Fuel reduction in coastal squid jigging boats equipped with various combination of conventional metal halide lamps and low-energy LED panels

Yoshiki MATSUSHITA*, Toru AZUNO and Yukiko YAMASHITA

Graduate School of Fisheries Science and Environmental Studies, Nagasaki University, Nagasaki, 852-8521, Japan

* Corresponding author. Tel.: +81 95 819 2803; fax.: +81 95 819 2803
E-mail address: yoshiki@nagasaki-u.ac.jp (Y. Matsushita).

Abstract

Application of the low-energy Light Emitting Diode (LED) is considered as a possible measure for fuel saving in the squid jigging fishery. We monitored fuel consumption of fourteen coastal squid jigging boats ranging in size from 6.6 to 19 gross tons (GT) operating in the northern and western waters of the Sea of Japan in 2009 - 2011. In summer in the northern waters, squid boats of 19 GT consumed approximately 900 litres in one operation that lasted from the afternoon to the next morning and 54 % of the fuel was used during jigging with 53 conventional metal halide lamps (MHs) of 159 kW in total. In winter in the western waters, the total amount of fuel consumed in conventional operations of the 6.6 to 16 GT boats was less, but fuel consumption during jigging with lamps accounted for 70-78 % of the total consumption due to close fishing grounds. The relationship between fuel consumption (litre) and energy (kW·h) during jigging with lamps was expressed as a linear regression containing effects of the boat size and the inherent character of each boat. Fuel consumption rate decreases on average 0.28 litre/kW·h by using LEDs with a reduced number of MHs. When 9 kW LEDs were employed with 24 MHs for 19 GT boat in the western water in summer, 24 % fuel saving was estimated.

Keywords: squid jigging, light fishing, metal halide lamp, light emitting diode, fuel consumption, general linear mixed model

Introduction

Fuel consumption by the world's capture fisheries in 2000 was approximately 50 billion litres and this accounted for 1.2 % of the global fuel consumption (Tyedmers et al., 2005). Due to a rapid rise of fuel prices after 2004 (Arnason, 2007) and increasing concerns regarding greenhouse gas emissions (Driscoll and Tyedmers, 2010), various studies have been conducted to reduce fuel consumption in capture fisheries (e.g. Thrane, 2004; Thomas et al., 2009, Suuronen et al., in press). To find appropriate measures to reduce fuel consumption and greenhouse gas emissions, it is necessary to understand fuel consumption pattern in various fisheries.

Strong artificial lights are used in the Japanese squid jigging fishery to attract squid close the fishing boat. In 2008, there was 4400 boats smaller than 19 GT in this fishery (Ministry of Agriculture, Forestry and Fisheries, 2011). Most fishermen in this fleet believe that stronger light leads to larger catch and there has been a competition that has gradually increased the power of light used in this fishery. The fuel consumption has increased at the same time. In 1990s, the light source output reached 300 kW for some coastal boats (Choi and Nakamura, 2003). In 2008 fuel cost typically accounted for approximately 40 % of fishermen's expenditure using 19 GT boats while in 2006 it was about 27% (Demura, 2008).

Introduction of high efficient (low-energy) Light Emitting Diode panels (LEDs) into the squid jigging fishery is considered as a possibility for fuel saving. Our previous study revealed that a combination of LEDs with sufficient number of conventional metal halide lamps (MHs) maintained squid catch (Yamashita et al., 2012). In this study, we present the fuel consumption of fourteen squid jigging boats ranging 6.6 to 19 GT using various combinations of LEDs and MHs. The objectives of this study is to (1) reveal allocation of fuel consumption in the fishing processes by boat sizes and fishing grounds, and (2) evaluate fuel saving effect of the lighting system composed of LEDs and MHs.

Material and methods

We used fourteen squid jigging boats ranging in size from 6.6 to 19 GT (Table 1) based on Iki and Tsushima islands, Nagasaki, western Japan (Fig. 1). We monitored fuel consumption for nine boats of 19 GT (Fig. 2, #1-#9; Table 1) during August to September (summer) 2009 and January to February (winter) 2010. Squid jigging boats are usually equipped with power generators which are connected to the main engine, but three boats (#1, #2, and #8) of these nine boats were equipped with auxiliary engine of 32 kW. In summer, these nine boats selected two different fishing grounds to target different species of squid. Boats #1-#5 operated in the western waters of the Sea of Japan (Fig. 1; hereafter referred to as “Iki”) to target swordtip squid (*Photololigo edulis*) and the other four boats (#6-#9) traveled to the northern waters of the Sea of Japan (Fig. 1; “Hokkaido”) to catch Japanese common squid (*Todarodes japonicus*). In the winter, all these boats returned to Iki to catch Japanese common squid.

