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GREEN GROWTH AND ENERGY USE IN FISHERIES AND AQUACULTURE

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NOTE BY THE SECRETARIAT

This document evaluates the determinants of energy use in fisheries. It is undertaken as part of the Committee for Fisheries' work on green growth in fisheries and aquaculture. Work on policy and energy use in fisheries and aquaculture will build on this document and is part of the 2013-14 Programme of Work of the Committee for Fisheries.

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EXECUTIVE SUMMARY

Energy use in capture fisheries comes mainly from use of fossil fuels to power fishing vessels. Fisheries worldwide are estimated to emit as much carbon dioxide as The Netherlands, and represent 1.2% of global oil consumption. At the same time, the cost of fuel for fishers is around 25% of all costs, and in many fisheries is the most important cost item for the fisher.

Understanding the nature of energy use in fisheries is an important first step in identifying how policies can improve energy efficiency in a way that does not distort markets and is compatible with the objectives of fisheries management in general. In particular, identifying cost-effective approaches to reducing energy consumption and the barriers that might prevent their uptake can help fishers reduce their costs while at the same time contributing to reducing greenhouse gas emissions.

There are three main determinants of energy use in fisheries.

1. The nature of the physical capital employed in fishing such as vessels and fishing gear.
2. The behaviour and strategies of fishers as they pursue their livelihood.
3. The incentives and constraints placed upon fishers by the management system and associated regulations.

A great deal of research attention has been paid to the first of these, improving the efficiency of vessels and gears. The literature reviewed in this document suggests that the potential improvements from changing behaviours and or management rules can be more important. Moreover, while improving vessel efficiency usually requires significant investment, either by fishers or the public, the costs associated with different behaviours or changes in the management system tend to be more modest. In fact, some techniques such as reduced steaming speed can be considerable money-savers. Improving the abundance of fish stocks through better management might be the most effective way to increase energy efficiency in fisheries where stocks are below the optimal level.

Saving energy in some cases can require trade-offs, such as with slower steaming speed which trades additional time for fuel savings. In other cases, such as improved stock status increasing the catch per unit effort, energy savings are part of an overall gain in efficiency.

Improving energy efficiency can support the objectives of a profitable, efficient fishery that contributes to mitigating climate change and reducing its environmental impact. The evidence suggests that this can be achieved in a way that helps fishers and supports broader fisheries management goals.

In the case of aquaculture and processed fish products, life-cycle assessments demonstrate that the majority of the energy used to produce the final product comes from the capture fisheries component of the production chain. For aquaculture, this is the feed input using wild fish. For processing, it is for the raw material used to produce fish products. In aquaculture, energy is used as a substitute for other inputs such as space (onshore vs. net-pen production) and environmental inputs (recirculating systems vs. open systems where effluent flows into the environment).

GREEN GROWTH AND ENERGY USE IN FISHERIES AND AQUACULTURE

Introduction

1. The purpose of this report is to examine energy use in fisheries and aquaculture from a green growth perspective. The OECD “Green Growth Strategy” represents a set of principles that aim to ensure that policies can best promote economic growth that is sustainable and matched to public objectives. In the case of energy use in fisheries, there are several reasons to believe that looking at policies through the perspective of Green Growth principles is important:

- Energy use is a strong proxy for the climate change impacts of the sector. Climate change is an important environmental externality that can have important and widespread long-term impacts. As such, many countries have objectives and policies in place to mitigate the risks of climate change. Good fisheries policies help the sector to contribute to climate change objectives.
- Energy, mainly in the form of diesel fuel, is a major component of the overall cost of fishing in many cases. Improved energy efficiency is one way to help improve the profitability of fisheries, which is an objective of fisheries policy in many OECD countries. Improved policy coherence can help improve efficiency while not compromising other objectives for the sector.
- Impediments can slow the adoption of new technologies or techniques that improve energy efficiency. Identifying and removing barriers that prevent cost-effective investments will improve efficiency and profitability.

2. Energy efficiency merits specific consideration primarily because of the first bullet point above. Carbon emissions are an externality to fishing (as well as other economic activities) and there is much interest in optimal ways to account for the environmental cost of carbon emissions. The second and third bullets indicate that energy efficiency is also of interest from a perspective of optimising profitability and productivity of resources. In this context, energy is an input in the production process like any other.

3. The scale of energy use and efficiency in the sector is an outcome of the conditions and options facing fishers and aquaculture producers. Operators are acting to maximise their profitability as best they can, so the current situation is economically optimal in the sense that there are not systematic and predictable errors being made on the part of individuals. Improving energy efficiency usually requires some investment, and some changes in behaviour. Some of these investments or changes increase profitability but are not undertaken because the benefits are uncertain, or costly to evaluate. In other cases they are not undertaken because the fisher does not internalise the external (social) costs of their energy use. In both cases, there is a role for policy to encourage improved energy efficiency.

4. The importance of policy coherence and a broad view of policy impacts are central principles of the OECD Green Growth strategy. Recognising that improvements in energy efficiency are possible and that reductions in climate change emissions will be necessary should not immediately lead the policy maker to conclude that policies should be put in place to maximise fuel efficiency. This is because it is important to maintain policy coherence with other objectives in the fishery that could be harmed by a single-minded focus on efficiency. Not only should improvements in fuel efficiency be compatible with profit-maximising behaviour, any improvements in efficiency should be the result of choices that maximise profits in efficient markets. Anything else is unlikely to be sustainable as a policy. In particular, subsidies and market interventions are by definition distortions of markets and imply deadweight losses and other costs that bring their long-term sustainability into question.

5. This report has the following objectives. It will review the literature on the relationship between energy use and other aspects of the fishery, including the management regime, technology, and the range of behavioural options available to the fisher. It will synthesise the results of this literature review in order to draw conclusions as to the likeliest path for improvement, taking into account the OECD Green Growth principles. It will set the stage for future analysis of the potential benefits available from different policy actions. While the document will have capture fisheries as a main focus, it will also evaluate energy use in aquaculture operations and from downstream in the marketing chain. The paper will conclude with recommendations for next steps for this work.

Assessing energy use in fisheries.

6. There exists a broad literature on the subject of energy use in fisheries, and more generally on the costs of fishing. There are many different ways to categorise this body of work. Energy efficiency can be considered on a fishery-specific basis, either by species or by gear type. It can be considered across countries, fleet types, or region. It can focus on the technical relationships between hull style, engine, propeller or other physical characteristics, or it can focus on the choice of the skipper regarding steaming speed or distance travelled to fishing grounds or to markets. Energy efficiency can be considered in terms of energy used per weight of fish caught or landed, or per value. The limitations imposed by the management regime can be studied, or the market forces at work, such as the price of fuel versus the price of fish.

7. Given the number of different angles at which one can approach this subject, there is no single best way to structure a discussion of the determinants of energy use. It is, however, useful to consider three main categories that divide along issues of technical efficiency, behaviour and the management system:

- **Technical efficiency** is the impact of investments in gear or vessel components that can increase fuel efficiency. That is, they increase fuel efficiency regardless of behaviour or management system. Some investments in efficiency may imply or require changes in vessel operation.
- **Behaviour** of the fisher or aquaculture producer describes the choices determining relative factor intensity between energy and other production inputs. Fishers can increase fuel efficiency by trading-off between time and other costs for example with respect to steaming time and other operational – on the fishing ground - choices.
- **The management system** sets the overall framework that is important in determining how energy is used by fishers. Not only can it shape decision-making, it can be decisive in technology and techniques of fishing through regulatory requirements. Most importantly, its effectiveness in maintaining a healthy stock status helps determine overall efficiency of fishing as measured by catch per unit effort (CPUE).

An Overview of Energy Use in Fisheries

8. The FAO (2006) estimates that capture fisheries consumed 41 million tons of fuel per year, costing USD 22 billion and corresponding to about 25% of the sector's revenue. Estimates of fuel costs over the past several years show an increasing share of costs of fuel over time (Table 1). OECD member country estimates of fuel costs are generally higher for mobile-gear fleets than for fixed-gear fleets, and higher for distant water fleets than for those that fish close to the coast (Table 2). For example, UK North Sea beam trawlers have fuel costs that can reach as much as 78% of all operating costs; while in some fixed-gear coastal fisheries fuel costs can reach a percentage as low as 3% to 5% of operating costs. While fuel costs are high as a share of total costs in fisheries, this does not imply that capture fisheries are inefficient relative to terrestrial food sources (Box 1).

Box 1. Fuel Consumption in fisheries vs. other food sources

Fisheries account for about 1.2% of global oil consumption and directly emit more than 130 million tonnes of CO₂ into the atmosphere. The energy content of the fuel burned by global fisheries is 12.5 times greater than the edible protein energy content of the resulting catch. While the fishing sector consumes a substantial amount of fuel, its use of energy is far more efficient than many other contemporary food production systems, a finding that flies in the face of some widely held perceptions of capture fisheries in general. This seeming incongruity between perception and reality may, in part, result from the relatively high proportion of total energy inputs, and resulting energy-related costs that accrue at the level of the fishing enterprise itself. In contrast, in the case of many other animal protein production systems, the majority of energy inputs tend to occur farther back in the production chain.

Source : Tyedmers *et al.* (2006)

9. Fuel use generally represents a higher share of costs in mobile-gear fleets. However, the “catch effectiveness” of fishing gear can make mobile gear more fuel-efficient per tonne landed than some fixed gears, e.g. Danish seine for mackerel vs. set nets for plaice. Higher value fish can be profitably targeted even when the required gear has higher fuel intensity - prawn is a good example of a high-value product with high fuel intensity.

Table 1. Fuel costs of developing and developed countries

as a percentage of revenue from fish landed

	1995-97	1999-2000	2002-03	2005
Developing Countries				
Active demersal	17.19	30.28	26.15	52.30
Active pelagic	17.33	17.60	16.99	33.98
Passive gear	18.78	17.06	19.33	38.66
Average	18.52	20.65	21.63	43.26
Developed Countries				
Active demersal	10.57	8.64	14.37	28.74
Active pelagic	n.a.	7.65	5.48	10.96
Passive gear	5.57	4.95	4.61	9.22
Average	11.08	9.78	10.20	20.40
Global Average	14.85	16.70	18.53	37.06

1 Estimate

Source: FAO

Table 2. Fuel costs as a proportion of operating costs in selected OECD countries

Country and fishery	Fuel costs as percentage of operating costs
Australia	
Torres Strait prawn	39
Commonwealth trawl sector	23
Eastern tuna and billfish	17
Gillnet, hook and trap sector	10
France	
Chalutiers de fond exclusifs (12-16m)	22
Chalutiers drageurs (12-16m)	16
Arts dormants (12-16m)	7
Iceland	
Pelagic trawlers / purse seiners	15
Trawlers	13
Freezer trawlers	15
Coastal vessels (<10m)	3
Norway	
Trawlers	19
Purse seiners (blue whiting)	15
Purse seiners (other)	12
Pelagic trawlers (herring, blue whiting)	20
Trawlers (cod)	20
Coastal vessels (<13m, cod)	5
Spain	
Mediterranean National waters/longliners	35.4
North Atlantic national waters/longliners)	30.5
North Atlantic No-National waters longliners	31.5
United Kingdom	
North Sea beam trawl (over 300 kW)	78
Area VIIA nephrops twin-rig trawl	38
Irish Sea demersal trawl	36
UK pelagic (over 40m)	25
UK pelagic (10-40m)	16
Potters and creelers (over 12m)	12

Source: Vieira and Hohen (2007), Vieira *et al.* (2007), Seafish Industry Authority (UK). Planchot and Daures (2008), STECF (2006).

10. In a study carried out in 1989, Watanabe and Okubo calculate the energy budget for several different fishing operations. This data is now quite old and likely unreliable as a measure of current fuel use. However, the distribution of energy in the fish production process remains interesting (Table 3). They demonstrate that direct fuel use by vessel operations strongly dominates the use of energy implicit in other inputs, representing 92% of the total for large trawlers.

Table 3. Estimated annual energy input per fisheries management unit for selected types in Japan

10⁹ kilocalories

	Large Pacific Trawl	Squid Angling	Tuna long- line	Salmon drift net
Energy input				
Fuel oil	20.20	1.63	9.92	0.40
Boat building and repair	0.50	0.04	0.22	0.03
Gear manufacturing and repair	0.94	0.05	0.24	0.07
Bait	0.00	0.00	0.99	0.00
Ice	0.19	0.00	0.00	0.00
Casing	0.12	0.03	0.00	0.00
Misc. goods.	0.13	0.02	0.00	0.01
Building and Facilities	0.03	0.00	0.00	0.00
Total	22.11	1.77	11.37	0.52
Ratio of direct energy to total	0.91	0.92	0.87	0.77

Source: Watanabe and Okubo (1989)

11. A majority of recent work to identify the fuel intensity of fishing appears to have taken place in Norway, though a number of other countries have been studied. The results indicate that, as expected, active forms of fishing are more fuel intensive and that there is a great variation in the fuel intensity across country and gears (Tables 4 and 5). It is likely that the differences between countries are driven by the nature of the fisheries in those countries, differences in fleet size and age of vessels (perhaps policy-driven) and difference in stock size with respect to MSY as well as the management system in place. It is possible that fuel tax concessions play a role as well. The age of each study can also be a factor. Newer studies will show the effects of improved fishing technology (which should reduce fuel use per amount landed) and perhaps worsening stock status (which has the opposite effect). In particular, the Watanabe and Okubo data is quite out of date relative to the other studies cited.

