FUEL CELLS IN SHIPPING:
HIGHER CAPITAL COSTS AND REDUCED FLEXIBILITY

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Abstract: The paper discusses some main economic characteristics of fuel cell power production technology applied to shipping. Whenever competitive fuel cell systems enter the market, they are likely to have higher capital costs and lower operating costs than systems based on traditional combustion technology. Implications of the difference are investigated with respect to investment flexibility by the use of a real options model of ship investment, lay-up and scrapping decisions under freight rate uncertainty. A higher capital share of total expected costs can represent a significant opportunity cost in uncertain markets. The paper highlights the significance of accounting properly for value of flexibility prior to investment in new technology.

Keywords: fuel cells, maritime transport, price uncertainty, flexibility.
JEL classification: O33, R40, D81.

1. Background and objectives

Due to its international character, the maritime transport industry has avoided many environmental regulations that other energy intensive transport services are usually faced with. Following this tradition, shipping is not included in the Kyoto targets for cuts in global CO_2 emissions even if the industry is responsible for approximately 2% of such emissions. Most likely, some of these rather unique arrangements for maritime transport will not survive the steadily increasing environmental concerns in international politics (Mæstad et al. 2000). Occasional accidents − most recently the sinking of the oil tanker Prestige outside Spain in November 2002 − also contribute to increase the political pressure towards a more strict environmental regime for all types of maritime transport.

Fuel cell technology[1] is often regarded as the ideal solution to the environmental problems that arise from carbon based power production in shipping and other transport industries.

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[1] See IEA (2003) for an informative website on fuel cell technology.

Wide use of fuel cells is expected to reduce local and global pollution from combustion engines currently dominating the markets, but any prediction on when fuel cell systems may take over as a major power production source is as uncertain as it is controversial. This is true even in road transportation, where the technology is maturing rapidly. A recent example: The General Motors Chairman, Jack Smith, forecasted recently that it can take 40-50 years before hybrid and fuel cell cars are fully commercialized due to their excessively high price tags. He said so even if his own company, and other car manufacturers, are spending large amounts on research in the field, and the first fuel cell vehicles are about to appear in the marketplace (FT 2003). This is in line with IEA projections saying that fuel cells will not play a significant role in global energy markets for the next 25 years (WEO 2002, p. 30). Some references cited below are far more optimistic.

As far as propulsion of ships is concerned, no fuel cell system yet exists that is of interest to any major market segment. Whenever such systems become competitive, the potential market is vast (Zvi et al. 2000).

This paper addresses some economic aspects of using fuel cells in shipping. The intention is not to fulfil the immense task of predicting when a fuel cell revolution may take place; nor is it to present a technical analysis of different fuel cell systems and applications. The focus is entirely on the economic side of the issue. The objective of the paper is to point at some main economic characteristics common to most fuel cell systems of interest, and to investigate one specific aspect that seems to be important, namely value of flexibility. Since shipping markets are volatile, flexibility can have great economic value. It is worth discussing whether the amount and character of flexibility could change by switching to fuel cell power production.

The remaining part of the paper is structured as follows: Section 2 describes some main economic characteristics of fuel cell technology, emphasizing implications for maritime markets. Even if the future of fuel cell technology is uncertain, many possible consequences of using the technology can be discussed parametrically, and in a shipping context, in order to improve the basis for investment and operations. Section 3 contributes to this discussion by investigating the value of flexibility in a market with freight rate uncertainty and options to lay up ships when prices are low. The analysis is based on a real options approach. It argues that significant amounts of flexibility could be lost by switching to fuel cell power production. Section 4 concludes.

2. Fuel cell costs

General characteristics

The chemical basis for any fuel cell regime is that energy is produced from hydrogen and oxygen by the reaction $2H_2+O_2 \rightarrow 2H_2O$+energy. Several hydrogen carriers can be used, and the exact chemical process could be more complex. Yet, this chemical relationship between two of the most common elements demonstrates, in its simplicity, the potential economic power of fuel cell power production as opposed to more traditional combustion engines. The main characteristics can be summed up as follows:

- Fuel cells are energy efficient because electric power is produced directly from a chemical reaction instead of indirectly through the thermal and mechanical energy of combustion engines. The efficiency of a combustion engine is typically in the range 25-30%, while the similar efficiency of a fuel cell system is 40-60%. This implies a potential for operating cost savings. Since fuel cells have no moving parts, maintenance costs may also be lower.

