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INVESTIGATION OF SUSTAINABLE TECHNOLOGIES FOR THE DESIGN, CONSTRUCTION, OPERATION AND DECOMMISSIONING OF RECREATIONAL CRAFT

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Summary

To ensure that boating can become both environmentally sustainable and economically viable the principles of sustainable engineering must be closely observed. This paper investigates sustainable technologies and methodologies potentially available for transfer into the inland craft market, and the applicable timescales and environmental and economic implications of such. In the case study area the charter boat market is well established and important to the local economy and environmental considerations are of importance to the area in general. An initial review of the international state of the art and elicitation of local stakeholder knowledge was validated by a summary analysis of the ecological, economic and social implications of the considered technologies. Further detailed analysis of selected technologies was undertaken in the form of environmental life cycle, life cycle costing, and cost-benefit analyses.

Nomenclature

BD: Biodiesel-Electric System
BM$_S$: Individual Benchmark System Cost
BM$_T$: Total Benchmark System Cost (= $\Sigma\{BM_S\}$)
D: Diesel Engine
DEFC: Direct Ethanol Fuel Cell
EOL: End of Life Scenario
FC: Fuel Cell-Electric System
GRP: Glass Reinforced Plastic
GW: Greywater
GWC: Greywater Collection and Mains Discharge
GWD: Greywater Direct Discharge
GWF: Greywater Filter
IC: Incinerated at End of Life
ICE: Internal Combustion Engine
LF: Landfilled at End of Life
NPV: Net Present Value
RE: Recycled at End of Life
SPW: Series Present Worth
T: Taxed: Domestic Fossil Diesel (incorporating the relevant UK tax regime)
UT: Untaxed: Commercial Fossil Diesel (known as “red diesel”, subject to tax relief in UK)
WE: Wood-Epoxy Hull

1 INTRODUCTION

This paper looks at the issues of environmental, economic and social sustainability in the small craft sector, in the context of the inland charter boat market, and specifically, the Norfolk Broads. The work presented in this paper was undertaken by Newcastle University in 2005 on behalf of the Norfolk and Suffolk Boatbuilders Association [1,2]. The Norfolk Broads is a useful case study area for this industry in Europe. It is recognised as an area of environmental importance, having National Park status, and the charter boat market is well established and widespread throughout the region. The Broads is one of the fastest growing tourist regions in the UK, and in complying with the associated regulations, both those in existence and those anticipated, the local boating industry is looking to assume the position of market leaders in sustainable waterborne tourism and boating in general.

Sustainability can be summarised as development which meets the needs of the present without compromising the ability of future generations to meet their own needs [3]. Sustaining the Norfolk Broads environment against the pressures of modern use has become increasingly important. To ensure that boating can become both environmentally sustainable and economically viable the principles of sustainable engineering have been closely observed in this analysis. In the context of this paper, a sustainable design must balance the economic, environmental and social costs and needs of the area and industry overall. Total system life cycle emissions should be reduced, or their effect nullified, as much as is economically viable with due attention paid to the social implications of any decisions.

In the first instance, it was necessary to look at the current best practice employed in all the major areas of sustainable design, production, operation and decommissioning. In order to encompass the widest possible solution envelope, enabling technologies were drawn from across all fields embracing concepts of sustainable engineering. The report looked at the latest international innovations in sustainable design, and how they could be applied to a specific area: small inland charter and private craft operating on the Norfolk Broads.

2 State of the Art

2.1 Technologies for reduced carbon emissions from propulsion systems

Technologies related to the powering of the craft and propulsion system are considered, including: biodiesel, fuel cells, electric, solar/PV, wind, gas and human-power. Utilisation of waste heat in co-generation and tri-generation is becoming popular due to the limited space available onboard. Wind power encompasses sailpower (traditional and innovative rig configurations), as well as wind turbines. The economic and social costs of a number of the systems are considerable and therefore reduce their applicability. The use of biodiesel offers significant advantages in terms of required labour skills and technology, since the technology involved is basically the same as that used by the majority of motorised small craft. However the fuel itself is considerably more expensive than the tax-relieved ‘red’ diesel available to pleasure craft operating in the UK [4].

The use of solar power or hydrogen fuel cells are highly environmentally sustainable, and the positive public perception of photovoltaics as a ‘green’ technology is a major benefit; however drawbacks include expense and lack of operating expertise. Fuel cells [5] produce electricity via a chemical reaction, greatly reducing emissions, but fuel cell technology (and the availability of hydrogen) is not yet sufficiently robust to replace onboard power systems for a motorcraft of this size.

