and Potting, 2011). However, results of analyses vary and will need 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 (Ellingsen and Aanondsen, 2006; Ayer and Tyedmers, 2009; Ziegler *et al.*, 2010), mainly for aquaculture production. However, the importance of energy sources in processing, storage and retail options may also be significant, and this has the potential to create substantial geographical variation in direct energy pricing and in potential GHG impacts. Here also, variations in fuel sourcing and pricing will have significant effects in terms of competition among national fleets, landing options and access to raw materials for onward value addition and potential food security.

Links with fuel and energy use and other thematic aims are also potentially significant, including: connections and trade-offs 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; and capacity building needs and potential. Specific connections can also be assessed across the wider range of environmental attributes (Mungkung, Udo de Haes and Clift [2005] exploring LCA in shrimp culture) – LCA environmental elements. They could also 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, it is likely that rising fuel and energy prices will create a range of changes across the fisheries sector at a global and cross-sectoral level. Fuel and energy supply and access will be among the most significant drivers of global economies and societies in the coming decades. Although 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 that 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 and provide effective investment environments.
- The need to connect and integrate with wider themes of development knowledge, local empowerment, vulnerability issues, and 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 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 (2012), 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 have been done in Europe or North America, and much more would be required to clarify regional and global characteristics.

- Regardless of location, better data are 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 the local or national levels (see Thrane, 2004a) 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 among multiple products or by-products. To date, capture fisheries LCA studies have commonly used mass-based allocation methods, while aquaculture and feed studies have used economic- or energy-based allocation. Across the sector, in some studies, multiple allocation methods have applied for different processes. As allocation methods can have a significant bearing on results (see Thrane, 2004b), 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 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, and varying sector dependence levels will justify wider explorations of interactions with policy, scenarios of response and consequences of change.
- Wider comparisons across the 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.

BIBLIOGRAPHY

Abernethy, K.E. & Kebede B. 2010. High fuel prices in temperate and tropical fisheries: Are the impacts the same? Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Abernethy, K.E., Trebilcock, P., Kebede, B.K., Allison, E.H. & Dulvey, N.K. 2010. Fuelling the decline in UK fishing communities. *ICES Journal of Marine Science*, 67(5): 1076–1085.

Ambler-Edwards, S., Mailey, K., Kiff, A., Lang, T., Lee, R., Simons, T., Marsden, D. & Tibbs, H. 2009. *Food futures; rethinking UK strategy*. London, Chatham House.

Andersen, O. 2002. Transport of fish from Norway: energy analysis using industrial ecology as the framework. *Journal of Cleaner Production*, 10: 581–588.

Andersen, O., Uusitalo, O., Suutari, U., Lehtinen, J., Ahlvik, P., Hjortsberg, H., Groven, K. & Brendehaug, E. 2001. *Energy saving in transport of goods – a pilot project in rural natural resource based industries*. Final report European Commission SAVE – project XVII/4.1031/Z/97-229. Vf-rapport 4/2001. Sogndal, Norway, Western Norway Research Institute.

Arason, S. 2003. The drying of fish and utilization of geothermal energy – the Icelandic experience. *GHC Bulletin*, pp. 27–33.

Asakereh, A., Asadalah, A., Rafiee, S. & Marzban, A. 2010. Energy consumption and greenhouse gases emission from canned fish production in Iran a case study: Khuzestan Province. *Research Journal of Applied Sciences, Engineering and Technology*, 2(5): 407–413.

Aubin, J., Papatryphon, E., van der Werf, H.M.G. & Chatzifotis, S. 2009. Assessment of environmental impact of carnivorous finfish production systems using life cycle assessment. *Journal of Cleaner Production*, 17(3): 354.

Aubin, J., Papatryphon, E., van der Werf, H.M.G., Petit, J. & Morvan, Y.M. 2006. Characterization of the environmental impacts of a turbot (*Scophthalmus maximus*) re-circulating production system using life cycle assessment. *Aquaculture*, 261: 1259–1268.

Ayer, N. & Tyedmers P. 2009. Assessing alternative aquaculture technologies: Life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner Production*, 17: 362–373.

Balash, C. & Sterling, D. 2012. Prawn trawl drag due to material properties. An investigation of the potential for drag reduction. *In: Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

Bankston, J.D. Jr & Baker, F.E. 1995. *Powering aquaculture equipment*. SRAC Publication No. 375. Southern Regional Aquaculture Center.

Bastardie, F., Nielsen, J.R., Andersen, B.S. & Eigaard, O.R. 2010. Effects of fishing effort allocation scenarios on energy efficiency and profitability: an individual-based model applied to Danish fisheries. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

Basurko, O.C., Gabiña, G. & Uriondo, Z. 2012. Energy audits of fishing vessels: lessons learned and the way forward. *In: Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

Béné, C., Macfadyen, G. & Allison, E.H. 2007. *Increasing the contribution of small-scale fisheries to poverty alleviation and food security*. FAO Fisheries Technical Paper No. 481. Rome, FAO. 125 pp. (also available at www.fao.org/docrep/009/a0965e/a0965e00.HTM).