In January and February 2011, we conducted the same research for 6.6-16 GT squid jigging boats (#10-#14; Table 1) based on Tsushima Island. These boats operated around their home port (“Tsushima”) which is close to Iki to catch Japanese common squid.

The above fourteen boats were equipped with blue LEDs (Takagi Corporation, Kagawa, Japan) in combination with existing MHs (3 kW output per bulb). The numbers of LEDs were different in different sizes of boat (19 GT, 16 GT and <10 GT, hereafter referred as CLASS) because of the difference in available deck space. Electric output of LEDs were 4.32 kW for a 6.6 GT boat, 4.68 kW for 7.9 and 8.5 GT boats, 6.48 kW for a 16 GT boat, and 9.00 kW for 19 GT boats. During the research periods, all boats employed different numbers of MHs with full-lighting of LEDs (Table 2).

We installed the positive displacement flowmeters (LS4976-460A for main engines of 19 GT, LSF40PO-M1 for auxiliary engines of 19 GT, LS5076/213A for engines in other boats, Oval Corporation, Tokyo, Japan) to these fourteen boats and fuel consumption was monitored in the wheelhouse on a real-time basis. The captain of each boat recorded the time and fuel consumption of every phase of the fishing process (departure from the port, arrival at the fishing ground, start of lighting/jigging, change of lighting, end of lighting/jigging, departure from the fishing ground, and arrival at the port) into the distributed log-books.

Fishing process was categorized as the following four processes; “OUTWARD” that is cruising from port to the fishing ground while searching for squid; “WAITING”, after arriving at the fishing ground, waiting until sunset; “LIGHTING” that captures squid with lamps; and “RETURN” that stops jigging and steams back to the landing port. Total amount of fuel consumed of any experimental boat F_{total} can be expressed as follows.

$$F_{\mathrm{total}} = F_{\mathrm{out}} + F_{\mathrm{wait}} + F_{\mathrm{light}} + F_{\mathrm{return}} \qquad (1)$$

where, F_{out} is the amount of fuel consumed for steaming from port to the fishing ground, F_{wait}, the amount of fuel consumed while waiting until the start of LIGHTING, F_{light}, the amount of fuel during lighting and jigging, F_{return}, the amount of fuel for the return back to the port, respectively. We analyzed items on the right side of equation (1) to show the allocation of fuel consumption in the operation processes by fishing grounds and CLASS.

Fuel consumption per kilowatt-hour increases according to efficiency reductions of the power generator and engine at low load condition, when small electric power was used by the high rated power generator, like a case of lighting with small number of lamps. Thus, fuel consumption rate is not constant against electric power used for LIGHTING and influenced by variations of generator and engine efficiencies (Sakai et al., 1995; Sakai and Sakamoto, 1999). But variation in fuel consumption rate of recent engines is not large in various load conditions (less than 8%, Fishing Boat and System Engineering Association of Japan, 2010). We therefore assumed that fuel consumption during LIGHTING is expressed as a linear relationship between a product of the sum of electric power for fish attraction lamps P and automated jigging machines M (Table 2), and lighting period t as the following equation.

$$F_{\mathrm{light}} = \alpha\,(P + M)\,t + \beta \qquad (2)$$

where, α is a constant of proportionality and β is an intercept. The fourteen boats however have engines of different powers and/or an auxiliary engine with their own fuel consumption characteristics. It is also known that fuel consumption differed even with the same engine and electric output, when maintenance conditions are different (Sakai and Tazawa, 2008). In addition, log-book records may contain errors or different levels of accuracy due to different observers (captains). Accordingly, we considered these inherent characters of boats as random effects assumed to follow a normal distribution and assigned to a slope and/or an intercept to the equation (2). This can be modeled as follows.

Model 1: Amount of fuel consumed during jigging with lamps (FUEL) includes a random effect of boats (BOAT) in addition to a linear relationship to a product of the electric output and lighting period, that is an amount of energy (kW·h) consumed during LIGHTING.

Model 1-1: The slope of a linear regression is different by BOAT, but the intercept is the same.

Model 1-2: The intercept of a linear regression is different by BOAT, but the slope is the same.

Model 1-3: Both the slope and the intercept are different by BOAT.