- Fuel cells are much cleaner than combustion engines, and except for technological breakthroughs, environmental policy can probably more than anything else make fuel cells competitive. Fuel cells are cleaner because higher efficiency implies lower emissions, and because some fuel candidates − hydrogen gas in particular − contain less pollutants than more common fossil fuels. Fuel cells do produce carbon monoxide (CO) and carbon dioxide (CO_2), sulfur and other pollutions as long as the energy carrier contains such substances, but usually in small amounts. Since no explosion occurs, noise is restricted to compressors, pumps etc. This could be especially valuable in short-sea shipping, cruise traffic and military applications. In a marketplace where increased taxation of external costs is expected, the low emission levels characterizing fuel cells represent a potential for further operating cost savings. Most emission taxes, e.g. a carbon tax in the aftermath of the Kyoto Protocol, generally favors fuel cells relative to other technologies of interest. Fuel cells can even more easily outperform other technologies in a close-to-zero emission regime for international shipping. Such a regime, which may soon be introduced by the European Union, could lead to more rapid changes than previously expected, since the cost of installing cleaning equipment in existing ships could be very high.

- Fuel cells need hydrogen in one form or another. Hydrogen is an explosive gas that is difficult to store, transport or convert (reform) from other substances before it can go into a fuel cell. For cost and safety reasons, hydrogen carriers other than pure hydrogen could be more useful for the shipping industry.

- The main challenge for the developers of fuel cells is to reach feasible technical solutions that are not too expensive. The prices of current fuel cell systems are 5-20 times the price of similar combustion engines.

- Five main fuel cell candidates are currently under development: PEM (proton exchange membrane), DM (direct methanol), PA (phosphoric acid), SO (solid oxide), and MC (molten carbonate) fuel cells. One important difference lies in the operating temperature, which spans from below 100°C (PEM/DM) to above 600°C (MC/SO). The major advantage of low temperature fuel cells is a short startup time. The major disadvantage is a need for expensive catalyzers and clean fuel. The latter is obtained by using hydrogen or by reforming other hydrogen carriers. High temperature fuel cells could require many hours for startup, but as they are less sensitive to pollution, more fuel candidates exist.

The characteristics above imply that various fuel cell systems appeal differently to different markets. The level of maturity also varies. All fuel cell cars under development seem to use the PEM technology. High temperature fuel cells, which may be more interesting in maritime transport, are still at a more experimental stage (Würzig 2002).

Most studies of marine applications of fuel cells, like Sattler (2000), Allen et al. (1998) and Bolind (2000), consider some direct cost aspects, but they pay more attention to technical issues. Karni et al. (2000) present a relatively detailed cost analysis of propulsion systems for a representative ship, comparing two types of (5.5 Mw) fuel cells with traditional diesel engines of similar size. The analysis indicates that the optimal choice of technology will be a trade-off between investment costs and operating costs. Without ignoring the fact that many parameters are uncertain, it is concluded that fuel cells can become competitive for reasonable levels of fuel costs. Bingen et al. (2000) focus on fuel cell propulsion in ferry operations in Norway, and conclude similarly.

Würzig et al. (2002) are more skeptical than the references above, emphasizing that all cost estimates are simply target values. Existing fuel cells are far more expensive, and any cost estimate long into the future is highly speculative. As far as propulsion in shipping is concerned, the technology has hardly been tried out in a scale of interest.

There seems to a general consensus that fuel cells will not become a major propulsion source in long-haul shipping in the foreseeable future, mainly for two reasons. First, much of this trade is fueled by crude oil. Crude oil is cheap, and it cannot be reformed by existing technologies. Nor are cleaner fuels such as hydrogen or methane satisfactory alternatives due to cost and safety concerns. Diesel is more promising, but its content of sulfur may also create technical problems and raise costs. Second, high temperature fuel cells – the most appealing type in this case – are most effective when operated at 20-40% of total capacity, while combustion engines are most effective at 70-90% loads. Efficient long-haul shipping based on high temperature fuel cells therefore requires much capacity that rarely would be needed. The situation is different in short-sea shipping, where spare power is in higher demand due to safety concerns and need for efficient harbor operations.