Boissy, J., Aubin, J., Drissi, A., van der Werf, H.M.G., Bell, G. & Kaushik, S. 2011. Environmental impacts of plant-based salmonid diets at feed and farm scales. *Aquaculture*, 321: 61–70.

Bosma, R, Thi Anh, P. & Potting, J. 2011. Life cycle assessment of intensive striped catfish farming in the Mekong Delta for screening hotspots as input to environmental policy and research agenda. *Int. J. Life Cycle Assess.*, 6(9): 903–15.

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I. & Corner, R. 2010. Aquaculture: global status and trends. *Phil. Trans. R. Soc. B*, 365: 2897–2912.

Boyd, C.E., Polioudakis, E. & Viriyatum, R. 2010. Energy use and carbon dioxide emissions (“carbon footprint”) for Alabama catfish aquaculture. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Brandsson, T. & Benediktsson, S.M. 2010. Saving energy by improving electric power quality in catching and processing. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Buglioni, G., Altosole, M. & Figari, M. 2010. Fuel cost savings and pollution reduction by alternative propulsion technologies for Italian fisheries Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Bunting, S.W., Pretty, J. & Muir, J.F. 2009. *Carbon and energy consumption futures for fisheries and aquaculture.* UK, Interdisciplinary Centre for Environment and Society, University of Essex, and Institute of Aquaculture, University of Stirling.

Canning, P., Charles, A., Huang, S., Polenske, K.R. & Waters, A. 2010. *Energy use in the US food system*. ERR-94, USDA Economic Research Service, March 2010.

Carbon Trust. (undated). *Footprint measurement methodology* [online]. www.carbontrust.co.uk/NR/rdonlyres/6DEA1490-254B-434F-B2B2-21D93F0B0C98/0/Methodology_summary.pdf

Caslake, R. 2009. *Fishing vessel fuel emissions*. Edinburgh, UK, Seafish Industry Authority.

Cao, L., Diana, J.S., Keoleian, G.A. & Lai, Q. 2011. Life cycle assessment of Chinese shrimp farming systems targeted for export and domestic sales. *Environmental Science and Technology*, 45(15): 6531–6538.

Collazo, A.C. & Fernández, A. S. 2010. Flow adapted rudder geometry for energy efficiency improvement on fishing vessels. *In: Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Colt, J. 2010. Conceptual integrated closed confinement systems. *In* M.J.P. Chadwick, G.J. Parsons & B. Sayavong, eds. *Evaluation of closed containment technologies for saltwater salmon aquaculture,* Chapter 7. National Research Council Canada.

Colt, J. & Cooper, J. 2010. Comparison of near shore and offshore netpen culture of Atlantic salmon in the Pacific Northwest using LCA . Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Colt, J., Summerfelt, S., Pfeiffer, T., Fivelstad, S., & Rust, M. 2010. Energy and resource consumption of land-based Atlantic salmon smolt hatcheries in the Pacific Northwest (USA). Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Curtis, H., Brodie, C., Metz, S. & Obeng, L. 2009. *Assessing the economic impact on the UK fleet of the Cod Recovery Plan, West of Scotland Measures and the economic downturn*. Final report. Edinburgh, UK, Sea Fish Industry Authority.

Curtis, H.C., Graham, K. & Rossiter, T. 2006. *Options for improving fuel efficiency in the UK fishing fleet*. Seafish. 47 pp.

Davies, T. & Konisky, D.M. 2000. *Environmental implications of the foodservice and food retail industries*. Discussion Paper 00-11. Washington, DC, Resources for the future.

Driscoll, J. & Tyedmers, P. 2010. Fuel use and greenhouse gas emission implications of fisheries management: the case of the New England Atlantic herring fishery. *Marine Policy,* 34(3): 353–359.

Driscoll, J., Boyd, C. & Tyedmers, P. 2010. The hidden effects of management: A comparison of the Maine and southwest Nova Scotia (LFA 34) lobster fisheries using Life Cycle Assessment. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Eayrs, S. 2012. Saving fuel to increase profitability and reduce environmental impact in a U.S. ground fish fishery. *In: Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

Ellingsen, H. & Aanondsen, S. 2006. Environmental impacts of wild caught cod and farmed salmon—a comparison with chicken. *International Journal of LCA*, 11: 60.

Ellingsen, H., Olaussen, J.O. & Utne, I. B. 2009. Environmental analysis of the Norwegian fishery and aquaculture industry – a preliminary study focusing on farmed salmon. *Marine Policy*, 33: 478–488.