2.2 Technologies for handling and treating waste

All blackwater (sewage) and greywater (drainage) handling and treatment systems are considered here. The systems are designated as either onboard or onshore, depending on where the active treatment occurs, and include: greywater reuse, membrane separation/bioreaction, reverse osmosis, anaerobic septic system, aerobic septic system, reedbed filtration and composting toilets.

The limited options for waste handling and treatment leave few alternatives. Ideally treatment of black water would occur onboard [6], but space is an issue. To improve the sustainability of the current system of storing waste and disposing of or treating it ashore, and make this a viable alternative, a system such as reedbed filtration could be introduced. The collection and storage of greywater raises the issue of available tank space; onboard filtering is a more realistic proposal in this instance.

2.3 Sustainable materials for lower resource use, and increased recycling and reuse

The construction of the hull and subsequent disposal of spent hulls, as well as waste from the production process is a major area of concern when attempting to reduce the environmental impact of the system as a whole. There are a number of options available with varying levels of sustainability. GRP, the most widely used material in Broads craft, does not have a high level of sustainability. The use of low styrene resins, low emission processes such as infusion, and recycling can increase this [7].

The more traditional material, wood, can be sustainable if it is sourced appropriately, despite the requirement to coat the hull to prevent moisture ingress and rot. The associated manufacturing technology for thermoplastic composites is not yet sufficiently mature, and the use of biocomposite materials and resins [8] is still in development, there are currently many issues with reliability, strength, and water absorption. Steel and aluminium processing is highly energy intensive, and steel hulls also require coating for corrosion protection.

2.4 Novel propulsion technologies

Vast improvements in efficiency over a single screw propeller are available, usually at the expense of simplicity, for example: waterjet, PDX marine drive, low speed foils, podded drive, whale tail wheel and the flapping foil vehicle. Increased propulsive efficiency generates greater fuel efficiency, thereby reducing

dependence on fuel supplies, and the associated emissions. Propeller fouling can be avoided by selecting systems which minimise underwater moving parts.

Developments have led to improved efficiency and reduced disturbance of the waterbody. The Whale Tail Wheel [9], for example, offers a significant potential increase in efficiency, as well as being ideally suited to wide, flat, shallow draft craft. These systems may be applicable in specialised circumstances; however, none are well enough developed to be applicable at the moment.

2.5 Design for minimum impact on waterways

The factors identified here: wash [10], air, noise and water pollution, riverbed disturbance, foul release systems [11], propeller fouling and biofouling, must all be carefully examined when preparing a sustainable design. The cumulative effect of degradation to waterways can be significant and it is vital that in the production of a sustainable boat these environmental factors are recognised and steps are significant in preventing further detriment to the environment.

The recognition of simple technologies and lifestyle choices as part of sustainable design as a whole and limiting waste and resource depletion is an important part of sustainability. Much of this technology will transfer from existing domestic and other industry markets.

3 Local Elicitation – Addressing the social aspect of sustainable design

The elicitation of local knowledge included the views of local boatbuilders and hire operators. The objective was to better understand the current business of the interviewees, their views upon, and understanding of, various environmental and sustainability issues, and to elicit their expertise in terms of practical restraints, and knowledge of any existing projects in the area which may fall under the banner of sustainability.

It was thought that more considerate, environment-aware tourists will pay more for a quality holiday. Customers in general need to be better educated as to the effect they have on their surroundings; air and noise pollution, and wash caused by excessive speed, should be better controlled through education of users and stricter controls. If an existing technology works well, then an industry will be reluctant to replace it with an alternative system if no immediate tangible benefits are available. Whilst respondents were open to suggestions of new technology routes, cost was a barrier in many cases. Lack of reliability and new technical knowledge requirement of systems were also raised as issues.

Overall, some respondents already operate in a manner similar to ecotourism; although they do not explicitly market their activities as such; this may be a profitable future market for the industry. The respondents were generally receptive to the idea of environmentally sustainable boating; existing schemes included fleets of electric- and biodiesel-powered boats. Several solutions were considered to be technically viable, but concerns were raised over their economic implications.

4 ANALYSIS and RESULTS

4.1 Initial Analysis

This initial analysis brings together the technologies identified in the state of the art review with the local expertise and opinions of the boatbuilders and operators in the Norfolk and Suffolk area, and the expertise of the academic team, to evaluate the most appropriate technologies for the advancement of sustainable boating in the area. All identified technologies were reviewed and assigned a score to enable competitive ranking. The scores are based on expert opinion and derived from the state of the art review and the elicitation exercise. The technologies are ranked with respect to: applicability to the Broads (now or in the longer term); acceptability to the stakeholders; local and global environmental impact; and economic viability. The sensitivity of the rankings to the weighting applied to these three factors (local and global environment, and economic) is explored.