Table 4. Fuel use by gear type, selected countries

litres diesel per kg fish landed

Country	Gear	Fuel use	Source	Country	Gear	Fuel use	Source
Australia	Danish seine, 16m vessel	0.48	<i>Thomas et al (2010)</i>	Japan	Trawl-Mothership	0.01	<i>Watanabe and Okubo (1989)</i>
	Demersal trawl (prawn)	4.99			Trawl-Large Pacific	0.04	
Belgium	Beam Trawl 12-24m	3.10	<i>STECF (2008)</i>		Trawl-Large Southern Ocean	0.08	
	Beam Trawl 124-40m	3.50			Trawl-Large East China Sea	0.15	
Denmark	Demersal Trawl or Seine	0.20	<i>STECF (2008)</i>		Trawl-Shrimp	0.09	
	Polyvalent Passive Gear	0.30			Trawl-Medium offshore	0.09	
Faroe islands	Pair trawlers	0.36	<i>Thomsen et al. (2010)</i>		Trawl-Medium offshore Pair	0.12	
	Large Single Trawlers	0.78			Trawl-Small coastal	0.08	
	Large Longliners	0.24			Purse seine-one boat tuna	0.15	
	Small Single Trawlers	0.50			Purse seine-one boat sardine	0.02	
	Factory Trawlers	0.63			Purse seine-large two boat	0.01	
	Pelagic vessels	0.08			Purse seine-small one boat	0.01	
France	Demersal Trawl or Seine	1.90	<i>STECF (2008)</i>		Purse seine-small two boat	0.01	
	Polyvalent Passive Gear	3.40			Saury dip net	0.06	
Ireland	Demersal Trawl or Seine 12-24m	1.40	<i>STECF (2008)</i>	Salmon gill net	0.18		
	Demersal Trawl or Seine 24-40m	1.70		Seine net-beach	0.01		
	Pelagic Trawl or Seine 24-40m	0.20		Seine net-patch	0.05		
	Pelagic Trawl or Seine >40m	0.10		Seine net-boat	0.08		
Italy	Demersal Trawl or Seine 24-40m	4.40	<i>STECF (2008)</i>	Set net-salmon large	0.08		
	Polyvalent Passive Gear	1.70		Set net-small	0.07		
	Pelagic Trawl or Seine	0.30		Tuna Long Line-Distant	0.40		
	Beam trawl	3.20		Tuna Long Line-Offshore	0.20		
Malaysia				Tuna Long Line-coastal	0.14		
				Lines	0.19		
				traps	0.24		
				gillnets	0.23		
				purse seines	0.25		
Netherlands				trawls	0.40		
				Beam Trawl 12-24m	1.80		
				Beam Trawl 24-40m	4.60		
			Beam Trawl >40m	3.80			

Table 5. Fuel use by gear type, selected countries (continued)

litres diesel per kg fish landed

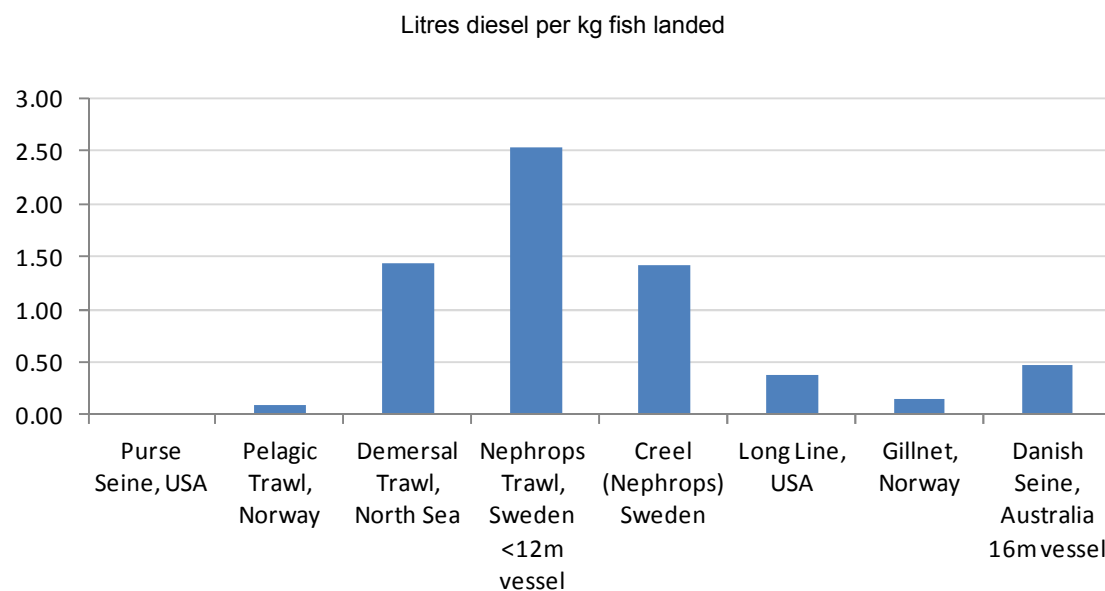
Country	Gear	Fuel use	Source	Country	Gear	Fuel use	Source	
Norway	Other long line	0.15	<i>Winther et al. (2009)</i>	Sweden	Gillnet	0.34	<i>Ziegler and Hansson (2003)</i>	
	long line (Autoline)	0.31			trawl	1.41		
	Bottom Trawl (Bunntral)	0.43						
	Trolling Line	0.14				Creel	2.20	<i>Ziegler and Valentinsson (2008)</i>
	Pelagic line	0.10						
	Pelagic trawl	0.10				Net, <12m	0.25	<i>Swedish Fisheries Agency (2007)</i>
	Pelagic pair trawl	0.09				Net, 12-24m	0.47	
	Hand line/jig	0.15				Cages and traps <12m	1.29	
	Gillnet	0.15				hook vessels	0.45	
	Purse Seine	0.09				nephrops (creel)	1.42	
	Danish Seine	0.12				nephrops (trawl) <12m	2.54	
	Undefined gillnet	0.25				nephrops (trawl) 12-24m	3.80	
	undefined seine	0.08				shrimp 12-24m	1.49	
						shrimp 24-40m	1.82	
	Bottom trawlers	0.63	<i>Eyjolfsdottir et al 2003</i>			demersal trawl <12m	0.87	
	Purse Seiners	0.08	<i>Tyedmers 2001 and 2004</i>			demersal trawl 12-24m	0.28	
	Long liners	0.03				demersal trawl 24-40m	0.41	
						Vendace <12m	0.26	
	Autolining	0.37	<i>Schau et al. (2009)</i>			Vendace 12-24m	0.24	
	Purse Seiners	0.11				Pelagic trawlers and seiners 12-24m	0.18	
	Shrimp trawling	1.25				Pelagic trawlers and seiners 24-40m	0.14	
	Bottom trawl	0.34				Pelagic trawlers and seiners >40m	0.13	
	Double trawl	1.21						
pelagic trawl	0.11			UK	Demersal Trawl or Seine 12-24m	1.00	<i>STECF (2008)</i>	
gillnet	0.23				Demersal Trawl or Seine 24-40m	1.10		
hand line and trolling line	0.18				Demersal Trawl or Seine >40m	1.40		
Danish seine	0.11				Pelagic Trawl or Seine >40m	0.20		
trap (crustaceans)	0.13				Beam trawl	2.50		
North Sea	Beam trawling	2.91	<i>Smith (2007)</i>	USA	Purse seine atlantic herring	0.02	<i>Driscoll and Tyedmers (2010)</i>	
	Bottom trawling	1.43			Midwater trawl	0.11		
	Shrimp trawling	1.41			Pair Trawl	0.12		
	Mid-water trawling	0.69			Average	0.09		
	Gillnetting	0.81						
	Danish pair seine	0.82			Gillnet	0.29-0.56	<i>Kitts, Schneider and Lent (2008)</i>	
	Danish Seine	0.20			Longline	0.38- 57		
					Otter Trawl	0.23-1.45		
				Pots/traps	0.92			
				Purse Seine	0.025			
				Mid-water pair trawl	0.49			
				Single mid-water trawl	0.1			
				Dredge	0.07-0.35			

12. Prawn trawling is the most energy intensive method studied, with demersal trawls also being relatively fuel intensive. (Figure 1 shows a selection of different gears from studies reported in Tables 4 and 5). Considering the high variation in fuel use by different gear types, Driscoll and Tyedmers (2010) observe: “*While such large differences in energy performance between gears within a fishery seem remarkable, it attests to the fact that fuel costs, while never trivial, have clearly not dominated decision-making amongst skippers and vessel owners.*” The relationship between fuel costs and profitability is not obvious, depending on other input costs, the price obtained for fish, and spatial dynamics of the fishery and “catchability”, i.e. how easy is it to catch the fish. Fuel subsidies lowering the price of energy below the market price faced by others (with or without taxes) may also play a role in sustaining fuel intensive techniques.

13. Not all gears or forms of fishing are appropriate for certain species. For example, prawn trawling is shown as particularly energy intensive, but in most cases there are few alternatives for targeting this species. For some species, there may be a number of gears that are both possible and profitable, and the choice of which to use will come down to the specifics of the fisher and fishery. Fisheries managers may

choose to influence that choice through various measures to improve energy efficiency (or indeed to meet other goals).

Figure 1. Fuel use by gear type, selected studies



Source: Winther *et al.* (2009), Thomas *et al.* (2010), Smith (2007), Swedish Fisheries Agency (2007), STECF, Kitts, Schneider and Lent (2008).

14. Taking a look at fuel efficiency of harvest by species rather than gear reinforces the view that fishers are willing to spend more on fuel when the value of the targeted species is high. Prawn and demersal flatfish consistently are seen to exhibit the highest fuel consumption per landed quantity (Table 6). In particular, pelagic species such as mackerel or herring tend to have relatively low intensities of fuel use (Figure 2). It is not inevitable that higher value fisheries are fuel intensive—in some cases it is possible to fish for high value species with low-energy techniques, one example being the pole and line Bluefin fishery

Table 6. Fuel use by species

Litres diesel per kg fish landed

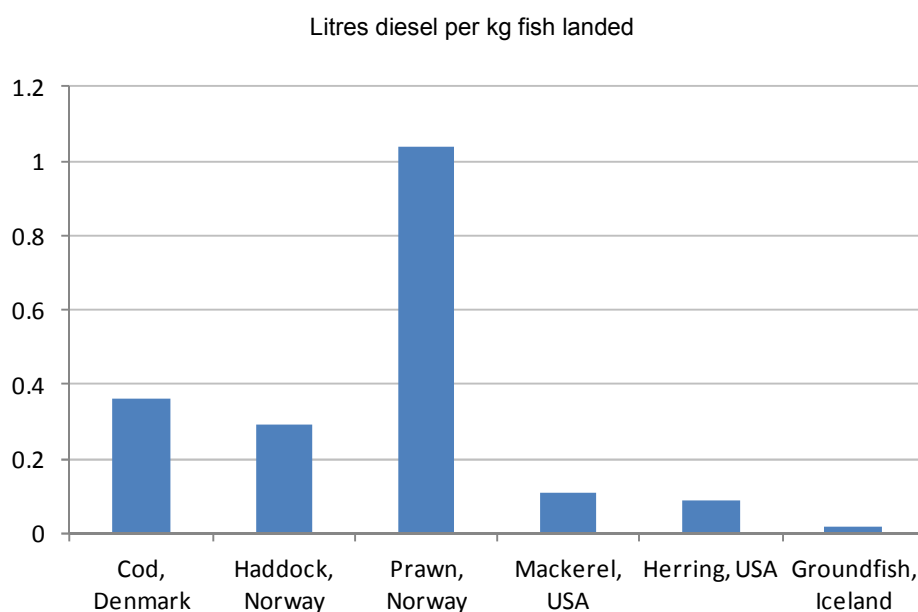
Country	Species	Fuel factor	Source	Country	Species	Fuel factor	Source
Denmark	Cod	0.36	<i>Thrane (2004)</i>	Norway	Cod	0.24	<i>Winther et al. (2009)</i>
	Flatfish	0.97			Haddock	0.29	
	Prawns	0.76			Saithe	0.29	
	Shrimp	1.03			Herring	0.09	
	Norway Lobster	6.05			Mackerel	0.09	
	Mussels	0.01					
	Herring	0.18			Cod	0.56	<i>Ellingsen and Aanonsen (2006)</i>
	Mackerel	0.06			pelagic for feed	0.08	
	Industrial Fish	0.06					
Iceland	Capelin	0.02	<i>Agustsson et al. (1978)</i>	Spain	Atlantic Tuna	0.53	<i>Hospido and Tyedmers (2005)</i>
	Groundfish	0.28	<i>Eyjolfsdottir et al. (2003)</i>		Indian Ocean Tuna	0.45	
					Pacific Tuna	0.63	
Cod	0.23	<i>Fulton (2010)</i>	Average all tuna		0.52		
Japan	Tuna	0.28	<i>Watanabe and Okubo (1989)</i>		horse mackerel (trawl)	0.60	<i>Vasques-Row et al. (2010)</i>
	Marlin	0.29			horse mackerel (purse seine)	0.21	
	Bonito	0.14		Sweden	Cod	1.01	<i>Ziegler and Hansson (2003)</i>
	Shark	0.22			Nephrops	7.32	<i>Ziegler and Valentinsson (2008)</i>
	Salmon	0.13		USA	Atlantic Herring	0.09	<i>Driscoll and Tyedmers (2010)</i>
	Pacific herring	0.10					
	Sardines	0.02			Alaskan Pollock (trawl)	0.04	<i>Fulton (2010)</i>
	Horse mackerel	0.02			Alaskan Pollock (catcher/processor)	0.10	
	mackerel	0.03			Alaskan Pink Salmon	0.06	
	pacific Saury	0.06					
	Flounder	0.08			Groundfish/Flat fish	0.94	<i>Kitts, Schneider and Lent (2008)</i>
	Pacific Cod	0.07			Groundfish/Round fish	0.73	
	Alaska pollock	0.06			Groundfish/Small mesh species	0.63	
	Crab	0.09			Summer Flounder	1.33	
	Squids and cuttlefish	0.16		Scup	0.58		
Shellfish	0.05		Black Sea Bass	1.12			
Norway	Cod	0.35	<i>Schau et al. (2009)</i>	Dogfish	0.36		
	Herring	0.09		Herring	0.09		
	Wolffish	0.34		Mackerel	0.11		
	Beaked redfish	0.48		Scallops	0.36		
	Blue Ling	0.32		Monkfish	0.57		
	Blue Whiting	0.09		Surf Clam/Ocean Quahog	0.07		
	Prawn	1.04		Squids	0.31		
	Dover Sole	2.45					
	Greenland Halibut	0.43					
	Haddock	0.4					
	Hake	0.29					
	Mackerel	0.09					
	Plaice	1.84					
Turbot	2.08						
Whiting	0.4						