Emanuelsson, A., Flysjo, A., Thrane, M., Ndiaye, V., Eichelsheim, J.L. & Ziegler, F. 2010. Environmental comparison of Senegalese shrimp production in industrial and artisanal fisheries using life cycle assessment methodology, focusing on carbon footprint and biological impacts. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Enerfish. 2008. *Enerfish* [online]. www.enerfish.eu

Enerhaug, B. & Pedersen, R. 2010. The next generation stern trawler. *In: Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

European Commission. 2006. *The European Climate Change Programme* [online]. EU Action against Climate Change. http://ec.europa.eu/environment/climat/pdf/eu_climate_change_progr.pdf

European Commission. 2009. *EU emissions trading - an open system promoting global innovation* [online]. http://ec.europa.eu/environment/climat/pdf/brochures/ets_en.pdf

EU/JRC/IPTS. 2011. Pilot reference document on best environmental management practice in the retail trade sector. Draft June 2011.

FAO. 1993. *Marine fisheries and the Law of the Sea: a decade of change. Special chapter (revised) of The State of Food and Agriculture 1992*. FAO Fisheries Circular No. 853. Rome, FAO. 66 pp. (also available at www.fao.org/docrep/009/u9345e/u9345e00.htm).

FAO. 2009. *The State of World Fisheries and Aquaculture 2008.* Rome. 176 pp. (also available at www.fao.org/docrep/011/i0250e/i0250e00.htm).

FAO. 2011. *Code of Conduct for Responsible Fisheries.* Special edition. Rome. 91 pp. + CD–ROM. (also available at www.fao.org/docrep/013/i1900e/i1900e.pdf).

FAO. 2012. *Report of the Expert Workshop on Greenhouse Gas Emissions Strategies and Methods in Seafood. Rome, 23–25 January 2012*. FAO Fisheries and Aquaculture Report No. 1011. Rome. 117 pp. (also available at www.fao.org/docrep/017/i3062e/i3062e00.htm).

FAO. 2014. The State of World Fisheries and Aquaculture 2014. Rome 223 pp. (also available at www.faor.org / publications.

FAO & SIDA. 1986. Reducing the fuel cost of small fishing boats. Bay of Bengal Programme. Working paper. BOBP/WP/27. (also available at ftp://ftp.fao.org/docrep/fao/007/ad967e/ad967e00.pdf).

FAO/World Bank/Worldfish. 2008. The Big Number Project.

Fernández, A., Rodríguez, D., García, M., Iturralde, M. & Gandoy, J. 2010. Potential of hybrid systems with permanent magnet motors for propulsion improvement on surface longliners. *In: Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Fitzgerald, W.B., Howitt, O.J.A., Smith, I.J., & Hume, A. 2011. Energy use of integral refrigerated containers in maritime transportation. *Energy Policy*, 39(4): 1885–1896.

Folke, C. 1988. Energy economy of salmon aquaculture in the Baltic Sea. *Environ. Managt.*, 12(4): 525–537.

Foster, C., Green, K., Bleda, M., Dewick, P., Evans, B. & Flynn, A. 2006. *Environmental impacts of food production and consumption: a report to the Department for Environment, Food, and Rural Affairs*. UK, Defra, Manchester Business School.

Friis, D., Bass, D., Qiu, W., Knapp, C., McGrath, R., Lane, S. & Gardner, A. 2010a. An overview of fishing vessel energy efficiency work in Newfoundland and Labrador, Canada. *In: Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Friis, D., Bass, D., Qiu, W., Knapp, C., McGrath, R. & Lane, S. 2010b. An overview of past and current fishing vessel energy efficiency work in Newfoundland and Labrador, Canada. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Garnett, T. 2008. *Cooking up a storm. Food, greenhouse gas emissions and our changing climate.* Food Climate Research Network.

Gaston, T., Thomas, G., Maynard, D. & Frost, R. 2012. Energy efficiency through bycatch reduction – a radical approach. *In: Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

Grönroos, J., Seppälä, J., Silvenius, F. & Mäkinen, T. 2006. Life cycle assessment of Finnish cultivated trout. *Boreal. Env. Res*., 11: 401–414.

Gudmundsson, E., Asche, F. & Nielsen, M., 2006. *Revenue distribution through the seafood value chain.* FAO Fisheries Circular No. 1019. Rome, FAO. 42 pp. (also available at www.fao.org/docrep/009/a0564e/a0564e00.htm)

Guide to PAS 2005. 2010. *How to assess the carbon footprint of goods and services.* Carbon Trust / Department for Environment, Food and Rural Affairs / British Standards Institute.

Gulbrandsen, O. FAO 2012. *Fuel saving for small fishing vessels – a manual*. Rome, FAO. 57 pp. (also available at www.fao.org/docrep/017/i2461e/i2461e00.htm).

Haimov, H., Bobo, M.J., Vicario, J. & del Corral, J. 2010. Ducted propellers. a solution for better propulsion of ships. calculations and practice. *In: Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Heller, M.C. & Keoleian, G.A. 2003. Assessing the sustainability of the US food system: a life cycle perspective. *Agricultural Systems*, 76: 1007–1041.