From the comments above, it is clear that fuel cells make more sense in short-sea shipping. This argument is strengthened by the fact that low emission levels are also more valuable in short-sea shipping. Although much of the discussion below is general in nature, it is probably most relevant to short-sea shipping with cargo and passenger ferries, shuttle tankers or ships sailing on inland waterways. New environmental policies may improve the opportunities in long-haul shipping, too, but there is a long way to go before a new VLCC is propelled by a fuel cell system. On the other hand, fuel cells could be useful for auxiliary power production even if not being efficient for propulsion. They could, for example, replace diesel generators in cruise traffic to reduce noise and other emissions.

Investment costs

Investment costs for propulsion system using state-of-the-art fuel cell technology are typically estimated to $4000-7000 pr kW, while predicted prices range from $100 to $1500 pr kW (Hörmandinger and Lucas 1996, Bolind 2000, Karni et al. 2000). Karni et al. (2000) estimated the cost of a representative fuel cell system (5.5 Mw) to $6500-6800 pr kW in a comparative study of alternative propulsion systems for ships. This was approximately 50% higher than the estimate for a similar IDE (integrated diesel) system, and almost three times the estimate for a CODAD (conventional diesel) system. Bolind (2000) is more optimistic with respect to large fuel cell installations suited for ships, expecting prices as low as $1000-1500 pr. kW before the end of the current decade. The spread in cost estimates reflect to some extent price differences between various applications, but mainly it demonstrates that reliable estimates cannot be obtained at the current stage of development.

Investment cost comparisons must, in order to be meaningful, take into account differences in expected lifetime, and degradation over the life-cycle. Fuel cells contain some components that tend to degrade over time due to air and fuel impurities. High-temperature fuel cells degrade each time the temperature in the cell is changed. Also, it may take hours or days to cool down or warm up the cells, so the temperature should be kept close to the operating temperature even when the cell is idle. This is of interest with respect to maintenance, since some complex trade-offs could arise between operating efficiency, overhaul and degradation.

The technological potential is uncertain as far as lifetimes are concerned. Initial marine MC (molten-carbonate) fuel cells may have to be replaced after approximately 40000 hours. Normally this covers no more than five years of service. Such a lifetime target is reached most easily when the fuel is natural gas. Stack replacement costs must be accounted for along with other maintenance requirements, but otherwise, most fuel cell power systems can probably live as long as other engines, typically 20-30 years (Allen et al. 1998, Würzig et al. 2002).

Operating costs

The main cost advantage of fuel cell power production lies in a potential for lower operating costs. The gains obviously depend on the choice of fuel, because the expected price of different fuels usually differ in efficiency terms. Differences in price uncertainty could also play a role due to switching options, e.g. when slow steaming is profitable at high fuel prices.

In a comparative study of an MC (molten-carbonate) fuel cell system and an IDE (integrated diesel) system, Karni et al. (2000) reported that the fuel cell system consumed 25% less fuel. Based on comparisons of various fuel cell and combustion systems, Allen et al. (1998) claim, more generally, that fuel cells could reduce fuel costs by 50%.

As for absolute cost levels, Karni et al. (2000) estimated total annual fuel costs to $80 pr kW for the MC fuel cells versus $110 for the IDE system. This is based on American data, and a diesel price of $270 per ton. The fuel cost reduction is not enough to compensate for higher initial investment costs in a life-cycle perspective. If the fuel cell were to be competitive over a 25-year life-cycle, the diesel price would have to be closer to $600. Since the latter is still below the price level in many European markets, the analysis by Karni et al. indicates that fuel cells could be competitive for some reasonable combinations of factor prices.

Infrastructure

The need for infrastructure is an obstacle to rapid introduction of fuel cells in transportation. Thomas et al. (2001) estimated long-run infrastructure costs to be lower for gasoline than for hydrogen as far as road transportation in the United States is concerned. Ogden et al. (1999) reported similar results. Total infrastructure costs do not amount to more than approximately $1000 per car sold, so the importance of differences in this regard should not be exaggerated. I am not aware of similar studies of shipping markets. Intuitively, lower infrastructure costs can be expected in maritime markets due to fewer nodes in the transport network.

On-board space requirements could also create an infrastructure cost barrier, but probably not a critical one. Allen et al. (1998) claim that the need for space is of similar magnitude as for traditional engines (2.5 cubic ft/kW for a representative MC fuel cell). Most systems could probably also be designed to avoid conflicts with the normal utilization of space in a ship.