Model 2: FUEL includes a random effect of CLASS, in addition to a linear relationship explained in Model 1. We prepared Models 2-1 to 2– 3 that have the same assumptions with a series of Model 1.

Model 3: FUEL includes random effects of CLASS and BOAT in addition to a linear relationship explained in Model 1. We prepared Models 3-1 to 3–3 that have the same assumptions as the series of Model 1.

We fitted the data into these general linear mixed models (Table 3) by using statistic software R (ver. 2.13.0) with lme4 package and adopted the model which showed the smallest AIC (Akaike's Information Criteria) among models.

Results

Average duration for steaming to and from the fishing ground (OUTWARD+RETURN) varied among 3.04 – 8.45 h depending on CLASS (Table 4). The duration was shorter (3.04-6.27 h) off Iki and Tsushima in winter where fishing grounds were closer the harbour and longer (8.45 h) off Hokkaido and Iki in summer for the opposite reason. Amount of fuel consumed reflected difference in steaming durations and CLASS. Boats of 19 GT used on average 415 litres of fuel off Hokkaido and 300 litres off Iki in summer but amount of fuel consumed decreased to 145 litres off Iki in winter (Table 4). Boats smaller than 10 GT consumed on average 45 litres off Tsushima in winter (Table 4).

Durations for LIGHTING were shorter in summer (Hokkaido, 9.25 h; Iki, 9.22 h) and longer in winter (Iki, 11.60 h; Tsushima, 8.74-9.59 h) relating to the length of night (Table 4). Fuel consumption with the 19 GT boats during LIGHTING in conventional operations in Hokkaido was on average of 487 litres when they used the 53 MHs (159 kW output in total; Table 4). This is almost the same as the upper limit of voluntary regulated electric output 160 kW. This suggests that 54 % of total fuel consumption in conventional operation was spent during LIGHTING. Similarly, fuel consumptions during LIGHTING accounted for approximately 70 % (371 litres) and 78 % (162 litres) of the total consumption for the 16 GT boat and boats smaller than 10 GT off Tsushima (Table 4).

Fuel consumption rate (litres/h) under various lighting conditions (Table 2) showed different tendencies for boats smaller than 10 GT and boats larger than 16 GT (Fig. 3). When all lamps were turned on, which is done in conventional operations, boats larger than 16 GT consumed 54-63 litres/h for lighting output more than 150 kW and boats smaller than 10 GT consumed 20-22 litres/h against 57-60 kW output. By reducing number of MHs but having full-lighting of LEDs, fuel consumption rate decreased. When LEDs were used in place of 23 MHs (30 MHs and LEDs, 99 kW total output; Table 2), for example, fuel consumption rate was on average 42.3 litres/h, that was 31 % reduction from conventional condition despite the output of lamps was 38 % reduced. Also, boats larger than 16 GT still consumed on average 22.4 and 25.5 litres/h of fuel (58 – 59 % fuel reduction) with only LED lighting (6.48 and 9.00 kW, 94 -95 % output reduction) and on average 5.4 and 9.3 litres/h (59 – 74 % fuel reduction) for boats smaller than 10 GT (4.32 and 4.68 kW LEDs, 92 % output reduction; Fig. 3). Thus, reduction of fuel consumption rate by reducing number of MHs did not coincide the reduction rate of electric output of lamps and fuel reduction rate was below the reduction rate of electric output of lamps (Fig. 4). This is probably due to fuel spent during jigging in addition to lighting (e.g. jigging machines).

When the electric output of jigging machines was considered, amount of fuel consumed increased in proportion to the products of electric output and period (the amount of energy; Fig. 5). By choosing a model with the smallest AIC value, fuel consumption during LIGHTING could be expressed as a linear function with amount of energy and random effects of CLASS and BOAT which have different intercept and slope (Model 3-3, AIC=8157; Table 5). Among coefficients expressing random effects, an intercept for CLASS was greatest (-36.46 to 47.18; Table 6) and contained most influenced to variances while a slope for CLASS was small (-0.01 to 0.01; Table 6). It can therefore conclude that 0.28, 0.29 and 0.27 litres of fuel can be saved per kilowatt-hour for boats of 19 GT, 16 GT and boats smaller than 10 GT by replacing appropriate number of MHs to low-energy LEDs.

Discussion

Large amount of fuel (54 – 78 % of whole consumption) was spent during LIGHTING in conventional operations conducted in various fishing grounds and seasons (Table 4). It is therefore important to reduce fuel consumption during this process. Replacement of adequate number of MHs to low-energy LEDs is promising measure for energy saving because LEDs has high luminous efficacy and application efficiency (directivity of light emission while other lamps emit in all directions) among existing light sources (Nakano and Shimizu, 2010).