Three main results sets were analysed:

- Set 1 considers all technologies applicable now and in the foreseeable future, and does not take account of the acceptability to the local boatbuilders.
- Set 2 takes account of the ability to implement the technology now (the applicability filter), but does not apply the acceptability filter.
- Set 3 applies both this applicability filter and the acceptance of the stakeholders (acceptability filter).

The key results are presented in Figure 1; these are for the average weighted condition, the most useful case for analysis. The choice of weighting system had little effect on many of the rankings, and almost never altered the ‘best and worst’ candidates; thus demonstrating the robustness of the results to conflicting attitudes and prejudices. A complete discussion of the results can be found in Landamore et al [1]. It should be recognised that these results do not include any factor for the social acceptability to the customers (hirers), this information not being part of the scope of this study.

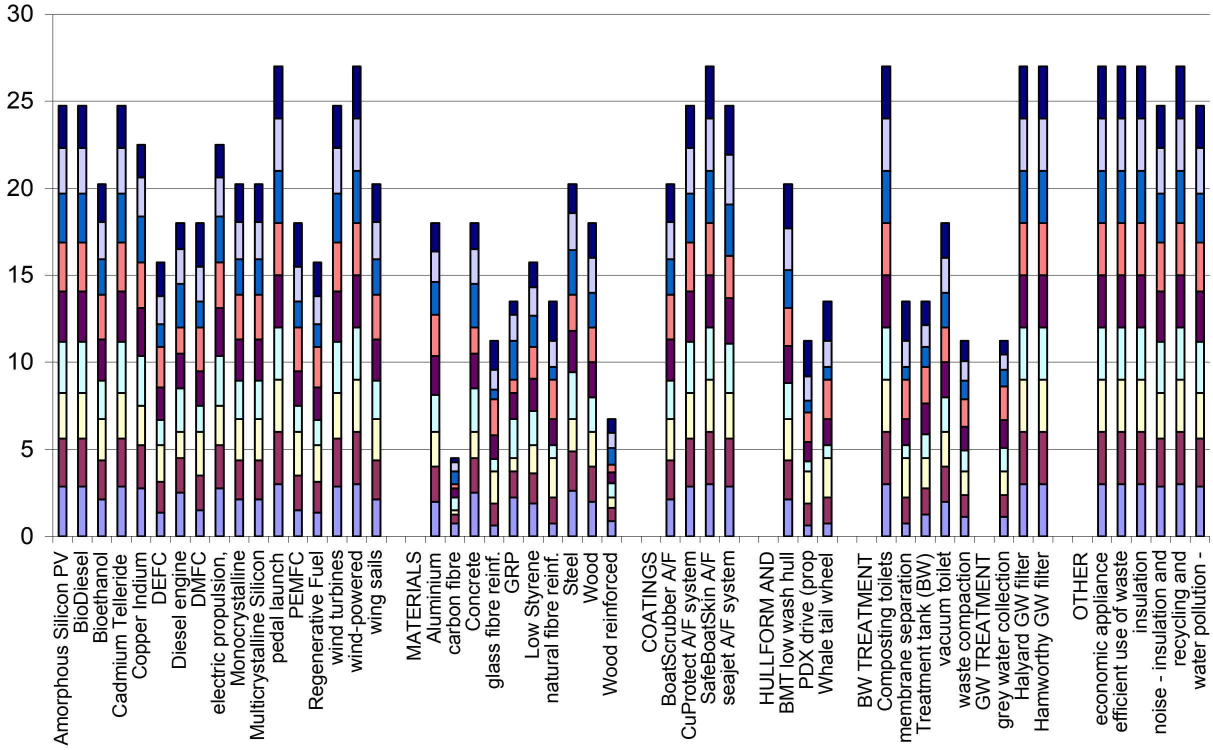


Figure 1: Initial Analysis: All Weighting Systems (Series 1-9), Stacked Columns

4.3 environmental Life Cycle Analysis

This section focuses on more detailed life cycle analyses of selected technologies. The technologies chosen by the stakeholders for further analysis against the benchmark fall into three categories:

- Powering: direct ethanol fuel cell-electric (DEFC) and biodiesel-electric systems; compared with the benchmark system, a standard direct drive diesel internal combustion engine (ICE).
- Hull Matieral: steel and wood-epoxy composite; compared with the benchmark technology, basic lay-up glass reinforced plastic (GRP).
- Greywater Treatment: filtering for ‘clean’ discharge overboard (or collection, discharge later); or a system which collects the greywater for disposal (untreated) into the mains drainage system; compared with the benchmark system, direct discharge to the waterways.

Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects associated with a product over its life cycle. In general, an LCA study consists of four main steps:

- Defining the goal and scope of the study;
- Making a model of the product life cycle with all the environmental inflows and outflows, the life cycle inventory (LCI) stage;
- Understanding the environmental relevance of all the inflows and outflows, the life cycle impact assessment (LCIA) phase;
- The interpretation of the study.

Results are normalised to the impact category indicators for Western Europe during a year; these are shown in terms of ‘Ecopoints’, enabling comparison against the standard of one

Ecopoint/area/year; highlighting significant contributions to an overall environmental problem. A benchmark system designation (see 4.4.1) enables meaningful comparison of impacts across all categories.

Powering - the largest impacts associated with the biodiesel-electric and diesel systems are almost entirely located within the usage phase of the life cycle. The DEFC system has a very low environmental impact in all categories considered.

Hull material - the three competing hull systems exhibit no impact during the usage phase. The steel hull impacts considerably more environmentally than the other systems. Wood-epoxy scores significantly better than GRP in a number of categories.

Greywater treatment: All greywater systems demonstrate major impacts from the production phase due to the manufacture of the steel tanks. The overall results show little variation; and choice may rely on individual bias toward impact category, for example, the filter system delivers minimum impact to local water quality.

A steel hull has the largest impact on the environment, the diesel engine power system after that. The next largest impact overall is the biodiesel-electric system; the choice of end of life scenario is relatively unimportant, it does not move the system's overall ranking position with the exception of DEFC. Landfilling rather than recycling this system has a relatively large impact, because there is almost no discernible impact from the usage phase, but on average 5 fuel cells are used and disposed of over the 30 year life compared to one diesel engine.

4.4 Life Cycle Costing Analysis

The case study fleet size is approximately 800 boats. The established base system requirement, to ensure results could be meaningfully compared, is:

- Generic 12.2m 4 berth motor-cruiser design, lifespan of 30 years, 30 weeks active use per year;
- Standard single skin hand lay-up GRP hull with marine ply bulkheads;
- Powered by a direct drive diesel engine (32KW, lifespan 30 years) on an average loading cycle;
- 100 litre fuel tank capacity, standard starter domestic backup batteries (life span approximately 6 years);
- Direct discharge of greywater into the river system, one freshwater tank.

All hull and tank materials have a 30 year lifespan. This benchmark system designation enables meaningful comparison of impacts across all categories, as well as within a category; it also enables comparison with other external systems, regulations and benchmarks.

All material, labour, overhead and end of life disposal costs must be considered for all components of all systems. Each system is costed over the predicted average life of the craft, using Net Present Value [12]. Some costs are difficult to define, especially where innovative technology is constantly evolving. Some costs fluctuate continuously with market influences, for example, fossil fuels. The cost of a DEFC capable of powering this system is currently unknown as these are not yet commercially available. Estimated current and future costs, assuming market success of this product, have been included, to give an idea of the potential for this technology at a later date.

4.5 Life Cycle Cost Breakdown Results

The average cost of each system is broken down into build, operation and end of life costs. Cost inputs are calculated for a range of values; some fluctuate regularly, while for others the input parameter must be estimated due to a lack of solid information from which to source the data. The powering systems (figure 2) display very little effect from end of life costs. The biodiesel-electric and fuel cell-electric systems cost more than the diesel engine to build and operate.

	Build inc materials	**Op inc materials**	**End of life LF**	**TOTAL**
Diesel(UT) BENCHMARK	**5740**	**20136.536**	**0.80**	**25877.34**
Biodiesel	7081.5	47441.52	0.82	54523.84
Fuel Cell	203149.5	190699.83	0.93	393850.26
Diesel(T)	5740	49344.963	0.80	55085.76

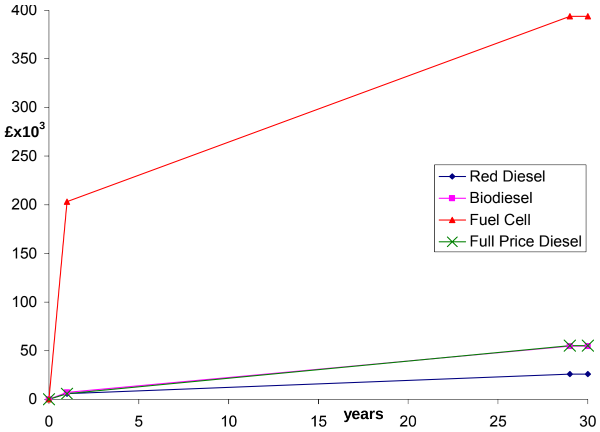


Figure 2 – Powering Life Cycle Cost Breakdown

The steel hull is cheaper to build, operate and recycle than the GRP (incinerated) benchmark system, but slightly more expensive to landfill. The wood-epoxy system is more expensive than the GRP in all three phases (figure 3). The greywater filter system is much more expensive to build and operate than the benchmark, but incurs the same end of life cost. The GW collect system is marginally more expensive initially and at end of life, and the same cost to operate, as the benchmark.