15. Tyedmers (2001) conducts a similar review of energy use for capture of different species, using older data in many cases. The data indicates a trend toward lower energy efficiency over time, despite higher fuel prices:

“The energy intensity of a fishery can change dramatically over time as the abundance of fisheries resources change, fleets expand, the average size of vessels increase, vessels travel further to fish, and become more technologically advanced. For example, Brown and Lugo (1981) estimated that between 1967 and 1975, while the fuel consumed by the U.S. fishing fleet (excluding vessels under 5 GRT)

increased from 150 to 319 million gal/year, the catch did not increase accordingly. As a result, the fossil energy input to edible protein energy output ratio for the U.S. fleet increased from 8:1 to almost 14:1 over the same period. Similarly, Mitchell and Cleveland (1993) found that between 1968 and 1988, the fuel energy input to edible protein output ratio of the New Bedford, Massachusetts fleet rose from ~6:1 to over 36:1.” (Tyedmers, 2001).

Figure 2. Fuel use by species, selected studies



Source: Winther *et al.* (2009), Eyjolfssdottir *et al.* (2003), Schau *et al.* (2009), Kitts, Schneider and Lent (2008), Thrane (2004).

Technical Efficiency

16. Investments in improvements in the technical efficiency of fishing operations can yield benefits in terms of increased energy efficiency. Improving technical efficiency increases energy efficiency independently of behavioural choices or the incentives and requirements of the management system. It is worth returning to the point that this does not imply that all such investments are desirable - this depends on the return to such investments relative to other possible investments (in fisheries or elsewhere). From a policy perspective, the question is whether the policy environment may be altered to render such investments more attractive without compromising other policy objectives, including importantly the green growth principles of market-orientation and trade openness.¹

17. Leaving aside the optimality of any particular investment in efficiency, this section will discuss some of the technical changes available to fishers to reduce the energy intensity of fishing operations. The range of possible improvements is large, but not all claimed improvements have been proven in practice. There are a number of modifications that are the subject of current research and development, and many of the products in the marketplace are associated with claims that cannot be independently confirmed.

1. This thread runs through this entire document; identifying a possible measure to increase energy efficiency is not sufficient to justify implementing that measure. Ultimately, investments need to be profitable for the fisher. The role of public infrastructure and policy in determining whether such investments are profitable is more relevant for the policy maker. For example, fuel tax concessions might contribute in certain cases to postpone the decision to invest in a technology leading to energy savings.

18. Potential areas for improvement are in hull design, propulsion systems, power-plants and engines, non-fishing power demand (mainly refrigeration), and gear modifications. The potential for improving fuel efficiency depends on the physics of energy (mainly diesel fuel) transformation into useful work (Box 2).

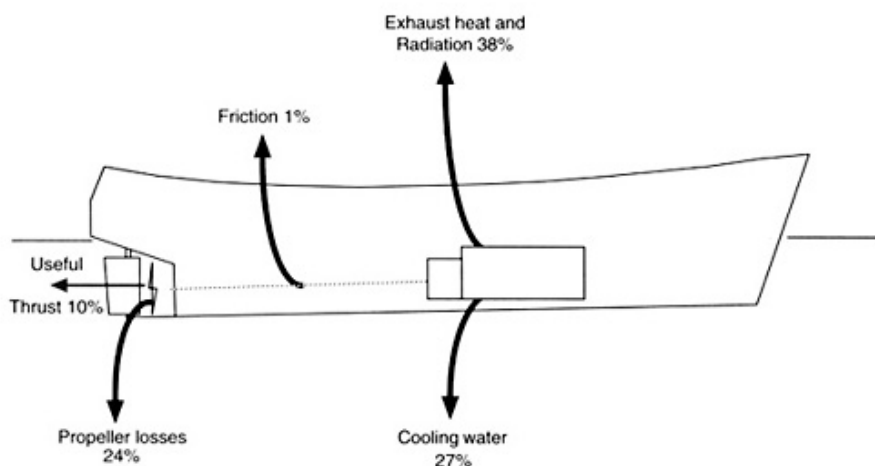
Box 2. Sources of Inefficiency

In addressing the problem of energy efficiency it is useful to understand just where the energy is expended in a fishing vessel and what aspects of this can be influenced by the operator, boat builder or mechanic.

In a small slow-speed vessel, the approximate distribution of energy created from the burning of fuel is shown in the figure below. Only about *one-third* of the energy generated by the engine reaches the propeller and, in the case of a small trawler, only one-third of this is actually spent on useful work such as pulling the net.

In a vessel that does not pull a net or dredge, of the energy that reaches the propeller:

- 35% is used to turn the propeller;
- 27% to overcome wave resistance;
- 18% to overcome skin friction;
- 17% to overcome resistance from the wake and propeller wash against the hull; and
- 3% to overcome air resistance.



Source : Wilson (1999)

19. The Institute for Marine Resources and Ecosystem Studies produced a report for the European Commission (IMARES 2006) that considers a number of different technology adaptations. This research covers independent work carried out in study countries as well as research comprising vessel case studies and simulation analysis (for larger modifications such as hull optimisation). They find that the benefits of different technological adaptations vary by vessel type and location such that generalised conclusions are

hard to reach. It is clear that there are a number of technologies available and more under development that have the potential to reduce energy costs and increase profits.

20. The IMARES study does identify some adaptations that are more likely to be feasible (Table 7). The authors estimate that the extent of feasible improvements in energy efficiency by technical or operational improvements for a fishing vessel ranges from between 5% and 30%. They note that the investment decision in improvements is very sensitive to the price of fuel, which is itself quite volatile. This volatility may delay investment decisions that may be profitable at a given moment but would be undesirable at lower fuel prices.

21. Many of the improvements cited in the literature refer not to overall fuel efficiency, but only to the efficiency gain for the particular system under investigation². The role of that system in overall efficiency has to be considered to determine the potential net gain (see Figure 14 for an example of this calculation). Bjorshol (2007) cites research demonstrating gains from using two ducted propellers instead of one. He also points out the potential from recovering the 60% of energy in diesel fuel that is lost as waste heat, either to supply on-vessel heating requirements or to generate electricity. Van Balsfoort, and Grandidier (2006) describe the efficiency gains and other benefits of the “pulse beam” modification to beam trawlers in The Netherlands. This design, which uses a hydrodynamic beam and replaces beater chains with electrical stimulation, also claims to reduce damage to the sea floor.

22. Sterling and Klaka (2007) identify a number of factors that increase resistance and reduce efficiency, including inefficiently designed rudders, poor trim, and hull appendages such as transducers or cooling ports. They suggest a number of improvements that could be retrofitted to existing vessels.

23. In most fisheries, towing gear represents the largest share of energy use. This mode of activity has the highest energy consumption and also usually the largest share of total operational time. However, in squid jigging operations, more than half of energy consumption is via lighting systems to attract squid. The potential energy savings by replacing a portion of the conventional metal halide lights with low-consumption LED versions can be up to 24% (Matsushita *et al.* 2012).

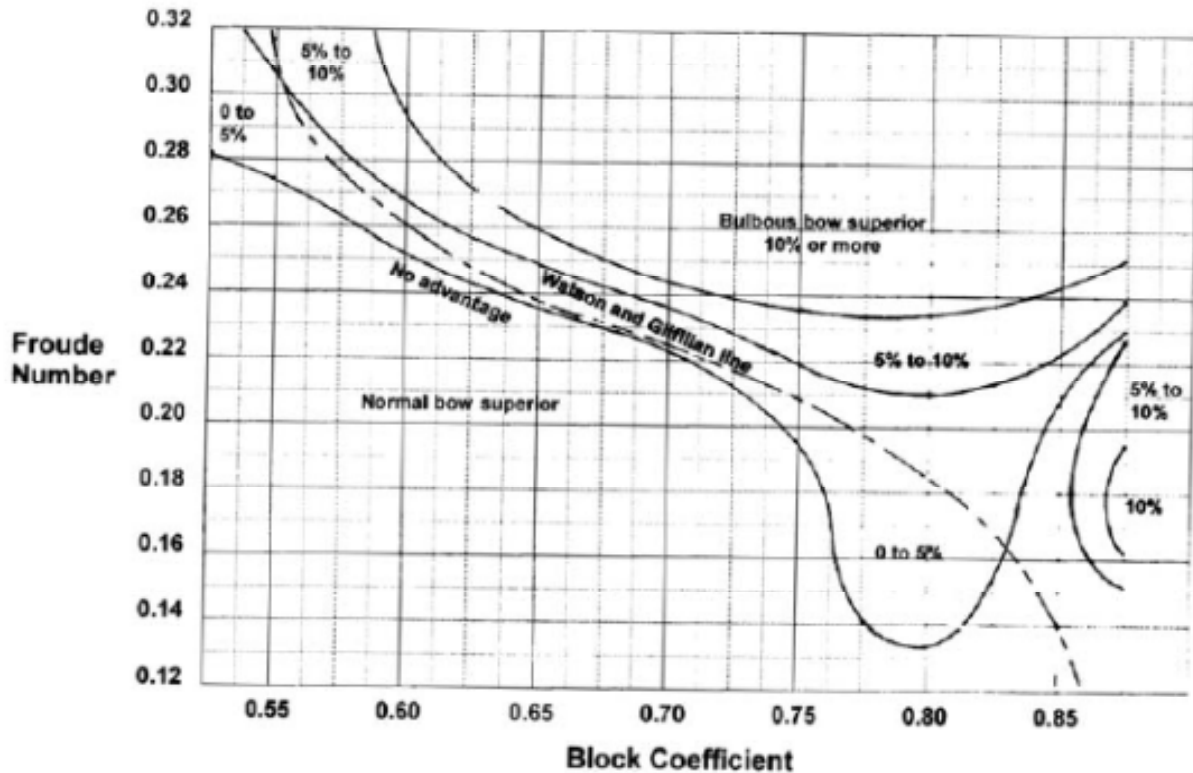
2. For example, an improvement in the efficiency of the vessel propeller of 20% does not mean the overall fuel efficiency of the vessel has improved by 20%. If the propeller losses amount to 24% of the total energy used while steaming, a 20% improvement in propeller efficiency leads to a 4.8% improvement in overall vessel efficiency.