Our previous study demonstrated that the catch amount of swordtip squid captured by 19 GT boats with 24 MHs and LEDs (81 kW in total) was equal to the catch in conventional operations using 53 MHs (159 kW) off Iki in summer (Yamashita et al. 2012). Estimated amount of fuel consumed by the 19 GT boat in a conventional operation in the same water were 532 and 835 litres during LIGHTING and during a whole operation respectively (Tables 4, 6 and Fig.5). When 24 MHs and LEDs are employed, amount of fuel consumed during LIGHTING is decreased to 333 litres. Consequently, the use of LEDs in combination with 24 MHs achieves 37 and 24 % fuel saving for during LIGHTING and during one operation respectively.

Prices of fuel oil A in Japan was 0.83 US$/litre (when 1 US$ = 80 JPY) in 2006, 1.44 US$/litre in 2008 (Demura, 2008) and approximately 0.88 US$/litre in 2011. Reduction of 24 % fuel consumption would contribute about 200 US$ saving in every operation of swortip squid fishing for an average 19 GT boat.

However, except for the swordtip squid fishing in summer, we are not sure on the optimal relationship between catch and electric output of fishing lamps. Nevertheless, rough and conservative estimation is available by using our results. If only 10% of fuel consumption during LIGHTING was saved by using LEDs in annual 180 operations, 7875, 6300, and 2363 US$ will be added to annual profits for average boats of 19 GT, 16 GT and a boat smaller than 10 GT respectively. In addition, cost for changing MH bulbs of 3 kW (475 US$ each) 0.81 times/year (unpublished data of 19 GT) can also be reduced by using long lifetime LEDs.

The introduction of LEDs may provide not only economical benefits but also a positive environmental aspect to squid jigging fishery by reducing the CO_2 emissions. When the total number of boats (in 2008, 1066 for 5-10 GT and 567 for 10-20 GT, Ministry of Agriculture, Forestry and Fisheries, 2011), CO_2 emission factor (2.710 kg CO_2/litre, Haseagawa 2008) and a conservative assumption of fuel saving (15 and 40 litres reductions for 5-10 GT and 10-20 GT per operation and 180 operations/year) are taken into account, annual reduction of CO_2 emission for coastal squid jigging fishery using 6.6-19 GT boats is estimated at 18863 t-CO_2.

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Table 1. Specifications of experimental boats, their fishing grounds, and monitored periods of fuel consumption

Boat ID	Length overall (m)	Beam (m)	Gross registered tonnage	Engine power (kW)	Auxiliary engine power (kW)	Fishing ground	Monitored period (dd/mm/yy)
#1	19.11	4.40	19	589.00	-	Iki	1/8/09-30/9/09, 8/1/10-24/2/10
#2	19.20	3.82	19	540.00	32.0	Iki	1/8/09-29/9/09, 8/1/10-24/2/10
#3	18.93	3.74	19	573.00	32.0	Iki	1/8/09-30/9/09, 8/1/10-24/2/10
#4	19.07	3.78	19	589.00	-	Iki	1/8/09-27/9/09, 8/1/10-23/2/10
#5	18.68	4.01	18	589.00	-	Iki	1/8/09-26/9/09, 8/1/10-24/2/10
#6	19.15	3.80	19	584.72	-	Hokkaido, Iki	4/8/09-13/9/09, 8/1/10-24/2/10
#7	19.12	4.41	19	584.72	-	Hokkaido, Iki	4/8/09-13/9/09, 8/1/10-23/2/10
#8	19.13	3.80	19	573.70	32.0	Hokkaido, Iki	4/8/09-13/9/09, 8/1/10-21/2/10
#9	19.52	4.21	19	478.08	-	Hokkaido, Iki	4/8/09-13/9/09, 8/1/10-23/2/10
#10	17.37	3.57	16	477.75	-	Tsushima	13/1/11-8/2/11
#11	14.41	3.46	8.5	463.05	-	Tsushima	11/1/11-7/2/11
#12	14.52	3.44	8.5	463.05	-	Tsushima	12/1/11-6/2/11
#13	13.14	3.24	7.9	433.65	-	Tsushima	14/1/11-7/2/11
#14	13.06	3.07	6.6	404.25	-	Tsushima	13/1/11-7/2/11