	Build inc materials	**Op inc materials**	**End of life RE/IC**	**TOTAL**
GRP BENCHMARK	**26478.13**	**1189.12**	**80.00**	**27747.24**
Steel	12350.00	8063.16	-750.00	19663.16
Wood-Epoxy	33262.91	2378.23	85.25	35726.40
GW Disch. BENCHMARK	**287.00**	**250.43**	**0.25**	**537.68**
GW Collect	322.00	250.43	0.50	572.93
GW Filter	1164.00	4936.99	0.25	6101.24

Figure 3 – Hull Material and GW Cost Breakdowns (in £)

4.6 Cost-benefit Analysis

Realistic comparison of technologies for adoption by industry must consider the economic and environmental implications of such a choice. The lifecycle cost can be compared against the environmental effects of each system to give an analysis of the cost versus benefit. Those systems demonstrating worse environmental performance than the benchmark are discounted from any further analysis as there is no environmental improvement available; they are: Steel hull (landfilled and recycled); GW Collect and Mains Discharge System (landfilled) and GW Filter (landfilled).

An assumption can be made whereby an acceptable level of cost increase exists for a unit reduction in environmental impact. The cost per ecopoint environmental improvement required to implement the system has been calculated; the value of an environmental impact reduction to the business, and the system cost required to meet that value, can be judged. The environmental score is measured in ecopoints saved, and represents the impact of the craft over its assumed 30 year life.

4.7 Cost-benefit analysis Results

Effective analysis of the two data fields (LCC and LCA) can identify cost-efficient and environmentally-sound solutions [2]. The cost per ecopoint saved is a comparison of the environmental improvement of the system against the technology benchmark (BM_S) (measured in ecopoints saved), and the additional cost of the system above the benchmark. If the system is cheaper than the benchmark (a negative cost), then it is deemed viable at this level (figure 4). The next levels assume that an additional cost premium of 1% or 5% benchmark system cost per ecopoint environmental improvement is acceptable. Evaluating the systems in this way, against BM_S, provides information relevant to the inclusion of that system into any craft.
In order to be able to compare the relative merit of alternative systems in different technology groups an analysis is needed that uses as its base the entire combination of technologies defined as the benchmark case. The required cost premium as a percentage of the entire benchmark cost (BM_T) for these three systems is calculated. The additional cost of each alternative is compared with the environmental improvement and the total benchmark cost.

	POWER 1			POWER 2			HULL		GREYWATER		
	D Re	BD Re	FC Re	D Re	BD Re	FC Re	GRP Lf	WE Lf	GWD Re	GWC Re	GWF Re
COST(**£**)/ ECOPT SAVED	**-11.33**	264	1,767	**-11.33**	**-6.90**	1,626	**-145**	2,036	**-8.85**	689	92,691
1% premium	**Yes**	No	No	**Yes**	**Yes**	No	**Yes**	No	**Yes**	No	No
5% premium	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	**Yes**	No	**Yes**	No	No

Figure 4: Cost (£) /Ecopoint and Viability of Systems under Different Acceptable Cost Premiums

Key:
D: diesel engine
BD: biodiesel-electric system
FC: fuel cell-electric system
WE: wood-epoxy hull
GWD: greywater direct discharge
GWC: greywater collection and mains discharge
GWF: greywater filter
Re: Recycled at end of life
Lf: Landfilled at end of life

POWER 1 Benchmark:	Diesel powered internal combustion engine using ‘untaxed’ diesel, components landfilled at end of life.
POWER 2 Benchmark:	Diesel powered internal combustion engine using ‘taxed’ (UK regime) diesel, components landfilled at end of life.
HULL Benchmark:	GRP hull, incinerated at end of life.
GREYWATER Benchmark:	Greywater discharged directly into surrounding waterways untreated, components landfilled at end of life.

The systems which show a reduction in cost against benchmark are:

- Diesel engine (recycled) against **‘**untaxed’ and ‘taxed’ diesel benchmark;
- Biodiesel-electric (landfilled and recycled) against **‘**taxed’ diesel;
- GRP hull (landfilled);
- GW direct discharge (recycled).