Table 7. Technical improvements to energy efficiency

Modification	Potential improvement <i>percent</i>	Comments	Source
Vessel Design			
Optimised Hull Shape	22	Total fuel saving based on simulation with respect to IT 606hp boat	IMARES (2006)
Bulbous Bow	6	Total fuel saving based on simulation of IT 606hp boat	IMARES (2006)
Additional Wind Power	20	Total fuel saving based on vendor estimate BE 1300hp vessel	IMARES (2006)
Reduced Hull protrusions	20	Change in total hull drag for all components	Sterling and Klaka (2007)
Bulbous bow	10	Reduction in hull resistance	Thomas et. al (2010)
Aerofoil rudder	4	Compared with flat rudder	Sterling and Klaka (2007)
Propulsion System			
Larger Propeller Diameter	4-15	Total fuel saving based on IT 606 and NL 2000hp vessels	IMARES (2006)
Fitting a Nozzle	18	Total fuel saving based on IRL 2000hp vessel	IMARES (2006)
Optimising Bollard Pull	1.5-4	Total fuel saving based on IRL cases	IMARES (2006)
Replacing fixed pitch with controll	4.5	Total fuel saving based on IT 606hp vessel	IMARES (2006)
Ducted propeller	20	For trawler	Wilson (1999)
Dual ducted propeller	20	With respect to single ducted propeller	Bjorshol, Nils Harald (2007)
Gear Design and Replacement			
Modified design and optimised components	5-25	Total fuel saving based on IRL 2000hp vessel	IMARES (2006)
Gear Replacement	15-50	Highest investment for IRL 700hp; highest saving for BE 1300hp	IMARES (2006)
Dynex Warps	5-15	Based on IRL cases	IMARES (2006)
Trawl lights	5	Change in total fuel efficiency due to bycatch reduction	Gaston et. al. (2012)
Hydrodynamic pulse beam	40	Improvement in total fuel efficiency over traditional beam trawl	Van Balsfoort and Grandidier (2006)
Power Systems			
Replacing Auxillary engines	15	Total fuel saving based on IRL 1000hp vessel	IMARES (2006)
Improved fuel quality	0.75	Total fuel saving based on UK 653hp vessel	IMARES (2006)
Switch to heavy fuel oil	6.7	Total fuel saving based on IRL	IMARES (2006)
Fitting a fuel meter	6.5-11	Total fuel saving based on Irish 606hp vessel	IMARES (2006)
Engine after-cooling	10	With respect to non-after-cooled motors. Improvement is with respect to fuel consumption per power output	Ziegler and Hansson (2003)
Waste heat capture	13	for heating or electrical production	Bjorshol, Nils Harald (2007)
Maintenance			
Antifouling	7	Reduced hull efficiency after one month without treatment	Swedish International Development Authority/FAO, 1986
Antifouling	44	After six months without treatment	Swedish International Development Authority/FAO, 1987
Propeller maintenance	4	Reduction in propeller efficiency after 12 months use without maintenance	Wilson (1999)
Engine maintenance	5-8	Total fuel saving based on Irish 606hp vessel	IMARES (2006)

24. Adding a bulbous bow can increase vessel efficiency by reducing wave resistance. Whether it provides a benefit depends on the Froude Number (speed divided by vessel length) and the Block coefficient (vessel cross-section), but an improvement of 10% can be achieved in the best case (Figure 3).

Figure 3. Benefits of a bulbous bow



Source: Sterling and Klaka (2007)

25. When actively trawling, about 80% of energy is expended on towing the trawl. For this reason, improving the energy efficiency of the gear can lead to significant improvement in the overall energy efficiency of fishing. Suuronen *et al.* (2012) suggest a number of modifications that can reduce the drag of gear in water, or improve gear performance (Table 8). They also compare the relative strengths and weaknesses of different types of fishing gear (Table 9). Gaston *et al.* (2012) find that trawling efficiency is affected by bycatch when the volume of bycatch increases the codend drag. This is relevant for tropical prawn trawling, where 80% of the catch can be bycatch. They propose a method that can reduce bycatch through using light to cause a phototactic response in small fish and crustaceans, causing them to avoid the net.

Table 8. Potential energy saving techniques and adaptations for demersal trawling

Technique/Measure	Effect	Constraints-Barriers
Use of thinner and stronger twines, super fibres, knotless netting, square mesh netting, T90 net, less netting, larger mesh size	Reduces the amount, weight and surface area of netting and increases water flow through the net, thereby reducing the overall drag.	High price and availability of materials; use of larger meshes can reduce the catch of marketable species and sizes; cost benefit analyses not carried out for most fisheries.
Use of smaller and/or multiple nets for species that exhibit poor avoidance behaviour to the presence of the fishing gear (e.g. shrimp, flatfish)	Reduces the overall netting surface area and thereby the weight and the drag without reduction in catch.	Policy, complexity of rigging, resistance to change.
Use of effective bycatch and benthos reduction devices (BRDs)	Allows the escape of unwanted species or sizes of fish and other unwanted objects thereby reducing the weight and overall drag.	Variability in performance, lack of technical support to test and optimize BRDs, loss of revenues of target species and sizes, perceptions.
Using four-panel design (instead of typical two-panel) in the belly, extension piece and codend, using square mesh netting in the belly.	Ensures easier installation of BRDs and better geometry and stability for the back end of the trawl.	Cost benefit analyses not carried out for most fisheries.
Use of hydrodynamic trawl doors and use of optimal warp length (that corresponds to optimal door efficiency).	Less drag (traditional trawl doors contribute up to 25-35% of the overall gear drag), less weight, better fuel efficiency.	Price, performance monitoring, control in different sea conditions and depths.
Use of raised or flying trawl doors where the weight element of the door is separated from the spreading element (doors can be flown above the seabed to open the trawl).	Better spread, less drag and less pressure on the bottom (less seabed disturbances).	Price, performance monitoring, control in different sea conditions, depths, not suitable for all species.
Better rigging of the gear, lighter ground-gear, shorter ground-gear, less discs and better rotation capacity, self-spreading ground gear, composite ropes, lengthened bridles, off-bottom bridles, lightweight warps, and proper matching of trawl net and trawl doors.	Lighter and reduced contact points to seabed, less seabed pressure, smaller impact area, less drag.	Performance monitoring.
Use of hydrodynamic shape of floats, kites, beams, pulse trawls, SumWing-design	Reduced drag, reduced seabed contact.	Performance monitoring, speed dependence.
Converting from single boat trawling to pair trawling.	Reduces fuel consumption, less seabed damages.	Policy, human behaviour.
Improving real-time monitoring and control of gear with acoustic gear surveillance technology.	Maintenance of optimal gear performance, reduces energy consumption and bycatch.	Price, training.
Installing real-time camera observation system for informing skipper of fish behaviour and composition in the trawl.	Helps to maintain optimal gear performance, reduces bycatch and collateral impacts. The next step may be an active mechanism to release unwanted catch.	Price, training.
Improving navigation and fish finding, and improving knowledge on fishing grounds (GPS, electronic charts, sea-bed mapping)	Maximises catches and minimises time, energy and collateral impacts.	Price, training.
Use of speed controls, reduction of towing speed.	Reducing speed directly reduces the fuel consumption.	Human behaviour
Vessel and propulsion system optimisation, preventive maintenance of vessel and engine, change in trip planning practices.	Reduces fuel consumption.	Price, human behaviour.

Source: Suuronen *et al.* (2012)

Table 9. Advantages and disadvantages of different demersal gears

Gear	Advantages	Disadvantages	Priority actions
Trap-net and pound-net	Low energy use Selective for species and sizes (if properly designed) Live capture (possibility) Minimal habitat impact	Not easily portable Operation may be labour intensive Maintenance labour-intensive Expensive to construct Operation limited to relatively shallow waters Occasionally significant bycatches	Development of designs and practices that prevent the entangling of non-fish species in the mooring ropes and nettings of the trap
Pot	Low energy use Flexible and transportable Can be operated in rough bottoms Selective for species and sizes Live capture - good catch quality Potential for low bycatch mortality Minimum habitat impact Precadator safe Availability of wide variety of suitable local (natural) materials Cheap to construct	Low capture efficiency for many finfish species Ghost fishing of lost pot Lost pots contribute to marine debris Low catch rates	Fish behaviour studies to enhance ingress and reduce escape Alternative attractants Comparative fishing experiments De-ghosting technologies Human behaviour - barriers to a change Research and development work at infancy
Long-line	Low energy use Portable Flexible and versatile Species selective Minimal habitat impact Good catch quality Cheap to manufacture	Labour intensive and time consuming to operate Incidental bycatch of non-target species Snagging on benthic epifauna Availability and price of bait Low catch rate for many species	Bait issue/bait availability Alternative attractants
Gill-net	Low energy use Easily portable Versatile and flexible Good size selectivity (except trammel-nets) Possible to target specific size range allowing effective exclusion of small and large fish Relatively cheap to manufacture	Labour intensive Most fish die during capture Catch quality Poor species selectivity Capture of non-target species, often sea birds, turtles and other charismatic species Ghost fishing of lost nets Benthic impacts	Development of practices and technologies that reduce bycatch
Bottom seine	Relatively low energy use Possible to operate with low horsepower vessels Reduced bottom impacts compared to bottom trawling Requires less space than bottom trawling (possible to operate in small patches of good ground) Allows easy moving between fishing ground Relatively low gear costs Less gear damage and wear than in bottom trawl fishery Easier to use and repair (than bottom trawl) High fish quality Great scope for modifications and improvements	Not as flexible and effective as bottom trawling Operation limited to relatively flat and clean grounds (warps snag easily on boulders) Operation can also be restricted by depth, strong tides, bad weather and lack of daylight Not effective for non-herded animals such as shrimp and nephrops Operation requires good skills Workload can be relatively high Relatively poor selectivity for species and sizes Potential poor selectivity for species and sizes Potential sea bed impacts A large seine can be expensive to manufacture	Research and development work needed in improving the operation on rough grounds, in sea currents, and in deeper waters Substantial energy saving possibility Training is needed because the technology not well known
Beam trawl	Effective Relatively easy and practical to use	Seabed impacts High fuel consumption Bycatch Suitable only for relatively clean grounds Expensive	see Table 1
Bottom trawl	Effective Versatile	Seabed impacts High fuel consumption Bycatch Expensive Operation requires high skills and advanced equipments	see Table 1

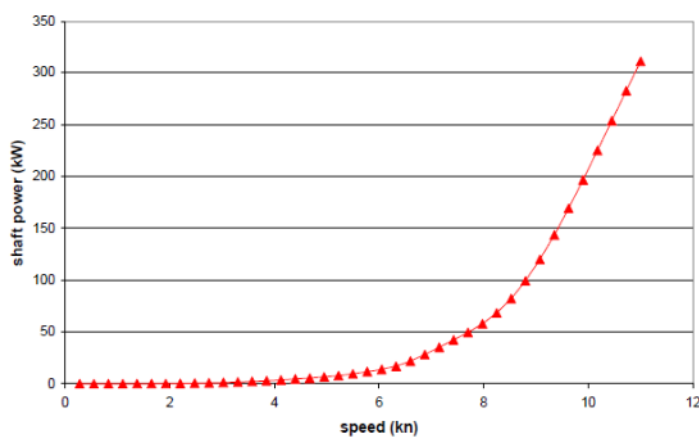
Source: Suuronen *et al.* (2012)

Fisher behaviour

26. Changing operational procedures on the fishing vessel can lead to important changes in energy efficiency. The most important of these is steaming speed. Because the wave resistance of the hull increases dramatically as speed increases, at higher speeds a small reduction in speed can lead to significant improvements in fuel efficiency (Figure 4). For example, a 15m vessel that reduces its speed from 10 knots to 9 can increase efficiency by 40% (Sterling and Klaka 2007). Providing feedback on fuel-consumption by the use of on-vessel fuel consumption meters can help to change the behaviour of vessel captains (van Marlen and Salz 2010). This feedback quantifies the savings from slower speeds, but such savings will be compared against the opportunity cost of time in determining optimal speeds. These results are reinforced by a report by the Instituted for Marine Resources and Ecosystem Studes (IMARES 2009) which find potential overall system savings of up to 25% for reduced steaming speed and up to 40% for reduced towing speed. The IMARES report cautions that not all changes in fishing tactics are costless. Adapting vessels and gear for slower operating speeds can be costly, and there may also be a cost in terms of reduced catching efficiency and lower overall vessel productivity.

27. Fuel meters are an important aid to fishers and can change behaviour, offering a means to help understand energy use over the course of a fishing journey. Other aids that have been shown to be helpful are energy audits (Notti *et al* 2012), routing optimisation from real-time data (Torres *et al* 2010) or seabed or habitat mapping. These tools and approaches can help fishers target operations in a way that maximises profits, while concurrently reducing total energy use. The use of spotter planes, fish aggregation devices (FADs) and other similar measures also fall under the heading of improving or optimising fisher behaviour.

Figure 4. Required shaft power vs. speed for 15 m fishing vessels



Source: Hullspeed (2006)

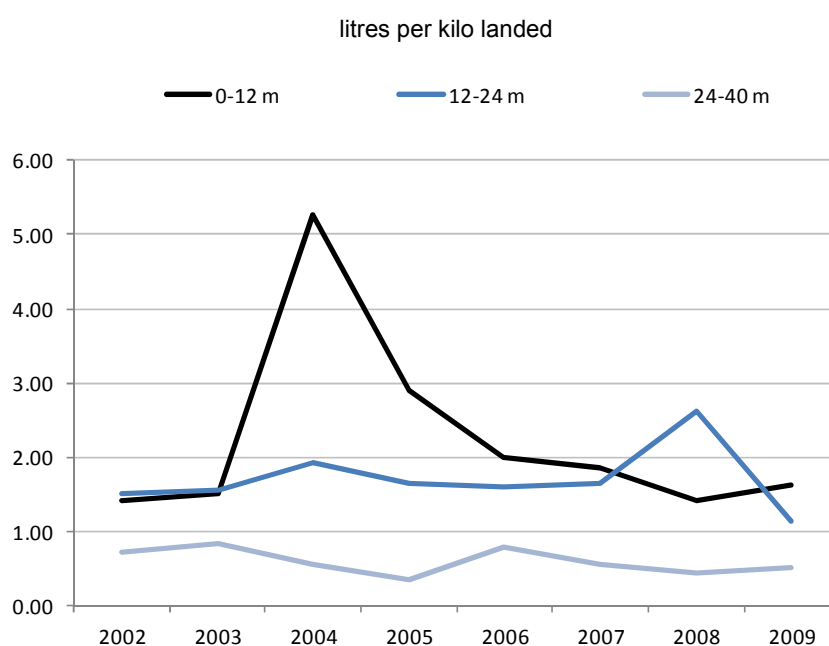
28. Aside from steaming speed, gear choice and use are crucial determinants of energy efficiency. It is typically the case that passive gears are less fuel-intensive than active gears, and trawling usually has the highest level of fuel consumption per quantity of fish harvested. Fishers chose the most profitable gear, not the most fuel efficient one, but increases in the cost of fuel can motivate changes in gear choice over the long term.