Uncertainty

Shipping markets are volatile due to the combined effect of inelastic and stochastic transport demand, capacity constrained supply, and fluctuating factor prices. Oil price changes can have surprising effects on freight rates and revenues because supply and demand shift in the same direction. Increasing oil prices are typically related to decreasing demand for some trades (oil in particular), but also to decreasing supply as the optimal speed goes down (Stopford 1992, Wergeland and Wijnolst 1996). Such effects make the markets highly dependent on external shocks, many of which originate from OPEC decisions and events in the Middle East.

One question in this respect is whether a hydrogen-based power production regime could change aggregate market uncertainty. The answer is not evident as it could depend on the market segment, and many economic forces could be involved. On the one hand, fuel cells make shipping even more capital intensive, and more influenced by irreversible investment and capacity constraints than today. This tends to increase overall risk and uncertainty. On the other hand, lower cost uncertainty may result, as operations become less dependent on the oil price, which is usually the most volatile factor price in shipping.

Most current fuel cells are fueled with hydrogen, which is most easily developed from natural gas. Alternative hydrocarbon fuels such as methanol, alcohol or ammonia cannot be excluded in the future, but natural gas, methanol and diesel are probably the most important alternative fuels (Bolind 2000). In a study of US energy security, Greene (1999) claims that use of natural gas will reduce OPEC market power, and make global fuel markets more competitive due to the availability and distribution of gas resources. It is an issue for further research whether this could also reduce the overall fuel price uncertainty by significant amounts.

3. Flexibility analysis

Objectives and models

The previous section described some economic characteristics that are important when fuel cells are to be valued up against traditional combustion engines in shipping. The core of the matter seems to be the distribution of capital costs versus operating costs and other costs spread over time. The question is whether some solutions are more flexible than others, and what the implications of the difference might be. This section uses a real options approach to exemplify and quantify experimentally the value of flexibility in a classical setting, with opportunities to lay up and to scrap ships when freight rates are low. I discuss the implications for optimal investment behavior and ship valuation arising from:

- the distribution of capital costs versus operating costs (expecting that fuel cells will be more costly to build, but less costly to operate than combustion engines)
- increased operating costs after a lay-up period (expecting that a fuel cell system could degrade by being shut down completely)
- restrictions with respect to the number of lay-up periods (for the same reason as above)

The analysis is parametric as it looks at alternative distributions of capital costs versus operating costs, starting with a baseline technology. In the most extreme case, the capital cost share is twice the similar share of the baseline technology. With reference to the cost estimates in the previous section, such a high capital cost share could reflect fully fuel cell based power production under certain assumptions. Some of the intermediate cases, where capital costs increase less, more likely reflect combined solutions where fuel cells systems are used for auxiliary power production.

The first part of the analysis is based on two standard real options models by Avinash Dixit: the entry-exit model and entry-exit-scrapping model. The second part also uses a modified version of the latter.[2]

The entry exit model can be described as follows (see Appendix 1 for details): A ship is either active (operating) or inactive (laid-up). No revenue or cost applies when the ship is laid-up. The annual cost of operation, c, is constant. Then the net present cost of continuous operation equals c/r, where r is a fixed interest rate. Lifetime restrictions are disregarded.[3] The annual revenue from operation is stochastic, given by a geometric Brownian process with no drift.[4] It can be shown that the expected net present revenue of continuous operation equals p/r, where p is the current value of the freight rate. A fixed activation cost, A, applies each time a ship starts to operate, while a fixed lay-up cost, L, applies whenever a ship is laid up.

From a standard net present value rule, a laid-up ship should be set to operate as soon as $p/r \geq A + c/r$. Then the expected net present value of a decision to enter the market, and remain active, is non-negative. Similarly, an active ship should be laid up as soon as $c/r \geq L + p/r$. Then the net present cost of sustained operations exceeds the total opportunity cost, which is the sum of the exit cost and the expected, net present income loss.

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[2] The original references are Dixit (1988&1989), which draw on pioneering work by Mossin (1968) and Brennan and Schwartz (1985). The models are explored numerically by Dixit and Pindyck (1994, ch. 7). The modified version of the entry-exit-scrapping model is a minor extension of a model discussed by Sødal (2001).

[3] More realistic representations complicate the model. The lifetime is usually so long that the error from this simplification is probably minor, unless the ship is very old.

[4] See Dixit and Pindyck (1994) for a discussion of stochastic processes of this kind. Operating costs are usually also uncertain, but since freight rates tend to be more uncertain, I abstain from modeling cost uncertainty.