There are a number of technologies which fall close to the ‘1% benchmark cost per ecopoint saved’ limit:

- Biodiesel-electric (recycled and landfilled, against ‘untaxed’ diesel) requires 1.02% and 1.03% benchmark cost premium, respectively;
- DEFC-electric systems (recycled and landfilled, against ‘taxed’ diesel) requires 2.94% and 3.02% benchmark cost premium, respectively.

5 discussion

5.1 Initial Analysis

This outcome provides a ranking of all the technologies considered, analysed in a systematic manner. The technologies to be adopted in a design are a matter of subjective choice but should logically belong to the groups with the highest rankings. The highest ranking technologies, which score well under any value system, present themselves clearly. The more interesting analysis involves the ‘mid-range’ results, where the selection of value system (weighting) alters the score of a technology.

5.2 Life Cycle Analysis

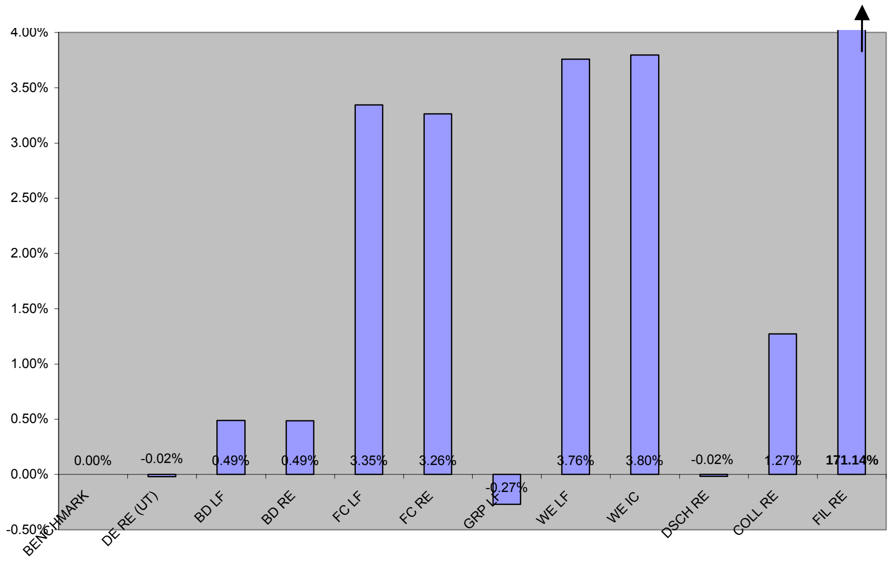
Powering - the biodiesel and fuel cell systems incur almost all their impact during the production phase; these impacts also exist for the diesel engine, but are overwhelmed by the usage phase. Aside from the production phase, there are few impacts associated with the use of DEFC; the LCA supports the use of this, providing the suggested system can be developed commercially for power generation on this scale.

Hull Materials - there are major environmental effects from the production of steel, this system shows the largest impacts across all categories and in total, whereas the GRP and wood-epoxy systems rank 4th and equal 5th respectively in terms of total impacts. The impacts of GRP are more than double those of the wood-epoxy hull.

Greywater Systems - the benchmark greywater system shows minor impacts related to the discharge of the polluted water, and major impacts from the manufacture of the steel tanks. The greywater collection and filtering systems show little difference overall and are small impacts when compared to the effect of the powering systems or hull materials; in terms of overall environmental impact, any changes to the greywater treatment system have a relatively insignificant impact. These results recommend the direct discharge system overall, but if the impact of building the tanks is ignored, it is likely the filter system would score best.

5.3 *Life Cycle Costing and Cost Benefit Analysis*

Although the biodiesel-electric system requires an additional input of just 1.02% BM_S (or 0.49% BM_T) per ecopoint environmental improvement, this is a significant absolute cost because of the net environmental improvement gained. It is clear from this analysis that some systems, e.g. the GW filter (recycled), will never represent good value; this system would require an extra 171% BM_T per ecopoint improvement.



DE: diesel engine
BD: biodiesel-electric
FC: direct ethanol fuel cell-electric
GRP: GRP hull
WE: wood-epoxy hull
DSCH: GW direct discharge
COLL: GW collect & discharge
FIL: GW filter
(UT): untaxed diesel
(T): taxed diesel
LF: landfilled
RE: recycled
IC: incinerated

Figure 5– Cost Premium required/Ecopoint saved as Percentage of the Total Benchmark System Cost

Figure 5 shows the distribution of the cost premium required per ecopoint improvement for each technology against the total benchmark base cost (BM_T): the three benchmark systems summed. Lower column height represents greater environmental benefit per £ additional investment. Negative figures represent cheaper than benchmark options demonstrating environmental improvement which therefore hold no barriers to implementation.