Henriksson, P.J.G., Guinée, J.B., Kleijn, R. & de Snoo, G.R. 2011. Life cycle assessment of aquaculture systems—a review of methodologies. *Int. J. Life Cycle Assess.*

Hill, F., Courtney, R. & Levermore, G. 2010 *Towards a zero-energy store a scoping study (ZEST).* UK, Sustainable Consumption Institute, University of Manchester.

Hospido, A. & Tyedmers, P. 2005. Life cycle environmental impacts of Spanish tuna fisheries. *Fisheries Research*, 76: 174.

Hospido, A., Vazquez, M.E., Cuevas, A., Feijoo, G. & Moreira, M.T. 2006. Environmental assessment of canned tuna manufacture with a life-cycle perspective. *Resources, Conservation and Recycling*, 47: 56–72.

Hua, J. & Wu, Y. 2011. Implications of energy use for fishing fleet—Taiwan example. *Energy Policy*, 39: 2656–2668.

Ichien, S., Harte, M. & Egna, H. 2010. The energetic implications of fisheries processing waste and fishmeal/fuel by-products. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

IFC. 2010. *Energy efficiency in aquatic product processing sector in Vietnam*. IFC Advisory Services in East Asia and the Pacific.

Inada, H., Sato, K., Inoue, T., Mino, T., Sano, E. & Daida, N. 2010. LED application for eco-harmonic light fishing. In Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

Infofish. 2007. *Fishing Technology Digest for Asia-Pacific*, Issue 57 Jan-March 2007.

Iribarren, D., Moreira, M.T. & Feijoo, G. 2010a. Life cycle assessment of fresh and canned mussel processing and consumption in Galicia (NW Spain). *Resources, Conservation and Recycling*, 55: 106–117.

Iribarren, D., Moreira, M.T. & Feijoo, G. 2010b. Revisiting the life cycle assessment of mussels from a sectorial perspective. *Journal of Cleaner Production*, 18: 101–111.

Irribaren, D, Vázquez-Rowe, I., Hospido, A., Moreira, M.T. & Feijoo, G. 2010. *Estimation of the carbon footprint of the Galician fishing activity (NW Spain). Science of the Total Environment*, 408: 5284–5294.

Jackson, A. 2011. The future of fishmeal and fishoil in aquaculture diets [online]. Presentation to SEAT, University of Stirling. (available at http://seatglobal.eu/wp-content/uploads/2011/10/Stirling-Inst-Aqua-Sep-20111.pdf).

James, S.J. & James, C. 2010. *The food cold-chain and climate change.* Food Research International.

James, S.J., Swain, M.J., Brown, T., Evans, J.A., Tassou, S.A. & Ge, Y.T. 2009. Improving the energy efficiency of food refrigeration operations. Proceedings of the Institute of Refrigeration, Session 2008-09, 5-1-5-8.

Johnson, T. 2010. Operating Strategies and Vessel Maintenance – simple guidelines. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Katsuya, S., Hiroshi, I., Yumi, S., Hideaki, U., Satoshi, T., Eisaku, S. & Satoru, H. 2010. Trial operation of led fishing light for squid jigging. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

Kelleher, G., Kolbe, E. & Wheeler, G. 2001. *Improving energy use and productivity in West Coast and Alaskan seafood processing plants.* ORESU-T-01-004. U.S. Department of Energy's (USDOE) Industrial Assessment Center (IAC)1 Program. USA, Oregon State University.

Kitts, A. 2010. Measuring Total Fuel Use in Northeast U.S. Commercial Fisheries. NOAA Fisheries Service. Energy in Fisheries Symposium, Seattle 2010.

Kobliner. 1994. *Efficient Portfolios for Saving For College*. Consequences of the Worst Case. p. 120.

Komiyama, R. 2005. *Asia energy outlook to 2030: impacts of energy outlook in China and India on the world.* Institute of Energy Economics, Japan – EDMC.

Larsson, J., Folke, C. & Kautsky, N. 1994. Ecological limitations and appropriation of ecosystem support by shrimp farming in Colombia. *Environmental Management*, 18(5): 663–676.

Levin, J. 2010. The market for sustainable practices. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

Le Rey, J.-M., Prado, J. & Tietze, U. 1999. *Economic viability of marine fisheries: findings of a global study and an inter-regional workshop*. Fisheries Technical Paper No. 377. Rome, FAO. 130 pp.

Lorenzen, K. 2008. Understanding and managing enhancement fisheries systems. *Rev. Fish. Sci.*, 16: 10–23.

MacKay, D. 2009. *Sustainable Energy without Hot Air* [online]. www.inference.phy.cam.ac.uk/withouthotair.