Both decision rules above are incorrect because the investments are (partly) irreversible, and the value of waiting for information is ignored. A correct, option based calculation will show that one should wait longer. A ship currently laid up should not start to operate before p/r exceeds $A+c/r$ by a fixed margin. The margin could be large if the freight rate is very volatile. An active ship should not be laid up until p/r is a fixed margin lower than $c/r-L$. This margin is also increasing in uncertainty. The optimal decision rules can be summed up as follows:

- If the ship is currently inactive, it should start to operate when the freight rate hits a certain value p_A from below (where $p_A>c+rA$).
- If the ship is currently active, it should be laid up when the freight rate hits a certain value p_L from above (where $p_L<c-rL$).
- The ship should remain in the current state – active or idle – as long as the freight rate stays between p_L and p_A.

The entry-exit-scrapping model is an extended model that also considers ship investment and scrapping (see Appendix 2 for details). If scrapping is ever to be of interest, we now have to add a small, but positive running cost during lay-up; i.e., a mothballing cost. We also include the cost of a new ship, and the scrap cost (or value) of an old one. Two additional investment thresholds will now encircle the two thresholds of the previous model (p_L, p_A) as follows:

- A ship should be acquired, and start operations, when the freight rate hits a fixed value p_I from below (where $p_I \geq p_A$).
- An existing ship should be scrapped when the freight rate hits a fixed value p_S from above (where $p_S \leq p_L$).

The two inequality signs are weak because lay-up is not always viable. If the mothballing cost is too high, it is better either to keep the ship active or to scrap right away, so $p_I=p_A$ and $p_S=p_L$. Then the model collapses to the simpler entry-exit case with a different interpretation of the switching costs; the entry cost represents the total cost of acquiring and activating the ship, while the exit cost represents the total cost of deactivation and scrapping.

As long as lay-up is viable, all four investment thresholds apply, in the order $p_S<p_L<p_A<p_I$. In other words: a ship is acquired when the freight rate gets sufficiently high (at p_I); an active

ship is laid up when the freight rate gets sufficiently low (at p_L); a laid-up ship is either activated (at p_A) or scrapped (at p_L), depending on which threshold is hit first.

Base case data

The entry-exit-scrapping model is explored by Dixit and Pindyck (1994, ch. 7) for a set of shipping data. The data, used here as a base case scenario, are shown in Table 1. They contain representative costs for a medium-sized (85000 dwt) oil tanker from 1992, based on industry information. Freight rate volatility is an empirical estimate from quarterly data of the period 1980-1992. The discount rate, set by Dixit and Pindyck, can be interpreted as a risk-adjusted interest rate. The capital cost share is not extreme, so even if the data are from oil trades, they may not be far from the truth in many other shipping segments where fuel cells are more likely to be introduced. (The negative scrap cost in Table 1 reflects a positive scrap value.)

Description	Value in mill. $ (1992)
Initial ship cost, I	40
Scrap cost, S	–3.4
Activation (entry) cost, A	0.790
Lay-up (exit) cost, L	0.200
Operating cost, c	4.4
Mothballing cost, m	0.515
Freight rate volatility (annual standard deviation), s	15 %
Discount rate, r	5 %

Table 1. Base case data.

The data in Table 1 lead to the following optimal investment thresholds: p_S=2.99, p_L=3.32, p_A=4.62 and p_I=9.59. Thus, the ship is acquired when the average freight rate corresponds to \$9.59 mill. in annual income. The requirement under a standard net present rule is \$6.4 mill. – i.e., the sum of operating costs (4.4 mill.) and annualized capital costs ($40\cdot 0.05$=2.0 mill.). The difference shows the importance of considering uncertainty upon investment.

Part 1: Alternative cost distributions

Table 1 is based on conventional technology for power production. Having in mind that fuel cells are likely to increase the capital cost share, we proceed by asking: How are investment decisions and ship values affected by the distribution of costs over time? Table 2 sums up an attempt to answer this question.

Operating cost, c	4.40	4.00	3.60	3.20	2.80	2.40
Initial ship cost, I	40.00	48.00	56.00	64.00	72.00	80.00
p_I	9.59	9.76	9.88	9.98	10.06	10.12
p_A	4.62	4.17	3.72	3.27	-	-
p_L	3.32	2.96	2.61	2.25	-	-
p_S	2.99	2.70	2.43	2.18	1.92	1.65
Ship value loss	0.0 %	1.6 %	2.9 %	3.8 %	4.6 %	5.1 %

Table 2. Investment with 15% freight rate volatility and alternative capital cost shares.