29. Changing fishing strategy can help maintain profits when fuel costs increase. Increased fuel costs have already led to some changes being observed. Some potential changes in strategy are as follows (Rossiter, 2006):

- Fishing on grounds closer to port, and focussing generally on inshore fisheries.
- Reducing effort during periods or conditions where CPUE is usually lower. This includes fishing in bad weather, fishing during tides and avoiding less “clean” fishing grounds.
- Changing the choice of port for landing catch, preferring ports closer to the point of catch to those with higher expected prices or home ports.
- Targeting (subject to quota availability and other restrictions) different species.
- Ceasing fishing activity entirely when fuel prices are high or fish prices low.

30. For species such as *Nephrops*, Ziegler and Hornborg (2012) asks whether broadening the targeted species can bring improvements in efficiency: *an interesting question is whether it makes sense that fisheries target one species at a time or rather should harvest the ecosystem as it is composed in a sustainable way? The mixed fishery where Nephrops and groundfish are targeted together is fuel efficient compared to dedicated trawling for Nephrops, especially for the largest trawlers, which used more than 8 litres per kilo landed in the targeted Nephrops fishery* (Figure 5—compare with Figure 9).

Figure 5. Fuel use of Swedish mixed *Nephrops* fishery



Source: Ziegler and Hornborg (2012)

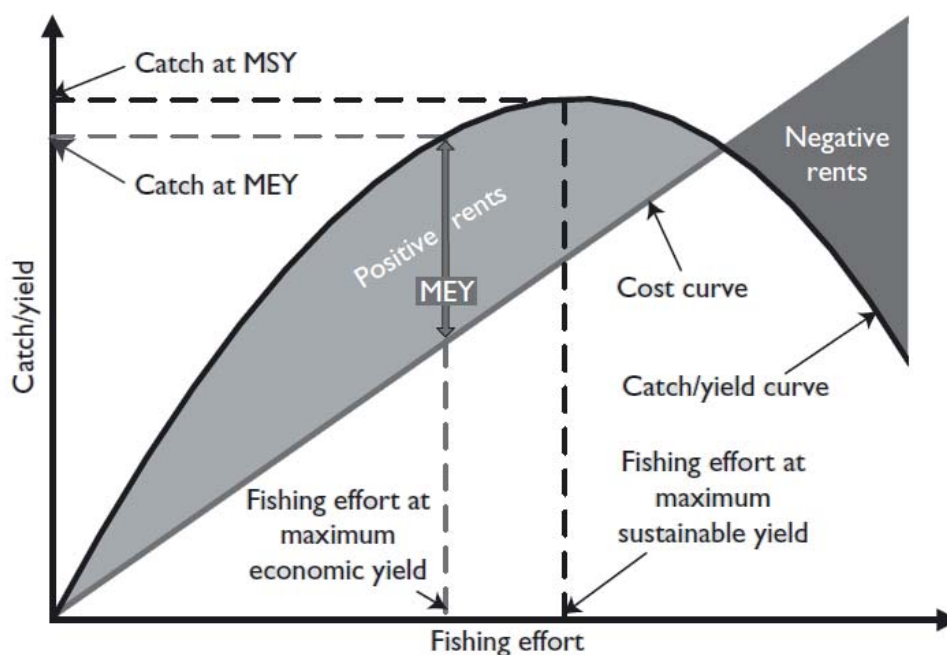
Management regime

31. Changing the management regime – including technical requirements - can have a direct influence on the fuel efficiency of the fishing fleet. The choice of the management regime comes from a

balance of social, economic and environmental objectives, of which energy efficiency is only one. The objective of this paper is not to identify the best management system, but to report on the impact of the management regime on energy use as observed in specific cases. Moreover, the view of the impact of the management system on energy use is incomplete. For example, ITQs have been studied for demersal (Grafton Squires and Fox, 2000, Dupont and Grafton, 2001) or static (Repetto 2001) fisheries, but little evidence for pelagic fisheries exists.

32. One of the most important single determinants of energy efficiency is the status of the fish stock. Depleted stocks, everything else being equal, lead to lower CPUE and therefore lower energy efficiency per quantity harvested. Maintaining stocks at maximum economic yield (MEY) can reduce fuel consumption by fishers by up to 50% and improve profitability generally by reducing effort and increasing the stock of fish (Figure 6). For example, fuel consumption by Icelandic fishers reduced by 45% after the introduction of the ITQ system that led to reduced numbers of vessels and improved fish stocks (Arnason 2010). Ishikawa *et al* (1987) studied a long-distance squid angling vessel to evaluate the relationship between CPUE and fuel consumption per kg harvested. They find that fuel consumption depends strongly on CPUE, and that the relationship between fuel consumption and CPUE is nonlinear, with small CPUEs requiring much larger amounts of fuel consumption. When CPUE is small fuel for steaming was the main energy demand. On the other hand, when CPUE is high, the majority of energy consumption is for refrigeration, lights and other on-vessel demands.

Figure 6. Profits vs. effort in fisheries



Source: World Bank (2009)

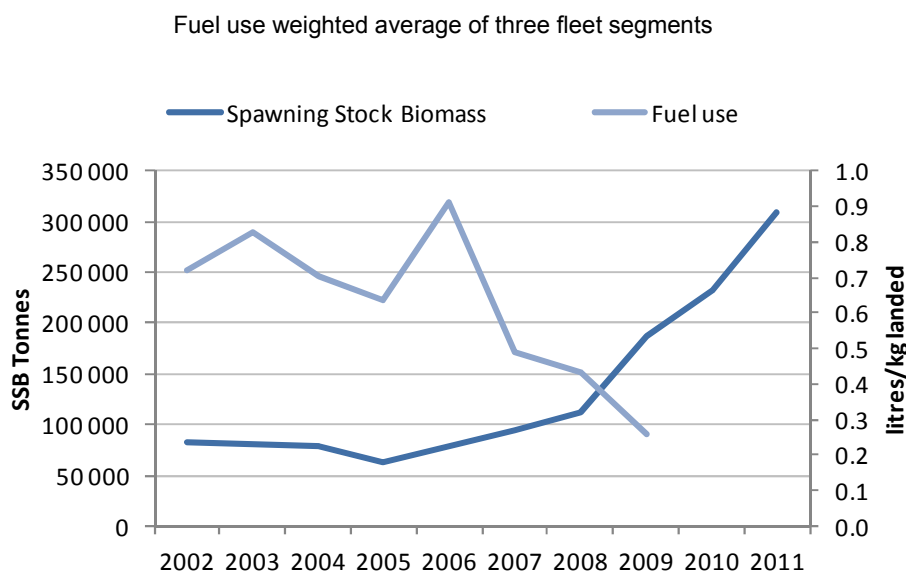
33. Improvements in energy efficiency subsequent to the introduction of an ITQ regime have also been observed in the groundfish fishery in eastern Canada (Grafton Squires and Fox, 2000) and the west coast Halibut fishery (Dupont and Grafton, 2001), as well as in Alaska longlining (Sigler and Lunsford, 2001). Deacon, Parker and Costello (2008) note that when management systems promote co-operation between fishers (in this specific case by allowing the formation of a profit-sharing cooperative), the result

can be improved energy efficiency. This is because fishers can fish over a longer period of time, closer to port, and spend less effort searching for fish.

34. Mitchell and Cleveland (1993) demonstrate how much energy efficiency can decline when efforts above MSY lead to lower stocks and lower CPUE. In a study of the fishery in New Bedford in the United States, they observe a 500% increase in energy intensity of production between 1968 and 1988 due to the large increase in the fishing fleet over that period and the concomitant decline in stocks. This effect was observed more generally for US fisheries by Brown and Lugo (1981).

35. Ziegler and Hornborg (2012) consider the determinants of fuel use in selected fisheries in Sweden. They identify improved stock status as the cause for recent improvements in fuel efficiency of the Swedish fleet (Figure 7). *“With the positive development of SSB between 2009-2011, it is not unlikely that the fishery will become even more fuel efficient. The fishing gear used is the same and no other major changes in the management system have been made the Swedish fishery is today not limited by effort nor by quota and the increase in fuel efficiency hence mainly seems to be related to the improvement of the stock.”* (Ziegler and Hornborg 2012).

Figure 7. Fuel use versus stock biomass of eastern Baltic Cod in Sweden, 2002-2011



Source: Ziegler and Hornborg (2012)

36. Driscoll and Tyedmers (2010) study the New England Atlantic Herring fishery, where a ban on mobile gear led to a conversion to purse seine and a resulting significant increase in fuel efficiency. Factors of interest here are that trawling had displaced purse seine before the ban, possibly because of the ease with which trawlers can target multiple fisheries, and that a profitable purse seine fishery was able to arise after the change in regulation. Whether trawling or purse seining are more profitable per unit harvest in any specific case depends on a number of factors.

37. Weninger (1998) develops a model to predict the impact of introducing ITQ systems based on the theory that these systems can improve capital structure and allocative efficiency over time: *“Quota rights provide a mechanism to eliminate redundant capital that may have accumulated under the pre-ITQ management regime and encourage cost-efficient production once industry restructuring is complete.*

Benefits emerge as retired capital is employed in other more productive uses, and as remaining fishers exploit production economies under the ITQ operating rules. For example, the elimination of input controls and harvest time restrictions can improve (input) allocative efficiency and vessel capacity utilisation on fishing vessels that remain active under the ITQ management regime.”

38. The benefits that accrue from introducing an ITQ system in Weninger’s model depend on the initial situation - how much excess capital is in the fishery and how great are the possible efficiency gains. Because restructuring can take time, the full benefits of moving to an ITQ system may not be seen for years. Premature evaluation of the effects of changing management regimes risks therefore underestimating total benefits. Weninger applies his evaluation method to the clam fishery in Maine, USA and predicts that the number of vessels would move from 128 to between 21 and 25 vessels with annual cost savings of between USD 11.1 million and USD 12.8 million (in 1998).³ Brandt (1999), examining the same fishery, estimated that productivity under the ITQ system increased by 39.8% relative to the prior limited-entry system. While fleet consolidation and productivity improvements are only indirect indicators of the energy use in a fishery, such significant changes in industry structure would seem to imply a certain gain in energy efficiency of production.

39. Repetto (2001) used the scallop fishery off the coast of eastern Canada and the United States as a natural experiment on the impact of management regime. The resource is sedentary and harvest techniques are similar in the two countries, so the impact of different management systems should be observable. The Canadian fishery operates under an ITQ system while the US system was based on effort controls limiting days at sea, number of crew, and gear restrictions. The main observed differences are that Canadian fishers supported efforts to rebuild the stock, while US fishers continued to resist them. The Canadian scallop stock successfully rebuilt with a better age structure than the US stock.

40. In terms of the CPUE of the scallop fishery, Repetto observes that the catch-per-day of the Canadian fleet increased by a factor of four over the 1986-99 study period, being seven times larger than the US catch per day at the end of the study period. Operating costs are seen to be a linear function of days at sea for scallop operations, though energy costs are not explicitly identified in his analysis. Improved stock abundance and significant reduction in the Canadian fleet size are behind the changes.

41. It is an open question as to why some fishing techniques continue to be used when more efficient alternatives exist (Ziegler and Valentinsson 2008, Ziegler and Hansson 2003, Hornborg *et al.* 2012). While part of the answer may have to do with excess capacity in other fisheries being available, there may also be reasons found in the management regime. For example, some quota allocations are made on the basis of fleet segment, with purse seiners and trawlers given explicit shares of the fishery. So long as both segments are profitable, such a fishery will continue to be pursued using mixed gears, regardless of the relative efficiencies of each.