Maersk. 2008. *Constant care for the environment*. Copenhagen, Maersk Line.

Martins, C.I.M., Eding, E.H., Verdegem, M.C.J., Heinsbroek, L.T.N., Schneider, O., Blancheton, J.P., Roque d'Orbcastel, E. & Verreth, J.A.J. 2010. New developments in recirculating aquaculture systems in Europe: a perspective on environmental sustainability. *Aquacultural Engineering,* 43: 83–93.

Mayorga, E. & Jones, D. 2010. Using IOOS to Increase efficiencies in offshore fisheries: the NANOOS Pacific NW experience. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

Montenegro, C. G. & Rodríguez, D. M. 2012. Application of Hybrid-Electric Power supply System in Fishing Vessels. *In*: *Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

Muir, J.F. 1995. Perspectives on aquaculture: aquaculture and food security. Study document commissioned by FAO. 224 pp.

Muir, J.F. 2005. Managing to harvest? Perspectives on the potential of aquaculture. *Philosophical Transactions of the Royal Society B,* 360: 191–218.

Mungkung, R. & Gheewala, S. 2007. Use of life cycle assessment (LCA) to compare the environmental impacts of aquaculture and agri-food products. *In*: D.M. Bartley, C. Brugère, D. Soto, P. Gerber &

B. Harvey, eds. *Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons.* FAO*/WFT Expert Workshop. 24-28 April 2006, Vancouver, Canada,* pp. 87–96. FAO Fisheries Proceedings No. 10. Rome, FAO. 241 pp. (also available at www.fao.org/docrep/010/a1445e/a1445e00.htm).

Mungkung, R., Udo de Haes, H.A. & Clift, R. 2005. Potentials and limitations of life cycle assessment in setting ecolabelling criteria: a case study of Thai shrimp aquaculture product. *Int. J. LCA,* (OnlineFirst): 1–6.

Myrseth, A. 1985. *Planning and engineering data. 2. Fish canning*. FAO Fisheries Circular No. 784. Rome, FAO. 77 pp. (also available at www.fao.org/docrep/003/r6918e/R6918E01.HTM).

New Zealand Ministry of Environment. 2006. *Energy efficient ways to improve the economic bottom line of your fishing business.*

Nguyen Phuoc Dan Visvanathan, C. & Kumar, S. 2010. *Cleaner production potentials in seafood processing industry: a case study from Ho Chi Minh City, Vietnam.*

North Sea Foundation. 2010. *The carbon footprint of fisheries*. Seas at Risk.

Notti, E. & Sala, A. 2012. On the opportunity of improving propulsion system efficiency for Italian fishing vessels. *In: Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

NRC/CIPEC. 2005. *Benchmarking energy use and costs in salt-and-dry fish processing and lobster processing.* Natural Resources Canada/Canadian Industry Program for Energy Conservation. ISBN 0-662-68762-0.

OECD/FAO. 2011. Biofuels. *In: OECD-FAO Agricultural Outlook 2011–2020.*

Olah, J. & Sinha, V.R.P. 1986. Energy cost in carp farming systems. *Aquacultura Hungarica (Szarvas),* V: 219–226.

Okos, M., Rao, M., Drecher, S., Roder, M, & Kozak, J. 1998. *A review of energy use in the food industry.* American Council for an Energy-efficient Economy.

Paige, E. 2010. Operating strategies to save fuel. Using AIS to Route Vessels for Optimum Efficiency. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

Palenzuela, J.M.T., Vilas, L.G. & Spyrakos Dominguez, E.L.R. 2010. Routing optimization using neural networks and oceanographic models from remote sensing data. *In*: *Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Papatryphon, E., Petit J., Kaushik, S.J. & van der Werf, H.M.G. 2004. Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). *Ambio*, 33(6)**.**

Parker, R. 2012. *Review of life cycle assessment research on products derived from fisheries and aquaculture*. Final Report. Edinburgh, UK, Sea Fish Industry Authority.

PAS 2050. 2008. *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.* Carbon Trust / DEFRA / British Standards Institute.

Peláez, G., Martín E., Lamas, A.M., Ulloa, A.F. & Prieto, D. 2010. Preliminary study of a new stern device to improve efficiency in a fishing vessel. *In*: *Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Pelletier, N. & Tyedmers, P. 2007. Feeding farmed salmon: is organic better? *Aquaculture*, 272: 399.

Pelletier, N. & Tyedmers, P. 2010. Life cycle assessment of frozen tilapia fillets from Indonesian lake-based and pond-based intensive aquaculture systems. *Journal of Industrial Ecology*, 14: 467–481.

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B. & Silverman, H. 2009. Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems. *Envir. Sci. Technol*., 43: 8730–8736.

Pimentel, D. & Pimentel, M. 1985. Energy use in food processing for nutrition and development. *The United Nations University Press Food and Nutrition Bulletin* 7(2).