The first column of results is for the base case scenario. The \$40 mill. price tag corresponds to \$2.0 mill. in annual capital costs. The variable "Ship value loss" is set to zero as it measures the total loss of ship value relative to the value of the baseline scenario.[5]

The second column reports the results when the capital cost is increased by \$0.4 mill. (which corresponds to increasing the price of the ship by \$8 mill.), and the operating cost is decreased by the same amount. There are two main effects of such a change. First, investment is discouraged as one should wait for a higher freight rate before investing in a new ship (p_I=9.76 versus p_I=9.59). Similarly, lay-up and scrapping are discouraged as both p_L and p_S decrease. The ratio p_A/p_L also increases, so the amount of irreversibility increases in all respects: one should wait longer before acquiring or scrapping a ship, and also wait longer before laying up a ship or before activating one that is laid up. Second, the value of an active ship, or (if investment has not yet taken place) the value of the option to invest, decreases by 1.6%. The reduction of ship value is a measure of lost flexibility, caused by the fact that capital costs apply even when the ship is laid up. The general message is simple: investments should not, *ceteris paribus*, be made more irreversible than necessary. In this market there is a value of flexibility in terms of an option to lay up when the freight rate is low. A certain capital cost increase is not equivalent to an equal operating cost decrease. If the two technology choices were to be equal when valued as alternative investment projects, the operating cost must be reduced further for the more capital-intensive alternative.

The rest of Table 2 demonstrates how decisions change, and more flexibility is lost, for higher capital cost shares. At a certain point lay-up is no longer viable, so the optimal investment

[5] The ship value is the expected, discounted net present value of future net revenues. Only the change is reported as the absolute net present value depends on the current freight rate, whereas the percentage change does not.

behavior changes qualitatively. With the assumptions of the two rightmost columns, the cost of lay-up relative to the cost of operation is so high that the ship should be scrapped directly when the freight rate is low enough. In the most capital intensive case, when the cost of the ship is twice the baseline cost, the value of the ship decreases by 5.1% It can be shown that the operating cost must be reduced by another 10% – from \$2.4 to \$2.2 mill. – to compensate for the flexibility loss by choosing such a capital intensive (fuel cell) technology.

Uncertainty is crucial for these results. The more uncertainty, the higher are the values of lay-up options and scrap options. Table 3 reports similar results when the freight rate uncertainty is increased from 15% to 25%. The latter appears to be in the upper end of long run estimates even in many specialized market segments. The value of flexibility increases, and the lay-up option now is valuable for all data sets. With the data set of the rightmost column, the value of the investment option is significantly lowered. It can be shown that the operating cost must be reduced by more than 20 percent – from \$2.4 to \$1.9 mill. per year – to compensate for the loss of flexibility. This indicates that flexibility options could be decisive for the choice of technology when the uncertainty is high enough.

Operating cost, c	4.40	4.00	3.60	3.20	2.80	2.40
Initial ship cost, I	40.00	48.00	56.00	64.00	72.00	80.00
p_I	11.81	12.20	12.53	12.81	13.06	13.26
p_A	4.95	4.48	4.01	3.54	3.06	2.58
p_L	3.12	2.78	2.44	2.10	1.76	1.43
p_S	2.24	2.00	1.79	1.60	1.43	1.26
Ship value loss	0.0 %	1.7 %	3.1 %	4.3 %	5.3 %	6.2 %

Table 3. Investment with 25% freight rate volatility.

Part 2: Lay-up restrictions

Some fuel cells can be damaged, and lose efficiency, by being switched on and off. Possible implications are lost flexibility as the number of switches could be restricted or increasing operating costs over time. Alternatively, low operating costs could be sustained by keeping the fuel cell active even when the ship is idle. The model can be adjusted to handle several such options. Here I restrict to a stylistic, stepwise analysis of two alternatives. First it is shown how investment and valuation are affected by restricting the number of lay-up periods. Then the effect of increasing the operating cost is added to this.

The complexity of the investment problem increases by restricting the number of lay-up periods, since the optimal investment thresholds now depend on the remaining number of switches. However, with these data it turns out to be sufficient to study the case with one lay-up period. As usual, the ship is built and set to operate when the freight rate exceeds some value p_I. When the rate is down to p_L, the ship is laid up. Then it is either scrapped at p_S or reactivated at p_A, depending on what comes first. All this coincides with the previous model. When no lay-up option is left, the ship must be scrapped directly when the freight rate gets sufficiently low. This threshold is denoted by p_X in Table 4. The table confirms the basic intuition that one should not wait quite as long before scrapping when the options to lay-up and reactive have already been used (i.e., p_X exceeds p_S).