Table 2. Electric outputs of monitored boats during jigging with lamps

Boat ID	Output in conventional operation (kW, w/o LED)	Output for LED (kW)	Output patterns for metal halide lamps (kW)	Output for automated jigging machine*
#1	159	9.0	0, 12, 24, 36, 51, 60, 72, 90, 111	14.4
#2	159	9.0	0, 12, 36, 51, 72, 90, 108, 111	14.4
#3	159	9.0	0, 12, 36, 51, 72, 90, 108, 111, 150	14.4
#4	159	9.0	0, 12, 36, 45, 51, 72, 90, 108, 147	14.4
#5	159	9.0	0, 12, 36, 72, 90, 108, 147	14.4
#6	159	9.0	24, 36, 51, 72, 90, 108, 150	14.4
#7	159	9.0	24, 36, 51, 72, 90, 108, 150	14.4
#8	159	9.0	24, 36, 72, 90, 108, 150	14.4
#9	159	9.0	24, 36, 72, 90, 108, 150	14.4
#10	150	6.48	36, 96, 141, 150	12.0
#11	60	4.68	0, 12, 36, 54, 60	7.2
#12	60	4.68	0, 12, 36, 54, 60	7.2
#13	60	4.68	0, 12, 36, 54, 60	7.2
#14	57	4.32	0, 12, 36, 51, 57	7.2

*Assumed as 1.2 kW/machine, (pers. comm.. Sanmei Co,. Inc., Shizuoka, Japan)

Table 3. Models expressing the fuel consumption during jigging with lamps

Model ID	Assumptions	Categories in random effects
1-1	F_{light}~ENERGY + random effect in a slope by BOAT	BOAT (ID #1-#14)
1-2	F_{light}~ ENERGY + random effect in an intercept by BOAT	BOAT (ID #1-#14)
1-3	F_{light}~ ENERGY + random effects in a slope and an intercepts by BOAT	BOAT (ID #1-#14)
2-1	F_{light}~ ENERGY + random effect in a slope by CLASS	CLASS(19 GT, 16 GT, <10 GT)
2-2	F_{light}~ ENERGY + random effect in an intercept by CLASS	CLASS (19 GT, 16 GT, <10 GT)
2-3	F_{light}~ ENERGY + random effects in a slope and an intercept by CLASS	CLASS(19 GT, 16 GT, <10 GT)
3-1	F_{light}~ ENERGY + random effects in a slope by CLASS and BOAT	CLASS(19 GT, 16 GT, <10 GT), BOAT (ID #1-#14)
3-2	F_{light}~ ENERGY + random effects in an intercept by CLASS and BOAT	CLASS (19 GT, 16 GT, <10 GT), BOAT (ID #1-#14)
3-3	F_{light}~ ENERGY + random effects in a slope and an intercept by CLASS and BOAT	CLASS (19 GT, 16 GT, <10 GT), BOAT (ID #1-#14)

Table 4. Duration of fishing processes and their fuel consumptions by fishing grounds and boat sizes

	Hokkaido (19 GT, summer)		Iki (19 GT, summer)		Iki (19 GT, winter)		Tsushima (16 GT, winter)		Tsushima (<10 GT, winter)	
Num. data[a]	70-120		122-153		245-260		19-20		76-80	
Duration (h)										
Outward	5.07	2.51	3.25	1.35	2.00	1.79	2.31	0.51	1.21	0.67
Waiting	0.23	0.31	1.37	0.88	0.97	0.58	0.55	0.40	1.62	3.33
Lighting	9.25	1.95	9.22	2.12	11.60	2.80	8.74	1.12	9.59	3.89
Return	3.38	1.12	3.02	1.18	1.55	0.53	3.35	4.20	1.83	3.08
Total	17.93		16.86		16.12		14.95		14.25	
Fuel consumption (l)										
Outward	202.50	79.06	148.12	72.23	74.07	29.48	70.9	18.52	19.69	20.84
Waiting	0.98	2.33	1.57	5.09	1.39	4.62	7.11	9.32	0.76	1.29
Lighting[b]	487.26	70.19	-	-	-	-	371.00	-	161.8	38.81
Return	212.16	107.59	152.45	80.53	71.37	334.67	81.7	24.33	25.1	23.36
Total	902.90		-		-		530.71		207.35	

a: available number of data varied by omissions in logs, b: data from conventional fishing by experimental boats; 10 data for Hokkaido (19 GT), 2 data for Tsushima (16 GT), and 5 data for Tsushima (<10 GT)