Poseidon. 2011. Lifecycle analysis and greenhouse gas emissions methods in seafood production systems. Background paper for FAO Expert Workshop on GHG and LCA methodologies in the fisheries sector. Jan 23–26, 2012, FAO, Rome.

Pretty, J.N., Ball, A.S., Lang, T. & Morison, J.I.L. 2005. Farm costs and food miles: an assessment of the full cost of the UK weekly food basket. *Food Policy*, 30: 1–19.

Priour, D. 2012. Improvement of trawl efficiency using measurements at sea and numerical simulations. *In: Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

Regenatec. 2008. *Biofuels for the fishing industry: an investigation into the use of pure plant oil as a replacement for marine diesel.*

Richard, G. & Tait, D. 2007. *Shrimp* Twin Trawl Technology. DFO/5516. Cat. No. Fs 23-300/2-1997E. Canada, Minister of Public Works and Government Services.

Rihan, D., O'Regan, N. & Deakin, B. 2010. The development of a "green trawler". *In: First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Roque d'Orbcastel, E. 2009. GHG emissions in aquatic production systems and marine fisheries.

Roque d'Orbcastel, E., Blancheton, J. P. & Aubin, J. 2009. Towards environmental sustainable aquaculture: comparison between two trout farming systems using life cycle assessment. *Aquacultural Engineering*, 40: 113–119.

Sala, A., Buglioni, G. & Lucchetti, A. 2010. Fuel saving otterboards. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

Salz, P. 2006. Economic performance of EU fishing fleets and consequences of fuel price increase. Contribution to the Conference on Energy Efficiency in Fisheries, Brussels, May 11–12.

Schau, E.M., Ellingsen, H., Endal, A. & Aanondsen, S. A. 2009. Energy consumption in Norwegian fisheries. *Journal of Cleaner Production*, 17(3): 325–334.

Schorr, D.K. & Caddy, J.F. 2007. *Sustainability criteria for fisheries subsidies options for the WTO and beyond*. Prepared for the United Nations Environment Programme, Economics and Trade Branch, and World Wide Fund for Nature (WWF). Geneva, Switzerland.

Schuur, A.M. 2003. Evaluation of biosecurity applications for intensive shrimp farming. *Aquacultural Engineering*, 28(1–2): 3–20.

Seafish. 2006. *Options for improving fuel efficiency in the* UK Fishing Fleet. Edinburgh, UK.

Seafish. 2007. *Seafood strategic outlook*. Edition 4 - Winter 2007. Edinburgh, UK.

Seafish. 2007. *Consumer attitudes to sustainability.* Seafish Economics. Edinburgh, UK.

Seafish. 2008. *Seafish CO_2 emissions briefing paper*. Edinburgh, UK.

Seafish. 2008. *Economic survey of the UK fishing fleet*. Seafish Economics. Edinburgh, UK.

Seas at Risk. (undated). Reaction to the Green Paper on market-based instruments for environment and related policy purposes with special emphasis on fuel tax exemption for fisheries.

Seas at Risk. (undated). Turning the tide for low impact fisheries. Ways to improve the CFP reform proposal.

SINTEF Fisheries & Aquaculture. 2009. *Carbon footprint and energy use of Norwegian seafood products.*

Smith, A. 2008. Internal draft manuscript of report on energy for fisheries. FAO, Rome.

Solla, M. 2012. Shymgen system: optimizing the performance of shaft generator and drive train on fishing vessels. *In: Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

Standal, D. & Utne, I.B. 2007. Can cod farming affect cod fishing? A system evaluation of sustainability. *Marine Policy*, 31: 527.**Sterling, D. & Eayrs, S.** 2010. Trawl-gear innovations to improve the energy efficiency of Australian prawn trawling. *In*: *Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Sterling, D. & Goldsworthy, L. 2007. *Energy efficient fishing: a 2006 review. Part A - Alternative fuels and efficient engines.* Project 2005/239. Australian Government Fisheries Research and Development Corporation.

Sterling, D. & Klaka, K. 2007. *Energy efficient fishing: a 2006 review. Part B – Hull characteristics and efficiency*. Project 2005/239. Australian Government Fisheries Research and Development Corporation.

Sonesson, U., Davis, J. & Ziegler, F. 2010. *Food production and emissions of greenhouse gases*. An overview of the climate impact of different product groups SIK-Report No 802 2010.

Sonesson, U., Thrane, M., & Ziegler, F. 2009. Eco-labelling of wild-caught seafood products. *Journal of Cleaner Production*, 17: 416–423.

Stewart, J.A. 1995. *Assessing the sustainability of aquaculture development*. Dept of Management Science, University of Stirling, Stirling, UK. (PhD thesis)

Stuart, T. 2009. *Waste – uncovering the global food scandal.* London, Penguin Books.