Operating cost, c	4.40	4.00	3.60	3.20	2.80	2.40
Initial ship cost, I	40.00	48.00	56.00	64.00	72.00	80.00
p_I	9.59	9.76	9.88	9.98	10.06	10.12
p_A	4.61	4.16	3.70	3.24	-	-
p_L	3.32	2.97	2.61	2.26		
p_X	3.14	2.82	2.51	2.21	-	-
p_S	2.98	2.69	2.43	2.17	1.92	1.65
Ship value loss	0.0 %	1.6 %	2.9 %	3.8 %	4.6 %	5.1 %

Table 4. Investment with maximum one lay-up period.

As observed by comparison with Table 2, the lay-up restriction plays a minor role. The initial threshold p_I increases slightly, but the change is so small that it does not show up in the second decimal place for any data set. There are three reasons for this: first, a possible second operating period is so long into the future when the ship is acquired that the profit effect is suppressed by discounting; second, the operating cost change is small; third, the operating cost represents only a fraction (about 30 percent) of total costs. Other changes in investment behavior are also minor except for the new scrapping threshold p_X. Note also that the restriction is irrelevant in the two rightmost columns, where lay-up is not viable.

It follows from the discussion above that lay-up is a rare event with these numbers. Most of the value of flexibility is captured by the option to lay up once. One main reason for this is that even the ship with traditional power production is quite capital intensive.

The last case to be investigated focuses on the effect of increasing the operating cost after the lay-up period. The operating cost is assumed to increase by three percent.[6] Having been through the previous analysis, such a change cannot be expected to influence investment behavior greatly. This is confirmed in Table 5. The interpretation of the last row is new; this row now reports the loss when comparing the project value prior to (or shortly after) the initial ship procurement with the similar value in Table 4, where the operating cost does not increase after the lay-up period.

Operating cost before lay-up, c	4.40	4.00	3.60	3.20	2.80	2.40
Operating cost after lay-up, αc	4.53	4.12	3.71	3.30	2.88	2.47
Initial ship cost, I	40.00	48.00	56.00	64.00	72.00	80.00
p_I	9.60	9.76	9.88	9.98	10.06	10.12
p_A	4.76	4.29	3.82	-	-	-
p_L	3.18	2.84	2.51	-		
p_X	3.25	2.91	2.59	-	-	-
p_S	3.08	2.77	2.49	2.21	1.92	1.65
Value loss due to cost increase	0.03 %	0.02 %	0.01 %	0.00 %	0 %	0 %

Table 5. Investment with one lay-up period followed by 3% operating cost increase.

For the data set closest to the base case data (the first column), the initial investment threshold p_I increases marginally, from 9.59 to 9.60. This is due to higher expected costs. The change also implies a gain from postponing lay-up, so p_L decreases (from 3.32 to 3.18, slightly more than the extra cost). The three other investment thresholds – p_H, p_X, and p_S – all increase. The changes in p_A and p_X are reasonable consequences of higher operating costs. The increase in p_S follows from an option argument: the cost of investing in a new ship has become relatively cheaper as the value of a laid-up ship is lower than before. Therefore scrapping should take place earlier.

Not unexpectedly, the value loss from the previous model is negligible (0.03 percent at most). This is because of discounting, because the operating cost increase is small, and because it represents only a fraction of total costs. Nonetheless, even this small cost change leads to a

[6] Such a small operating cost increase is sufficient to detect the characteristics of the model. A larger increase easily makes lay-up irrelevant for all of the investigated distributions of costs.

qualitative change in investment behavior for one data set. Lay-up is no longer viable in the middle column, whereas lay-up was indeed viable with the related data set in Table 4.

Criticism

The assumptions behind the analyses above intend to reflect market characteristics of various power production systems in shipping. Their representativeness can obviously be questioned. In addition to the cost parameters, which may not be credible, one might object to the choice of stochastic process. Freight rates are clearly not geometric Brownian, since that implies they could grow beyond all limits. Some kind of mean reversion is more likely, by which the freight rate is prevented from deviating too much from a long run mean. Typically, the mean value will not be far from long run average costs. In the model of this paper, we might expect massive ship investment when the freight rate hits the trigger value p_I. That would increase aggregate supply, and prevent the freight rate from increasing further. Similarly, aggregate supply could shrink as a result of scrapping if demand remains low enough for a long period of time. This would push the freight rate up again.