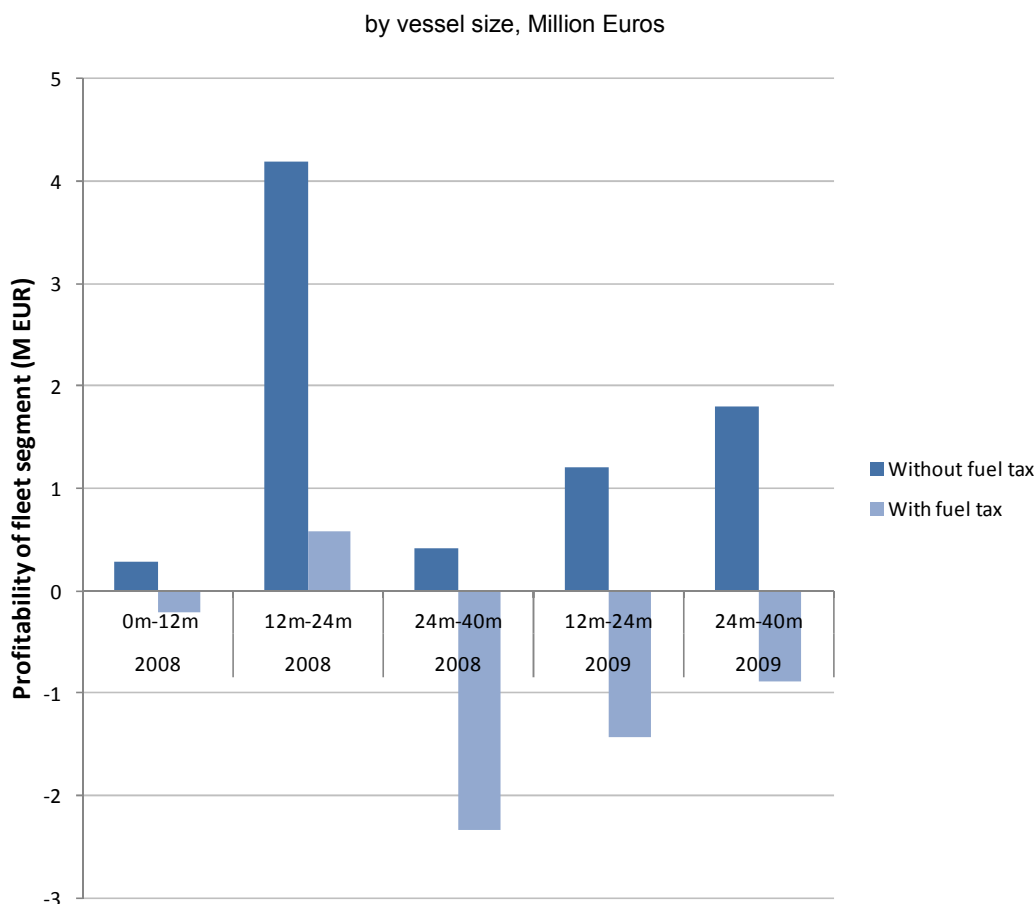
Support Policies

42. Fisheries support policies deliver financial transfers to fishers and many of the support policies will influence decisions regarding costs and hence energy use. Among the most important of these are fuel tax concessions, investment aids for vessels or gear, and capacity reduction schemes. In this context, fuel tax concessions have received the most attention as they directly influence the cost of energy (as fuel) for fishers. These policies have also received attention for their potential conflict with broader environmental goals in terms of climate change and resource conservation.

3. More recent NOAA data states the size of the combined surf clam and ocean quahog fleet was 43 vessels in 2009 (<http://www.nero.noaa.gov/nero/regs/frdoc/10/10SCOQ2011-2013FishingQuotasEA.pdf>)

43. Fuel tax concessions can be expected to favour fleet segments with higher fuel use. The more fuel consumed by a vessel, the higher the value of the transfer provided by the credit. In Sweden it was observed that demersal trawlers were highly dependent on tax credits to remain profitable (Ziegler and Hornborg (2012) (Figure 8).

Figure 8. Impact of fuel tax concessions on profitability of demersal trawlers



Source: Ziegler and Hornborg (2012)

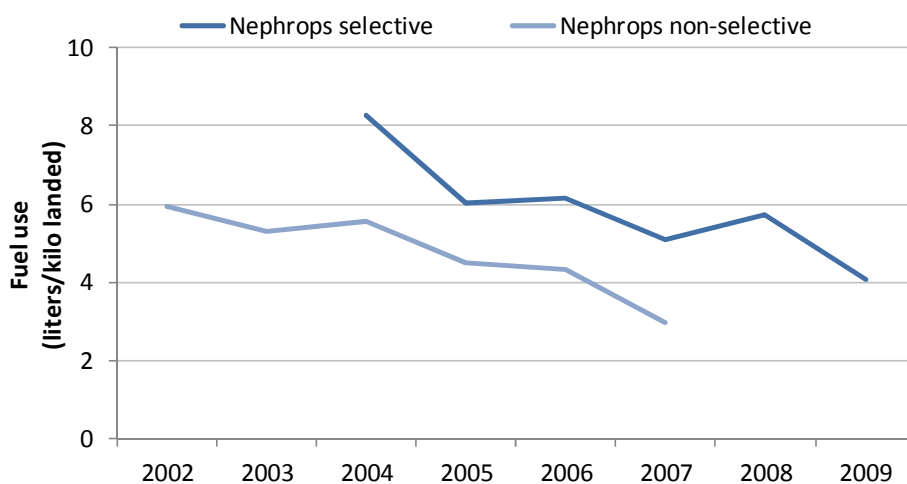
44. The impact of investment aids and decommissioning schemes are more complicated. Investment aids for engine replacement or other efficiency improvements have been justified on the basis of improved fuel efficiency, but they may also have a confounding expansionary impact on total fishing capacity when anticipated by fishers (Clark, Munro and Sumaila, 2005). Decommissioning schemes can encourage the least efficient vessels to exit the sector, but this feature alone is not enough to conclude that such schemes increase energy efficiency. The impact of these types of aids may be most important through indirect effects on stock size and CPUE. Improved CPUE tends to improve energy efficiency. At this point it is sufficient to observe that some connection between fleet capacity (or overcapacity) and energy efficiency exists, however conditioned by the specifics of the fishery and management regime.

Regulatory restrictions

45. Restrictions on gear use, such as those mandating bycatch reduction devices or similar, can influence the amount of energy required to harvest fish. Bycatch reduction devices can also reduce gear

efficiency, so duration of trawls must increase to yield the same quantity of catch. For example, data from Sweden show that more selective gear in the *Nephrops* fishery led to higher fuel use per landed tonne (Ziegler and Hornborg (2012), Hornborg *et al.* 2012) (Figure 9).

Figure 9. Selectivity and fuel use in the Swedish *Nephrops* fishery



Source: Ziegler and Hornborg (2012)

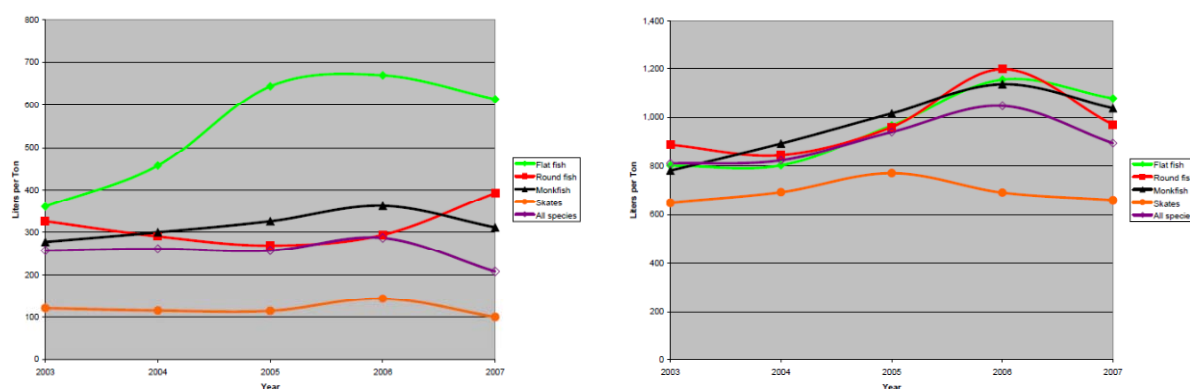
In the Northeast United States groundfish fishery, changes to regulatory restrictions on fishing may have led to higher fuel consumption per tonne landed (Kitts, Schneider and Lent 2008). This effect may also be a result of stock changes (Box 4). The authors found that after the regulatory changes, average days-at-sea for trips increased for all species, but some saw increased landings per trip (groundfish, monkfish) while others did not (flatfish).

Box 3. Trends in the NE USA Groundfish fishery

Northeast Fishery Observer Program (NEFOP) data was used to estimate annual fuel usage rates in the Northeast multispecies groundfish fishery during 2003 through 2007. Over the five-year time period, significant management changes have occurred -- particularly the implementation on 1 May 2004 of Amendment 13 to the Northeast Multispecies Fishery Management Plan. This amendment reduced the amount of fishing days allocated to the groundfish fleet, imposed limits on the amount of fish landed per trip, closed fishing areas, and established sector allocations and day-at-sea trading, among other measures. A number of subsequent management alterations also occurred from 2005 through 2007. Trips with combined landings of round fish, flat fish, monkfish, and skates greater than 50% of total landings were examined as these were most likely to be affected by the days-at-sea restrictions.

For gillnet gear, vessel fuel consumption rates for round fish, monkfish, and skates remained relatively constant during the 5-year period – at about 300 litres of fuel per ton of fish for round fish and monkfish and about 120 litres per ton for skates (see Figure). However, the rate for flat fish species increased from 360 litres per ton in 2003 to a high of 669 litres per ton in 2006 (an increase of 86%). For all four gillnet species categories combined, fuel consumption during 2003-06 remained rather stable at about 250 litres per ton, but declined to 200 litres in 2007. For otter trawl gear, vessel fuel consumption rates for round fish, flat fish, and monkfish increased from about 800 litres per ton in 2003 to a high of about 1 100 litres per ton in 2006 (an increase of 38%). Fuel consumption rates for skates during 2003-07 remained constant at about 700 litres per ton. For all species combined, otter trawl vessel fuel consumption increased from 800 litres per ton in 2003 to slightly more than 1 000 litres per ton in 2006, and then declined to about 900 litres in 2007.

Litres per tonne landed, Gillnet and Otter trawl



Source : Kitts, Schneider and Lent (2008)

46. Regulation on length and other vessel characteristics can also impact fuel economy, as more efficient hull shapes can be prohibited by specific effort restrictions (Ferlin and Weber 2010).

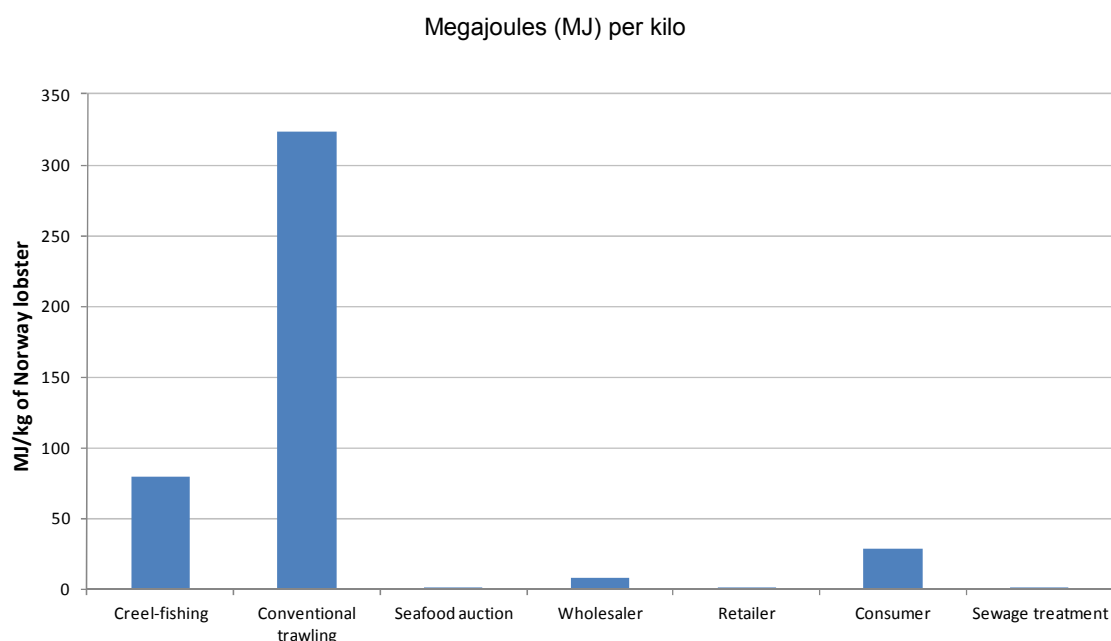
Processing and aquaculture

Life cycle analysis

47. Life cycle assessment (LCA) is a process of accounting for the different elements in the production chain of a particular good. LCA is a useful tool for understanding the total impact of a product on specific indicators. In this context, it provides some information on the contribution of processing and transportation to the total energy required to produce a fish product and deliver it to the market.

48. A majority of the energy used in the production of fish products (including aquaculture where wild fish are used as feed) tends to occur at the capture stage, and results from direct fuel inputs to fishing (Eyjólfssdóttir *et al.* 2003, Ziegler *et al.* 2003, Tyedmers 2004, Hospido & Tyedmers 2005, Thrane 2006, Pelletier *et al.* 2009, WorldFish 2011), though there are some exceptions to this when airfreight is involved (Fulton 2010, Winther *et al.* 2009) or when the fishery has a very low energy use (Ziegler *et al.* 2011). While important in specific contexts, energy use by fleets other than direct fuel consumption (vessel construction, maintenance and gear) have not been found to be the crucial factors determining energy use in capture fisheries (Hayman *et al.* 2000, Huse *et al.* 2002, Ziegler *et al.* 2003, Tyedmers, 2004). For example, energy inputs into Salmon aquaculture are more than 90% from feed inputs (Pelletier *et al.* 2009). Tilapia production systems have had a reputation for being more efficient as the fish is omnivorous. But, even for pond-grown Tilapia, more than 50% of the energy inputs come from feed (Pelletier and Tyedmers 2010). For Tilapia, only about 5% of feed is fish-based, while for salmon the percentage is closer to 40% (Pelletier *et al.* 2009). There are few studies that move beyond the processor to the retail/consumer stage, but energy use further down the consumption chain still appears to be small compared to that of the harvesting stage (Figure 10).