Sturrock, H., Newton, R., Paffrath, S., Bostock, J., Muir, J., Young, J., Immink, A. & Dickson, M. 2008. Prospective analysis of the aquaculture sector in the EU. JRC/IPTS 2008. http://ftp.jrc.es/EURdoc/JRC45686.pdf

Sumaila, U.R., Teh, L., Watson, R., Tyedmers, P. & Pauly, D. 2006. Fuel subsidies to global fisheries: magnitude and impacts on resource sustainability. *In* U.R. Sumaila & D. Pauly, eds. *Catching more bait: a bottom-up re-estimation of global fisheries subsidies*, pp. 38–48. Fisheries Centre Research Reports 14(6). Vancouver, Canada, Fisheries Centre, University of British Columbia.

Sumaila, U.R., Teh, L., Watson, R., Tyedmers, P. & Pauly, D. 2008. Fuel price increase, subsidies, overcapacity, and resource sustainability. *ICES Journal of Marine Science*, 65: 832–840.

Taal, K. 2010. Cooperation in energy saving in the Dutch fisheries examples of initiatives of Dutch fishermen developing and sharing knowledge. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Taal, K. & Hoefnagel, E. 2010. Pulse trawl on flatfish as an alternative for beam trawl. The economic performance and the environmental impact of the innovative Pulse trawl in comparison to the conventional Beam trawl. *In: Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency. E-Fishing, Vigo, Spain, May 2010.*

Tacon, A.G.J. & Metian, M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. *Aquaculture*, 285: 146–158.

Takayama, G., Takahashi, K., Yamashita, H. & Tamaru, O. 2010. Details of energy use by Japanese squid jigging boats: attempts for fuel saving. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Tassou, S.A., Ge, Y., Hadawey, A. & Marriott, D. 2011. Energy consumption and conservation in food retailing. *Applied Thermal Engineering*, 31: 147–156.

Thomas, G., O'Doherty, D., Sterling, D. & Chin, C. 2009. Energy audit of fishing vessels. *Proc. IMechE.*, Vol. 224 Part M: J. Engineering for the Maritime Environment.

Thomsen, B., Zachariassen, K., Eliasen, M., Hansen, P. & Heinesen, S. 2010. Fuel optimisation in the Faroese fishing fleet. *In: Proceedings of the First International Symposium on Fishing Vessel Energy Efficiency*. E-Fishing, Vigo, Spain, May 2010.

Thrane, M. 2004a. *Environmental impacts from Danish fish product hot spots and environmental policies*. Department of Development and Planning Aalborg University, Denmark. (PhD thesis)

Thrane, M. 2004b. Energy consumption in the Danish fishery. Identification of key factors. *Journal of Industrial Ecology*, 8(1–2): 223–239.

Thrane, M. 2006. LCA of Danish fish products. New methods and insights. *International Journal of LCA*, 11(1):66–74.

Tietze, U., Prado, J., Le Rey, J.-M. & Lasch, R. 2001. *Techno-economic performance of marine capture fisheries*. FAO Fisheries Technical Paper No. 421. Rome, FAO. 79 pp. (also available at www.fao.org/docrep/004/Y2786E/y2786e00.htm#toc).

Tietze, U., Thiele, W., Thomsen, B. & Rihan, D. 2005. *Economic performance and fishing efficiency of marine capture fisheries*. FAO Fisheries Technical Paper No. 482. Rome, FAO. 68 pp. (also available at www.fao.org/docrep/008/y6982e/y6982e00.htm#Contents).

Torring, P. & Hansen, U.J. 2012. Best available technology makes drastic cuts in fuel expenses in trawl fisheries. *In: Proceedings of the Second International Symposium on Fishing Vessel Energy Efficiency E-Fishing, Vigo, Spain, May 2012.*

Troell, M., Tyedmers, P., Kautsky, N. & Rönnbäck, P. 2004. Aquaculture and energy use. *In* C. Cleveland, ed. *Encyclopedia of energy*, Vol. 1 pp. 297–108.

Tunsutapanich, S., Mungkung, R. & Gheewala, S.H. 2006. Energy Performance Evaluation of Aerators for Shrimp Farming. The 2nd Joint International Conference on "Sustainable Energy and Environment (SEE 2006)" 21-23 November 2006, Bangkok, Thailand.

Tyedmers, P. 2001. Energy consumed by North Atlantic fisheries. *In* D. Zeller, R. Watson & D. Pauly, eds. *Fisheries impacts on North Atlantic ecosystems: catch, effort and national/regional datasets*, pp. 12–34. Fisheries Centre Research Reports 9(3),

Tyedmers, P. 2004. Fisheries and energy use. *In:* C. Cleveland, ed. *Encyclopedia of energy*, Vol. 2 pp. 683–693.

Tyedmers, P., Watson, R. & Pauly, D. 2005. Fueling global fishing fleets. *Ambio*, 34: 8.