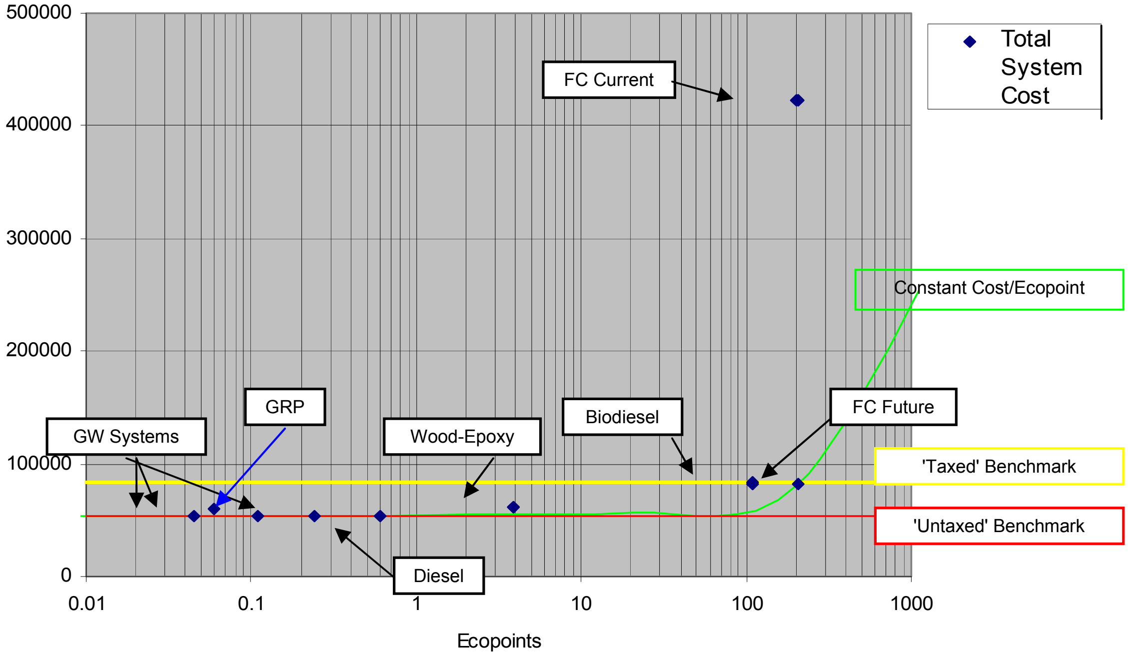


Figure 6 – Representation with x axis plotted as a logarithmic scale (base 10): Absolute Cost of Systems plotted against Ecopoints Saved

The direct ethanol fuel cell-electric (DEFC) has an average system cost of £393,850. This unproven and currently unavailable (for this application) technology has been attributed a high cost of £100,000 per fuel cell, however successful development and market implementation of this technology should see costs fall dramatically. Therefore the 'FC Future' figure of £10,000 per cell has been included (figure 6). The lower system cost is greater than the benchmark with 'untaxed' diesel, but £879 less than the 'taxed' diesel benchmark, with a lifecycle environmental benefit of 208.2 ecopoints. The exact costs of DEFC units of this size are very difficult to predict; assuming the unit price falls to near £10,000, this system can become cost efficient against 'taxed' diesel. It is highly likely that this cost could fall even further.

Figure 6 shows all technologies plotted against absolute cost of system and number of ecopoints saved (against benchmark) with the x-axis plotted as a logarithmic (base 10) scale. Minimum cost with maximum ecopoints saved is desirable. The contour (figure 6) is equivalent to the DEFC system cost: 'FC Future'. Any technologies falling on or below this cost/ecopoint contour exhibit environmental properties per £ extra investment similar to or better than this; and of the current technology costs, Biodiesel-electric clearly exhibits the greatest environmental improvement. Compared with the 'taxed' (UK regime) BM_T, there is a small saving if this system is used. The remaining technologies exhibit little environmental improvement in comparison.

The wood-epoxy system exhibits greater environmental improvement, at a greater absolute cost and cost/ecopoint saved than the GRP, Diesel Engine (recycled, 'untaxed' diesel) or GW collect or discharge systems: these all fall within the 0.25% BM_T/ecopoint contour. Better performing technologies will be preferred for equivalent cost/ecopoint saved.

If a finite level of additional funding were available, lower scoring technologies may be reintroduced into the decision-making process. For example, if £10,000 funding were available to improve the overall environmental performance of a fleet of 50 boats, the optimum solution would be introducing one wood-epoxy hull (figure 7).