Table 5. Parameter estimates for fixed effects in the linear mixed models

Model ID	Intercept	S.E.	Slope	S.E.	AIC
1-1	48.95	3.45	0.27	0.02	8318
1-2	60.22	10.79	0.28	0.01	8195
1-3	64.49	11.93	0.28	0.01	8172
2-1	76.66	3.93	0.36	0.01	8360
2-2	47.74	22.90	0.28	0.01	8242
2-3	60.31	37.98	0.33	0.01	8241
3-1	50.36	3.47	0.26	0.06	8300
3-2	48.54	23.69	0.28	0.01	8181
3-3	45.24	25.90	0.28	0.02	8157[a]

a, adopted in this study

Table 6. Parameter estimates in Model 3-3

fixed effect		random effect in CLASS		range of random effect of BOAT
Intercept	45.24	19 GT	47.18	-9.33 to 11.52
		16 GT	-10.72	-0.63
		< 10 GT	-36.46	-4.07 to 4.28
Slope	0.28	19 GT	-0.01	-0.03 to 0.04
		16 GT	0.01	0.03
		< 10 GT	0.00	-0.02 to 0.01

Figure captions

Fig. 1. Fishing grounds. Only 19 GT boats operated off Hokkaido.

Fig. 2. Squid jigging boat (19 GT) lighting metal halide lamps and LED panels. (Left; lighting with metal halide lamps, Middle; combination lighting with metal halide lamps and LED panels, Right; lighting with LED panels)

Fig. 3. Change in fuel consumption rate by reducing electric output of lamps (reduction in number of metal halide lamp) with full-lighting of LED panels. Vertical bars designate standard deviations.

Fig. 4. Relationship between reduction of electric output of lamps from conventional condition and reduction of fuel consumption rate.

Fig. 5. Linear relationships between the amount of energy (the product of the electrical output of lamps and jigging machines and their operating duration) and amounts of fuel consumed. The broken line shows a regression estimated from the fixed effect and solid lines for regressions of the fixed plus random effects of CLASS, estimated from the linear mixed model (Model 3-3) chosen in this study.