Figure 10. Energy use in the life cycle of 1kg of *Nephrops*; creel vs. trawl



Source: Ziegler and Valentinsson (2008)

49. The long distances that fish products can travel between fishing ground, processing facility and final consumer has raised concerns on energy efficiency grounds. However, most LCA studies confirm that modern containerised transportation of frozen goods contributes a relatively small amount to the total energy used to produce and deliver fish products. This is because of the high fuel efficiency per kilo of this form of transportation. For example, for Tilapia fillets delivered from Indonesia to Rotterdam, transport makes up only about 10% of the total energy budget (Table 10). Transport mode can be an important part of total energy use in some cases, such as air freight for fresh rather than frozen products (Karlsen and Angelfoss 2000, Andersen 2001, Horvath 2006, Fulton 2010, Winther *et al.* 2009).

Table 10. Energy used in production of one tonne of frozen Tilapia fillets in Indonesia

Gigajoules per tonne	
Fish Production	18.2
Processing	7.0
Packaging	2.1
Transport	3.9
Total	30.3

Source: Pelletier and Tydemers, 2010

50. Ellingsen *et al.* (2008) find that the energy use implied by different transport modes for export of fish products from Norway can be significant. They find that transport mode, speed and distance are more important than product form for the overall energy consumption. Changing from road and air freight to sea and rail can be more efficient, but replacing whole gutted fish by fish fillets and traditional refrigeration by superchilling would also reduce emissions (Table 11).

Table 11. Energy use of selected product and transport mode combinations

Chain	MJ/kg
Superchilled salmon fillets to Paris by ship/truck	2.9
Frozen salmon fillets to Paris by truck/train	3.3
Frozen salmon fillets to Paris by truck	5.3
Superchilled salmon fillets to Paris by truck	5.3
Frozen whitefish fillets to Paris by truck	6.4
Fresh salmon fillets in MAP to Paris by truck	6.8
Fresh low-processed salmon fillets to Paris by truck	8
Fresh gutted salmon to Paris by truck	10.1
Fresh gutted salmon to Poland and fillets to Paris by truck	13.3
Frozen gutted whitefish to Paris via filleting in China by ship	35.6
Superchilled gutted salmon to the US by high-speed vessel	52.8
Fresh salmon fillets to the US by plane	83.3
Fresh gutted salmon to Tokyo by plane	168.7

Source: Ellingsen *et al.* 2008

51. In processing, capital goods do not appear to be important relative to the impacts made by direct energy inputs to processing, though some types of packaging can be energy intensive (Thrane, 2006) (Box 4.). Other factors include product yield from processing and product loss between capture and market (Ziegler & Hansson, 2003; Boyd, 2008).

52. Winther *et al.* (2009) provide detailed calculations of the greenhouse emissions from capture fisheries and aquaculture, which is a close analogue to energy use, the main difference being the impact of refrigerants with a large greenhouse effect and biogenic emissions from aquaculture. They find a relatively

more important impact from transportation when compared with Pelletier and Tyedmers, but the conclusion that most of the energy is from fish or other inputs into feed production is supported by their research. They break down the energy inputs in some of the steps in processing salmon from aquaculture, showing that filleting is the largest component but a total much less than reported for Tilapia by Pelletier and Tyedmers (Table 12).

Table 12. Energy use in selected components of processing salmon from Aquaculture in Norway

	<i>GJ/tonne</i>
Slaughter	0.29
Filleting	2.69
Freezing	0.48
Drying	0.77
	<i>Kj/Kg/day</i>
Cold Storage	0.44
Frozen Storage	2.60

Source: Winther *et al.* (2009)

53. LCA considers the energy used in the production and use of inputs and at different processing stages. The scope of the analysis depends on the objectives and interests of the researcher, but typically covers the main inputs into capture plus an accounting of processing and transportation (Figure 12). When transportation is part of the analysis, specification of the origin and destination of the product is required, as is the mode of transportation.

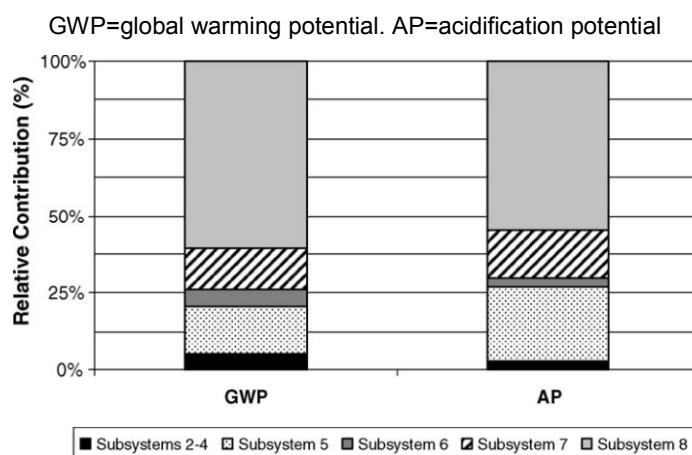
Box 4. A closer look: Canned tuna

Hospido *et al.* (2006) examine the environmental impact of canned tuna manufacture. Unlike most LCA work in fish products, they exclude the catching sector to focus on processing. They divide the process into several subsystems as follows:

1. Transport of frozen tuna carcasses from port to factory
2. Reception, thawing and cutting
3. Cooking
4. Manual cleaning
5. Liquid dosage and filling
6. Sterilisation
7. Quality control and packaging
8. Ancillary activities.

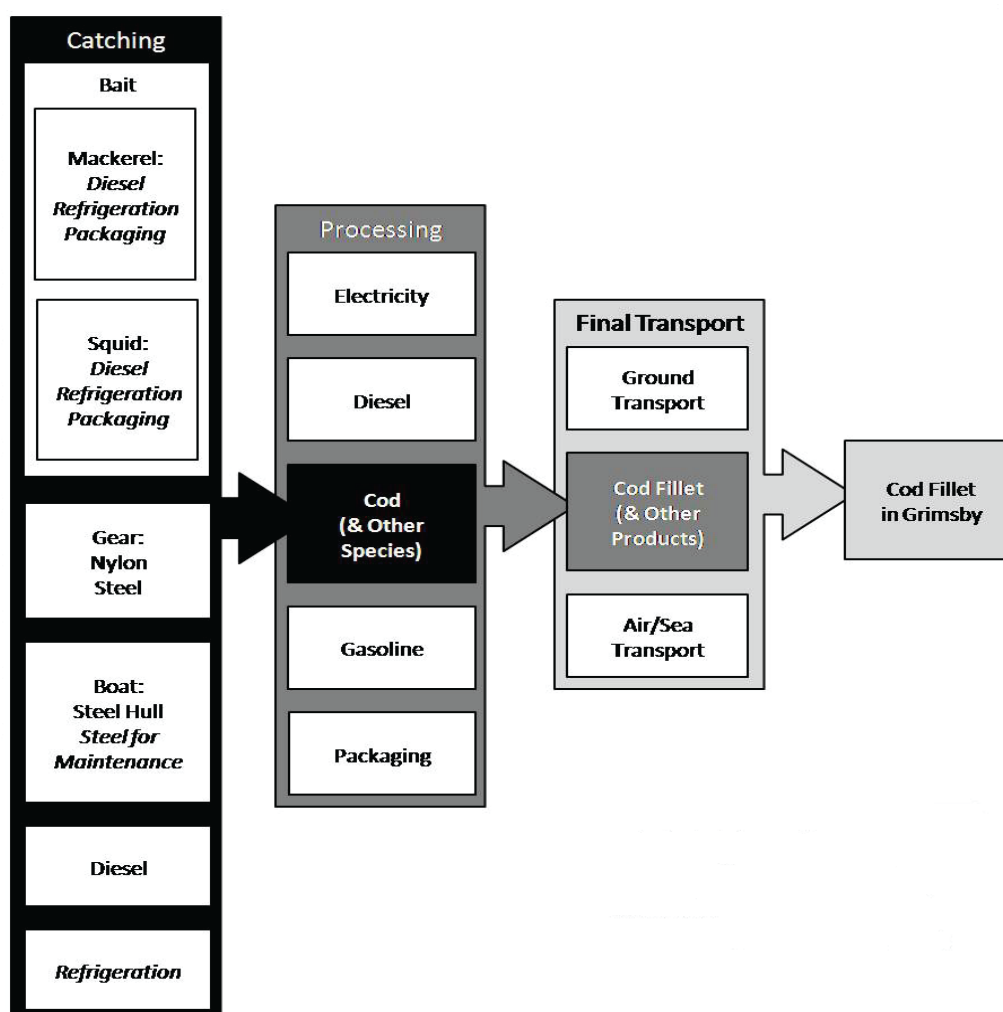
They find the largest impact on global warming potential (a close analogue of energy use) to come from tinplate production for cans under subsystem 8 (ancillary activities) (see figure). That is, 60% of the supply chain energy use for a can of tuna comes from the production of the metal can. They recommend plastic packaging as an alternative, along with increased recycling of tin cans post-consumer.

Contribution analysis for canned tuna in Spain



Source : Hospido *et al.* (2006)

Figure 11. LCA of Icelandic Cod fillet delivered to UK



Source: Adapted from Fulton (2010)

54. Most of the fish products considered in LCA studies are variations of fresh or frozen fillets; market-ready, but without a good deal of value-added. In this context, the conclusion that most energy in their production is expended in the capture of fish is not surprising. But what about products that undergo more significant processing? Parker (2011) carries out a LCA of Antarctic krill products and finds that, for krill meal and oil destined for aquaculture feed, harvesting and vessel steaming to port do indeed account for the majority of energy use. Krill oil capsules, which are used as an Omega-3 supplement, are produced in France using krill meal from the same source. In this case, the total energy consumption is dominated by processing of meal into capsule form, which represents 50% of the total energy budget. Krill meal and oil are directly processed on the harvesting vessel using fuel oil, while additional processing for capsule production uses electricity as the main energy input.

Aquaculture

55. The conclusions of the LCA work described in the preceding section typically apply as well in the case of aquaculture. The production of feed inputs is where most energy is used and this is especially the case for animal inputs such as marine or livestock-derived ingredients which dominate energy use

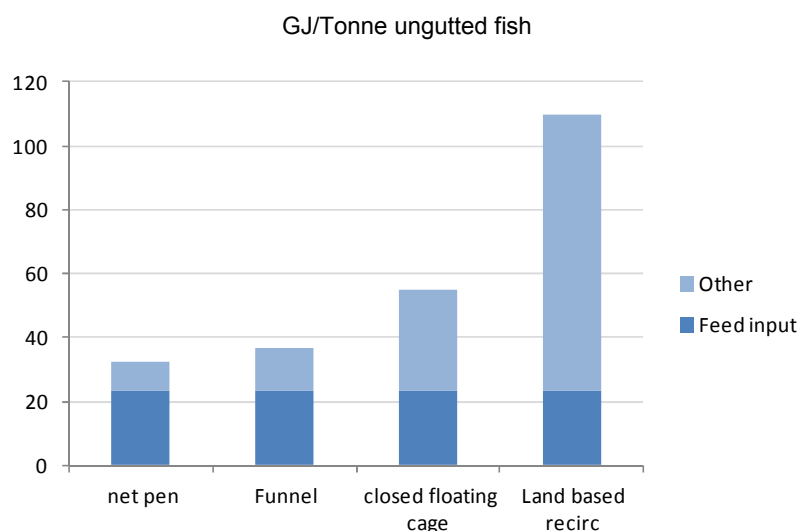
calculations when they constitute a major part of the feed. This seems to be the case for a broad variety of species and production types (Aubin *et al.* 2006, 2009, Pelletier and Tyedmers 2010, Pelletier *et al.* 2009). However, exceptions to this exist for certain types of aquaculture production.

56. Most aquaculture uses open net pens, and these are considered the lowest cost method for aquaculture production. But these are not appropriate everywhere, and alternatives exist. Land-based recirculation systems have been developed in response to a number of factors, of which limited access to coastal zones and control of effluent are the two most important. In many cases, closed recirculation systems are trading capital and energy for scarce or unavailable environmental inputs (coastal access and dilution of effluent). For this reason, these systems are often more energy-intensive than their net-pen equivalents.

57. Different systems respond to the constraints and opportunities offered by specific locations and species of fish produced. Each system will represent a different trade-off between energy and other inputs. For example, Aubin *et al.* (2006) studied a recirculating system for turbot production that used 250 000 MJ of energy per tonne of fish. This was five times the energy use per tonne for flow-through trout production, but used only 8% of the water (Papatryphon *et al.* 2004).