System	Additional system Cost (£)	Ecopoints saved	No. of systems	'Fleet Cost' (£)	'Fleet' ecopoints saved
Wood-epoxy	7,962	3.91	1	7,962	**3.91**
GW collect	31	0.045	50	1,550	2.25
GW discharge	5,561	0.06	1	5,561	0.06

Figure 7: £10,000 (3.7% fleet BM_T) additional funding available, fleet of 50 boats

Equally, if a fleet of 100 craft were considered, a £10,000 additional budget (1.85% fleet BM_T) provides a different optimum solution: installing 100 GW collection systems for 4.5 ecopoints improvement. Assuming the owner (fleet size ≥1) could spend an additional £30,000, then 1 biodiesel-electric system would provide the greatest benefit. For a fleet of 100 boats, £30,000 equates to only 5.5% fleet BM_T.

These are through life costs, and as such the total cost may not be borne by one person or company; the cost is also spread over the entire 30 year life of the craft (figure 2). If the current UK tax regime is considered (ignoring the dispensation for pleasure craft to use 'red' tax-relieved diesel), then the performance of the biodiesel-electric system improves dramatically against this 'taxed' diesel benchmark.

The cost of environmental improvement in one particular category per ecopoint is also calculated. However, considering one category in isolation can give misleading results. If a particular area is of specific interest, possibly to facilitate the achievement of National, European or International standards, then this method may be valid as a comparison of different options.

6 Conclusions

The technologies considered have varied impacts upon the environment which are not always intuitive. The smaller impacts should not be ignored; when balanced against the cost of implementation these may become efficient methods for reducing a craft's impact on the environment whilst remaining commercially viable. Overall, the life cycle analysis demonstrates that environmentally the best technologies are the wood-epoxy hull, direct ethanol fuel cell-electric powering system and the direct discharge GW system; with biodiesel-electric, GRP and the remaining GW systems also scoring well. Excepting steel as a hull material, the major impacts are within the powering system.

The inclusion of economic factors produces an alternative set of results: the high cost of the most environmentally effective technologies (fuel cell-electric and wood-epoxy) makes them an ineffective way to spend resources at this time. This cost benefit analysis demonstrates that the most cost effective use of resources is firstly, the implementation of the 'cheaper than benchmark' systems which still exhibit an environmental improvement (all benchmark systems with alternative end of life {EOL} scenario). In addition, both biodiesel-electric (landfilled and recycled) systems cost less than the 'taxed' diesel benchmark, whilst still exhibiting an environmental improvement.

If it is accepted that additional costs can be incurred to reduce environmental impact, then systems incurring the smallest cost penalties per ecopoint improvement should be used. These are the biodiesel-electric system (both EOL, against 'untaxed' diesel benchmark), and the GW collection system (recycled EOL). All other systems, with the exception of the GW filter and those demonstrating no environmental benefit, fall within 3.8% additional BM_T per ecopoint improvement (see Figure 5). This analysis against entire combined benchmark cost (BM_T) does not include the 'taxed' diesel option, as this would alter the benchmark case. However, when comparisons are made against a 'taxed' diesel benchmark system, the biodiesel-electric systems are 'cheaper than benchmark' and the DEFC systems score significantly better than when compared with the ‘untaxed’ diesel system; they also fall within an additional 3.8% ‘taxed’ BM_T/ecopoint improvement range.

Any technologies falling on or below the marked contour (See Figure 6) exhibit environmental properties per £ extra investment similar to or better than “FC Future”; of the lower scoring technologies, the wood-epoxy system exhibits the greatest environmental improvement. The other systems fall below this contour due to low cost, but exhibit minimal environmental improvement.

A finite level of additional funding could revalidate lower scoring technologies. The optimum solution if £10,000 is available to improve the overall environmental performance of a fleet of 50 boats is one hull replaced with wood-epoxy. For a fleet of 100 craft, an additional £10,000 would install 100 GW collection systems. For an additional £30,000, the optimum solution becomes 1 biodiesel-electric system.

To improve the environmental performance of a small charter craft for use on the Norfolk Broads for today’s market:

- Powering - biodiesel-electric, recycled at end of life or diesel engine (recycled). However, if the red diesel concession were removed, the biodiesel-electric (recycled) would become the cheapest system overall, the fuel cell-electric systems (landfilled and recycled) would also then incur a relatively lower premium;
- Hull material - a GRP hull, landfilled at end of life should be used;
- Greywater - should be discharged directly into the waterways, and the system components recycled at end of life. As an alternative, the greywater collection system also represents good value at 1.27% total system cost/ecopoint.

In conclusion, a number of systems can be implemented without extra cost to the builder/operator, and the majority of systems can be implemented if a premium of a small percentage of system cost is applied per ecopoint environmental improvement gained. It is clear that environmental improvements can be made without additional total cost, often simply by changing end of life strategy.

7 References

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