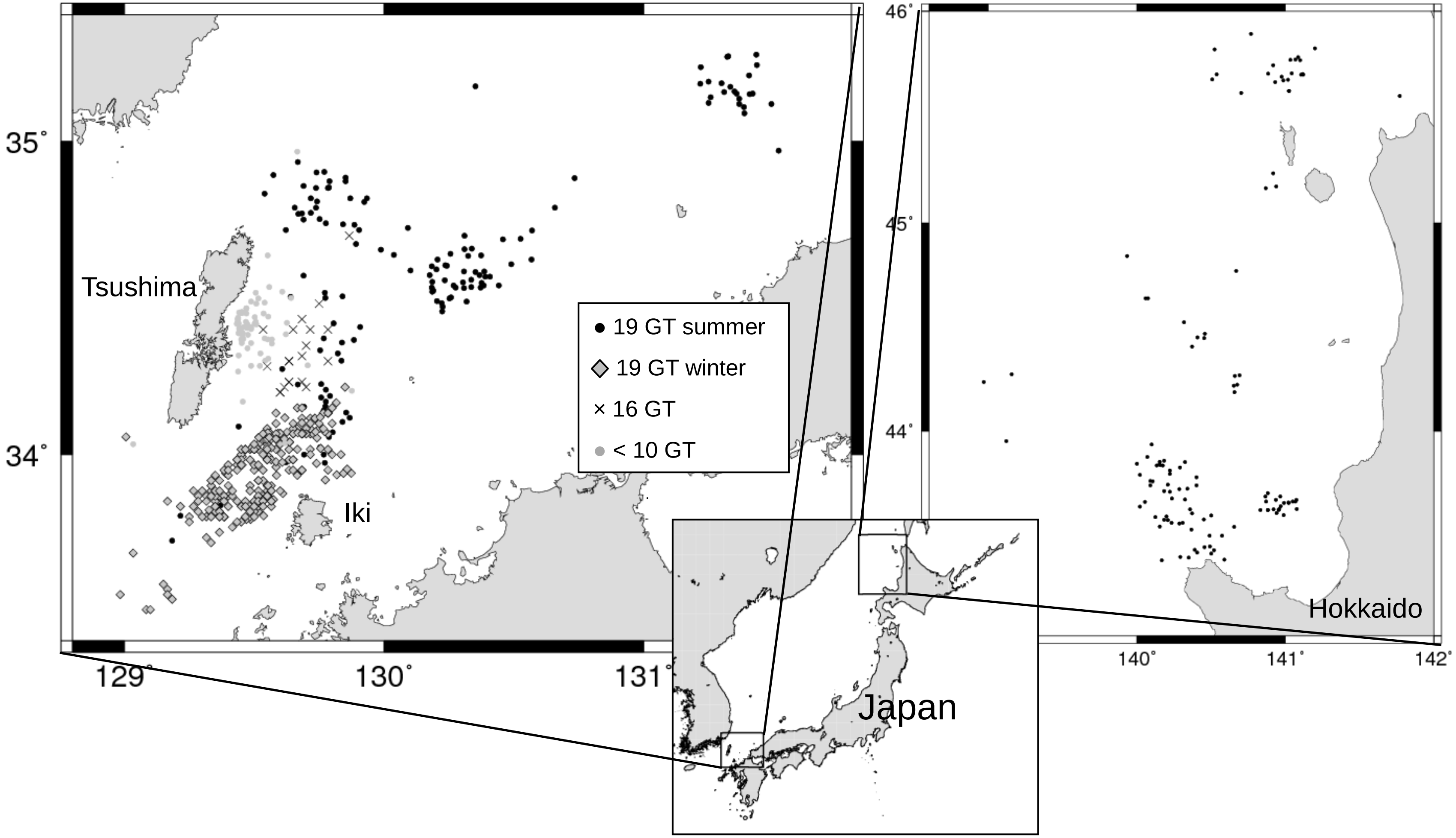

Fig. 1. Matsushita et al.

Fig. 2. Matsushita et al.

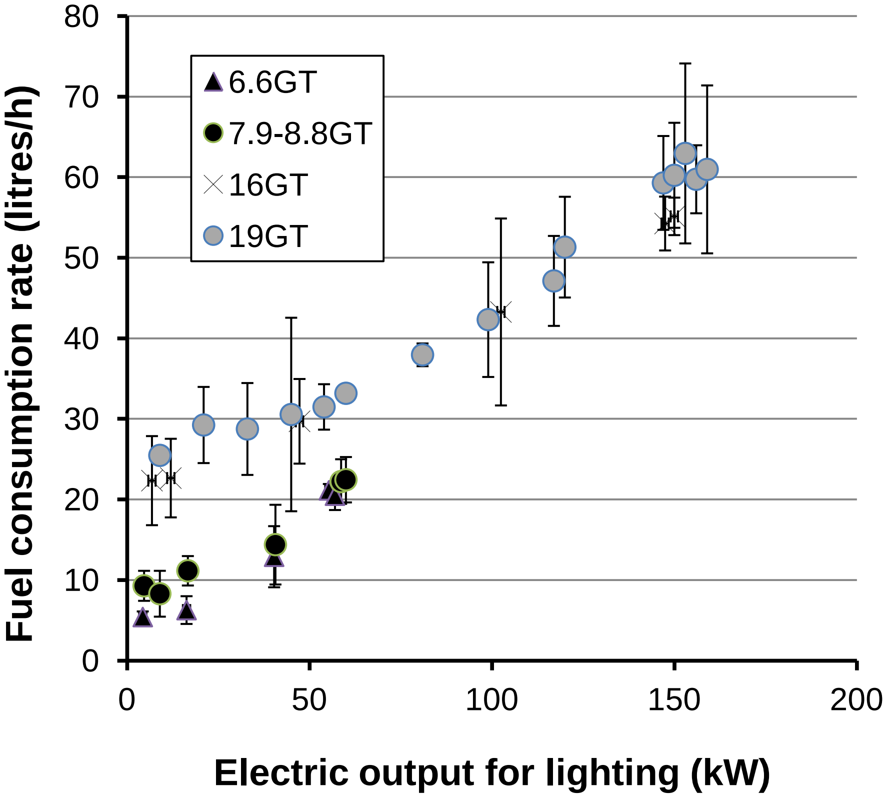

Fig. 3 Matsushita et al.