Tyedmers & Pelletier. 2007. *Review of life cycle assessment research on products derived from fisheries and aquaculture: a report for Seafish as part of the collective action to address greenhouse gas emissions in seafood.* Halifax, Canada, Robert Parker.

Uchida, H. & Watanabe, M. 2010. A managerial solution to reduce fuel cost for small-scale fisheries: case from walleye pollack fisheries in Japan. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective. November 14-17, 2010. Seattle, USA.

UNEP/Danish Environmental Protection Agency. 1999. *Cleaner* Production Assessment in Fish Processing. Denmark, COWI Consulting Engineers and Planners AS.

Utne, I.B. 2007. *Sustainable fishing fleet — a systems engineering approach.* Department of Production and Quality Engineering. Trondheim, Norway: Norwegian University of Science and Technology. (PhD thesis)

Van Marlen, B., ed. 2009. *Energy saving in fisheries.* (ESIF) FISH/2006/17 LOT3 – Final Report. Report number C002/08. IJmuiden, Netherlands, IMARES.

van Vugt, J. & van Marlen, B. 2010. The use of a generic energy systems model for fishing vessels. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Ventour, L. 2008. *The food we waste* [online]. Banbury, UK, WRAP. (available at www.wrap.org.uk/).

Walton, H. 2010. Towards a strategy for sustainable energy and marine resources in Pacific Island rural coastal Communities. Preliminary findings in New Ireland Province, Papua New Guinea. Presentation Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

Watanabe, H. & Okubo, M. 1989. Energy input in marine fisheries of Japan. *Bull. Jap. Soc. Sci. Fish*., 53(9): 1525–1531.

Weber, C.L. & Matthews, H.S. 2008. Food-miles and the relative climate impacts of food choices in the United States. *Environ. Sci. Technol.*

Williams, K.S. 2011. Life cycle assessment of bulk packaging used to transport fish products: case study. *In* G.M. Hall, ed. *Fish processing: sustainability and new opportunities*. West Sussex, UK, Blackwell Publishing Ltd.

Wilson, J.D.K. 1999. *Fuel and financial savings for operators of small fishing vessels*. FAO Fisheries Technical Paper No. 383. Rome, FAO. 46 pp. (also available at www.fao.org/docrep/x0487e/x0487e00.htm#TopOfPage).

Winther, U., Ziegler, F., Skontorp Hognes, E., Emanuelsson, A., Sund, V. & Ellingsen, H. 2009. *Carbon footprint and energy use of Norwegian seafood products*. SINTEF Fishery and aquaculture Report December 2009. 89 pp.

Woods, J., Williams, A., Hughes, J.K., Black, M. & Murphy, R. 2010. Energy and the food system. *Phil. Trans. R. Soc. B*, 365: 2991–3006.

World Bank & FAO. 2008. *The 'sunken billions'. The economic justification for fisheries reform.*

WRI. 2011. *EIA energy price projections by policy* scenario (2014–2020).

WWF. 2006. *The impacts of the European emissions trading scheme on competitiveness and employment in Europe – a literature review.*

Zetterberg, L. 2009. *Proposals on sector crediting –towards a global carbon price?* [online]. http://unfccc2.metafusion. com/kongresse/090601_SB30_Bonn/downl/090604_Mistra_Zetterberg.pdf

Ziegler, F. 2009. *Fishing has larger climate impact than long-distance transports.* SIK annual report 2008: SIK document 183. Göteborg, Sweden, Swedish Institute for Food and Biotechnology. 15 pp.

Ziegler, F. & Hansson, P.A. 2003. Emissions from fuel combustion in Swedish cod fishery. *Journal of Cleaner Production*, 11: 303.

Ziegler, F. & Valentinsson, D. 2007. Environmental life cycle assessment of Norway lobster (*Nephrops norvegicus*) caught along the Swedish west coast by creels and conventional trawls—LCA methodology with case study. *International Journal of Life Cycle Assessment*, 13: 487.

Ziegler, F., Hognes, E.S., Emanuelsson, A., Winther, U., Ellingsen, H. & Sund, V. 2010. There is more to greenhouse gas emissions of fisheries than carbon dioxide from fuel combustion. Energy Use in Fisheries: Improving Efficiency and Technological Innovations from a Global Perspective November 14-17, 2010. Seattle, USA.

The Twenty-ninth Session of the Committee on Fisheries recommended that FAO provide Members with information on fishing industry contributions to climate change, and on ways to reduce the sector's reliance on, and consumption of, fossil fuels, respecting the principles embodied within the United Nations Framework Convention on Climate Change. In 2012, FAO convened an Expert Workshop on Greenhouse Gas Emissions Strategies and Methods in Seafood. It highlighted options for the use of tools and emphasized gaps in information and practice and the need for a basic level of common understanding and for more effective communication.

ISBN 978-92-5-108934-7 ISSN 2070-6065

9 789251 089347

I5092E/1/10.15