58. Gronroos *et al.* (2006) consider the production of rainbow trout in Finland. They find significant variation in terms of energy use per tonne of production. The variance is found to be mainly due to certain production methods that use additional energy in order to reduce local pollution loading. Systems that are more closed in order to collect effluent must do so via increased energy used in pumping (Figure 12). For the basic net-pen system, energy inputs into feed production dominate the total, but are only a fifth of total energy use for a land-based recirculating system.

Figure 12. Energy input in Rainbow Trout production in Finland



Source: Gronroos *et al.* (2006)

Comparison with terrestrial agriculture

59. The wide differences in energy use by the different fish production systems considered here complicate simple comparisons with terrestrial production systems. Agriculture itself is not a monolith; across countries and regions different systems are in place with different energy inputs. Perhaps more

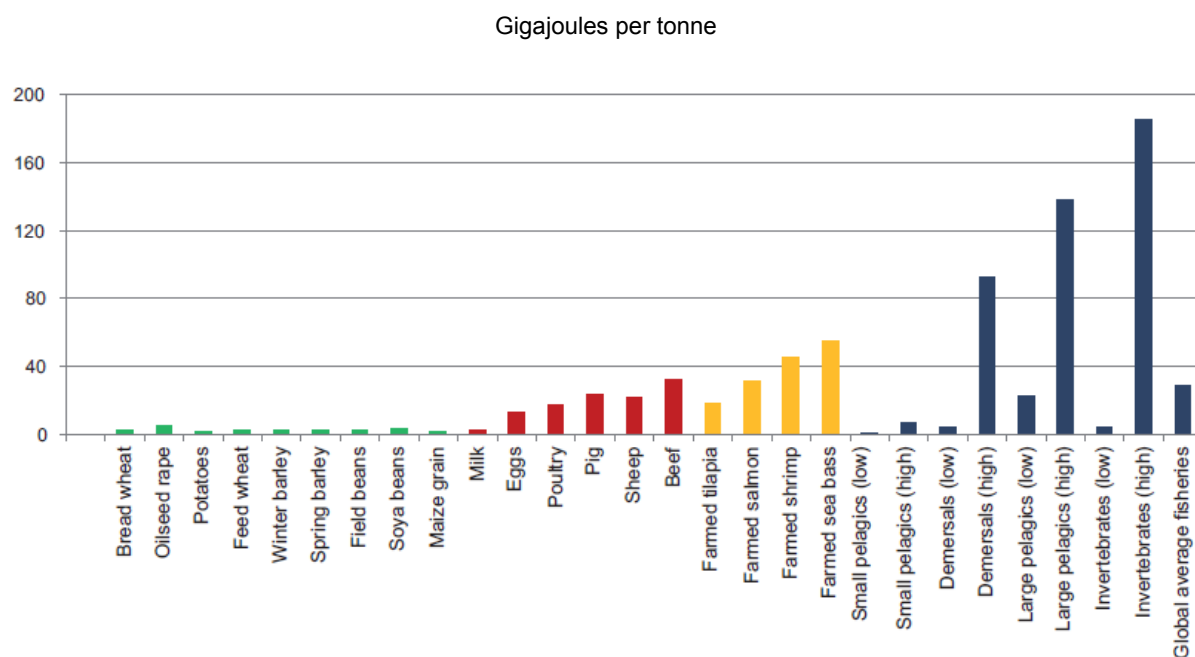
importantly, the composition of energy inputs can also vary, whereas in fisheries and aquaculture consumption of diesel or fuel oil for vessel propulsion dominates the energy use profile. Pelletier *et al.* (2011) provide a good overview of energy use for a broad set of foods, and conclude that the situation is both complex and that consumer choice is likely to be a key determinant of overall energy use (Box 5).

Box 5. Key points with respect to energy use in agriculture and food systems

- Contemporary food systems are heavily reliant on non-renewable energy resources, including both direct and indirect life cycle inputs.
- Relationships between energy-dependent inputs and food system productivity are complex and nonlinear. In some cases, diminishing returns are obvious, whereas in others, increased energy use is warranted to improve energy return on (energy) investment ratios.
- In industrialised economies, food production, processing, and household-level activities, such as refrigeration and cooking, account for the largest proportions of total energy use in the food system. Food miles do not contribute as much to the energy intensity of food products as is commonly assumed, with certain exceptions such as air-freighted products.
- Energy use per unit of caloric output in intensive livestock and aquaculture production is typically much higher than for agricultural crops. Energy associated with feed inputs has been estimated to account for 53% to 86% of the total energy intensity of livestock products.
- Given the wide variation in energy intensity within and between crop and livestock products, dietary choice is a key determinant of food system energy use.
- Considerable opportunities exist for improving energy efficiencies, but the scale of food system energy use will likely continue to increase due to population growth and changing consumption patterns. Social and political drivers must be considered alongside appropriate technologies.
- Energy efficiency must be considered from a variety of perspectives, including both anthropocentric and ecological perspectives. Whereas, the majority of research regarding energy use in food systems has focused on non-renewable energy resources, biotic energy use efficiency demands increased attention, in particular, with respect to biodiversity objectives.
- In light of the volatility of energy prices and uncertainties with respect to long-term fossil energy availabilities, the energy intensity of food systems has important implications for food security. Risks are unevenly distributed.

Source : Pelletier *et al.* (2011)

60. A comparative analysis of energy inputs shows that, on average, fish products use a comparable amount of energy as terrestrial forms of protein production (Pelletier *et al.* 2011). As noted earlier, within the fisheries sector there are large variations, with some segments such as shrimp trawling using many times more energy per tonne produced than alternatives (Figure 13). On the other hand, production of small pelagic species such as herring can be one of the most energy-efficient ways to produce protein. However, the most energy efficient fish products tend to be those that are not directly intended for human consumption.

Figure 13. Energy inputs of different foods

Source: Pelletier *et al.*, 2011

Discussion

61. It is clear that the determinants of energy use in fisheries are complex. The wide variation in energy intensity across fisheries and gear types indicates that fuel costs alone are not the prime determinant of fishing behaviour, even though fuel is the largest single costs in many fisheries. Moreover, fisheries objectives seldom target fuel efficiency directly. Stock management and the economic health of the sector are by and large the first priority of fisheries policy and management, and energy efficiency policy should not lose sight of this. On the other hand, evidence in the literature discussed in this report indicates that sustainable and responsible management is central to improved energy (and resource) efficiency.

62. There remains a role for better policy coherence. Energy use in fisheries is an important issue not just because of recent increases in fuel prices, though this has had a significant impact on fisheries in many countries. It is also important because countries have goals and objectives with regard to climate change, renewable energy, and energy independence and security. The vast majority of energy used in fisheries and the entire fish marketing chain is in the form of fossil fuels, mainly diesel. Reducing the amount of fossil fuels used by the sector can contribute to reaching those objectives that lie outside the fisheries sector, as well as potentially improving the economics of fishing for the sector. For OECD countries, the GHG contribution of the sector is relatively small, but for some nations, such as small island states, emissions of the fishing fleet can be the largest single source of emissions and as much as half of the total (Thomsen *et al.* 2012)⁴.

4. Even if the share of GHG emissions from fisheries is small, this typically does not eliminate the obligation of the sector to reduce emissions as part of national plans.

63. The challenge is for governments to find the means by which energy efficiency in fisheries can be improved in the context of broader sector and social objectives. In particular, these improvements must not compromise the objective of competitive, profitable, well-managed fisheries. Fortunately, there seems to be considerable opportunity to do this. Fossil fuel subsidies have been singled out by the G20 as inefficient and counterproductive in light of climate change objectives. The fisheries sector in most countries enjoys exemptions from fuel taxes that can impact fuel efficiency in important ways.

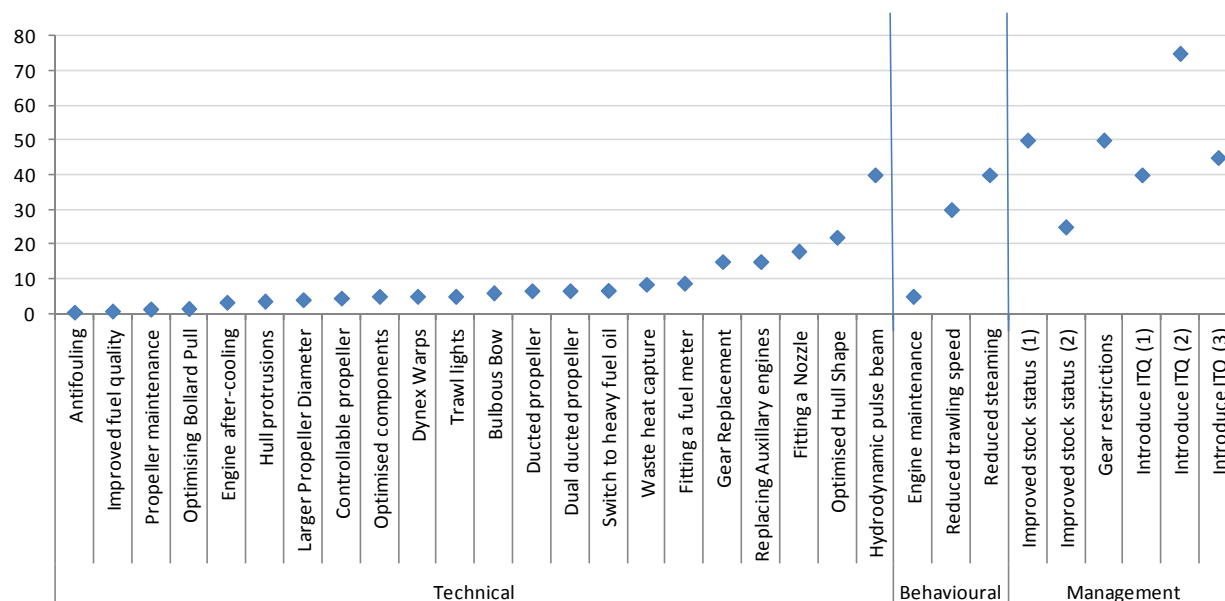
64. Even more potential seems to exist in simply doing fisheries management better. Maintaining a healthy stock has been identified as a key way to increase the efficiency of fishing in general, with concomitant reductions in fuel use, in particular when fleet capacity is matched to available resources. The behaviour of skippers also seems to be more important than the characteristics of the vessels they operate. Reduced steaming and trawling speed and travelling shorter distances have good potential to reduce fuel consumption and improve profitability. Several technical aids have also been identified to help fishers optimise their strategies. However, in many cases, these behavioural decisions are strongly influenced by the nature of the management regime, leaving scope again for a well-designed management system to give proper incentives to maximise profits and efficiency.

65. In particular, market-based approaches to fisheries management seem to provide opportunities for fishers to minimise their costs and to change fishing tactics in a way that increases fuel efficiency while fostering growth. Better matching fleet capacity to resources also helps to reduce energy consumption, in addition to its other benefits. The OECD Green Growth Strategy points out the need to find ways to increase economic output without increasing pressure on the resource base. The degree to which this occurs is called “decoupling” and the OECD had developed indicators to measure progress.

66. This report considered energy use in fisheries from three main perspectives: Technical efficiency having to do with the nature of the vessel and the gear it uses, the impact of behaviour and the choices made by fishers, and the role of the management system in influencing fuel use. While much interest and research has been conducted into technical improvements, the potential of changes in behaviour and management systems stand out (Figure 14).

67. Most of the research presented in this report shares the result that the energy use in the capture fisheries stage of production represents the most important share of the total. This is true also in many cases for aquaculture, where feed is derived in part from fish meal and oil produced from wild harvested stocks. While there are exceptions to this, the largest gains in energy efficiency and reduced greenhouse gas emissions will likely come from improvements in the way wild stocks are managed and harvested.

Figure 14. Potential improvements in energy efficiency by type



Note: improvements from technical efficiency as shown in Table 7 show improvements for specific elements of vessel efficiency only. Those values are converted to changes in overall vessel efficiency here. Results for different management improvements come from multiple studies.

Source: See Table 7, Wilson 1999, Driscoll and Tyedmers 2010, Sigler and Lunsford 2001, Arnason 2010, Brandt (1999), Repetto (2001), IMARES (2006).

68. While research into potential technical improvements holds lots of potential - theoretical improvements of 40% or more are claimed for certain gear improvements - available technologies offer improvements that are much more modest. Moreover, those technical changes that yield large gains also tend to require larger investments to implement. Governments can help by providing the necessary incentives and infrastructure for research and development, a role many governments are already playing.

Next steps

69. This document sets the stage for work to come in the 2013-14 Programme of Work of the Fisheries Committee. The next phase of the project studying energy use in fisheries and aquaculture is to consider the policy implications of the information presented here, and develop specific recommendations based on analysis of this information. This study concludes that the largest potential gains and therefore the most policy attention should be paid to capture fisheries, which is by-in-large the major energy user in the fisheries production chain. In particular, the role of the fisheries management system will be discussed, and green-growth-compatible recommendations for improvements made. This encompasses both stock management and regulatory aspects of the fishery. The role of support in fisheries with respect to energy use will be investigated, covering both potential positive incentives for improvement and the impact of existing policies such as fuel tax concessions.

70. Once the policy-focussed work is completed, it is anticipated that a full report including this document will be produced.

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