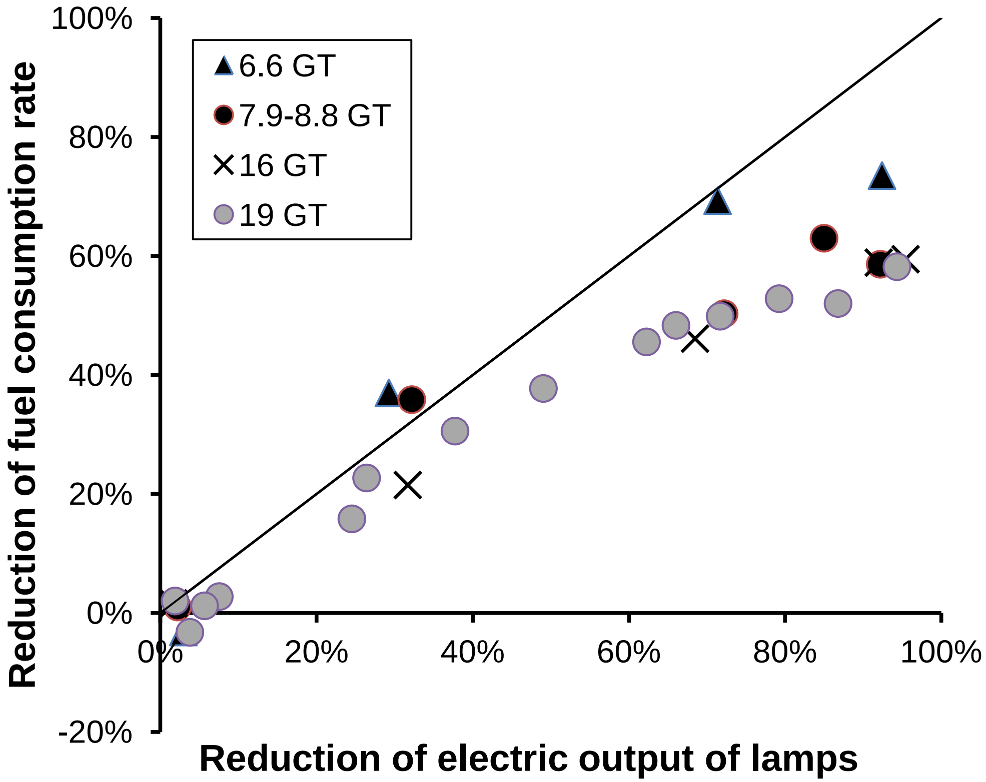

Fig. 4 Matsushita et al.

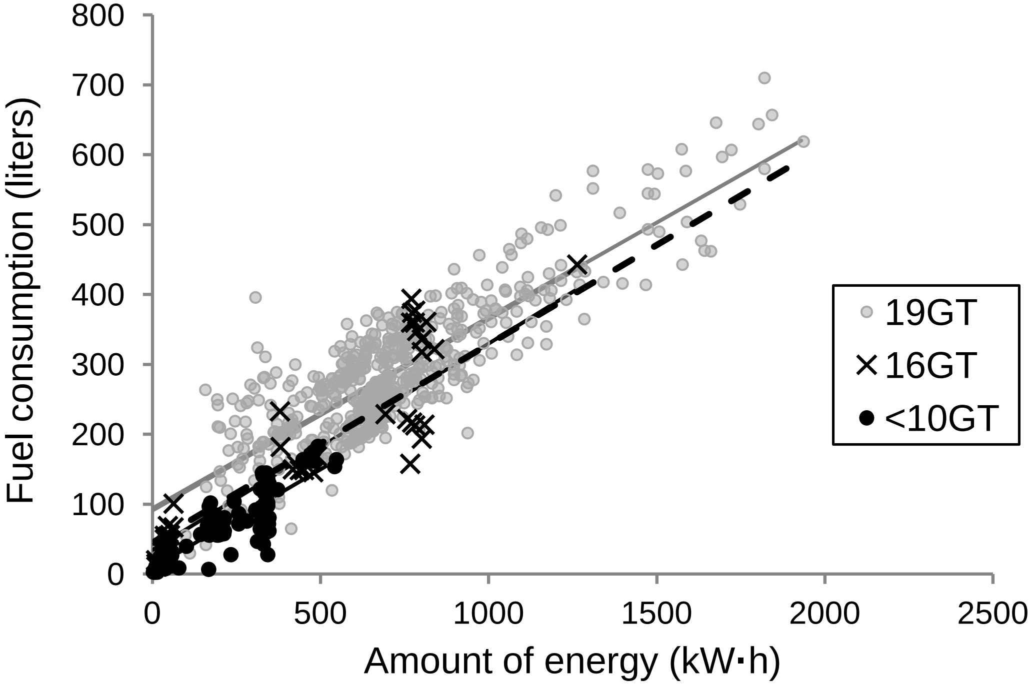

Fig. 5 Matsushita et al.