When considering the issues focused in this paper, such arguments may not be important in practice despite being correct in principle. It can be shown that the optimal investment rules need not change much by turning to industry equilibrium even if the underlying assumptions are different (Leahy 1993). Moreover, the objective of the numerical analysis is not to end up with specific investment recommendations. Maritime fuel cell technology is far from being mature enough for that. Yet, the analysis exemplifies the potential importance of flexibility by numbers that are hopefully in the ballpark of correct values under some relevant technological and economic conditions. When comparing system solutions, the point of the matter is not ship values or price levels in absolute terms, but differences and marginal values of change. I believe the analysis carries some truth in this respect. It should also be mentioned that the models could be extended to more complex stochastic processes, which include mean-reversion. When more reliable data are available, such extensions could be worthwhile.

4. Final remarks

This paper has pointed out some economic characteristics of fuel cells applied to shipping. Possible implications for valuation and decision making have been investigated through experiments, using market data and alternative fuel cell cost projections. The numerical analysis in the previous section demonstrated, quantitatively and formally, some typical effects of changing the capital cost share and various other cost parameters that are likely to be different for a fuel cell power regime. On general conclusion stands out from this analysis: valuation of fuel cell investments must account for possible losses of flexibility.

The analysis also showed that the optimal investment behavior could change qualitatively by switching to fuel cell power production. Here this occurred when lay-up turned out to be irrelevant with high capital cost shares, but the investment policy could also change as a result of options to switch between market segments, or options to increase efficiency by alternating between fuels, adjusting speed etc. Real options models is the proper tool to improve the understanding of all such options for both economic researchers and technical innovators. This statement will be even more valid when the fuel cell technology matures, and more reliable data appear.

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Appendix 1: The entry-exit model

This appendix and Appendix 2 supplement the text in deriving the optimal policy of the various models in section 3. The presentation does not use stochastic calculus which is needed to obtain formal proofs, but more details and references can be found in Sødal (2001). The objectives are mainly to document the models sufficiently that the analysis can be replicated, and to enable the reader to undertake similar investigations using other numbers.

The optimal entry policy in the entry-exit model is to activate a ship up when the revenue from operation (the freight rate) hits a certain threshold p_A from below. Similarly, the optimal exit policy is to lay up when the freight rate hits a certain threshold p_L ($\leq p_A$) from above.

The stochastic process for the freight rate is a geometric Brownian motion with constant volatility, s. Somewhat simplified, the percentage freight rate change from this year to next year is given by a normal distribution with standard deviation s. The mean value is the current rate, so the expectation of the change is zero even if the freight rate indeed will fluctuate due to uncertainty. (A drift term on top of the uncertainty can easily be included.)

The optimal policy can be derived by assuming that the ship is currently idle, and by starting from a fixed, low freight rate p_0. Define a decision policy by two arbitrary freight rates, p_A and p_L ($<p_A$), at which activation (entry) and lay-up (exit) take place, respectively. The value of the policy at the initial point – when the freight rate equals p_0 – is defined as the expected net present value of all future net benefits. Define this net present value by W_0, and the similar values when p_L and p_A are reached by W_L and W_A, respectively. The following relations hold:

(1.1) $$W_0 = E[e^{-rT_{0L}}]W_L$$

(1.2) $$W_L = E[e^{-rT_{LA}}](p_A/r - c/r - A + W_A)$$

(1.3) $$W_A = E[e^{-rT_{AL}}](c/r - L - p_L/r)W_L$$

In Eq. (1.1), E[·] is the expectations operator, r is the interest rate, and T_{0L} is the (stochastic) time it takes for the freight rate to hit p_L. Technically, T_{0L} is the first hitting time or first passage time from p_0 to p_L, while $E[e^{-rT_{0L}}]$ is the expected discount factor. The equation says that W_0 is the expected and discounted value of W_L, which is true as nothing but waiting, takes place when the freight rate moves from p_0 to p_L.

Eq. (1.2) contains a similar expected and discounted value for W_L. Entry occurs as soon as p_A is hit, so if the ship remains active forever, the expected future net benefits equal the expected and discounted net revenues, $(p_A-c)/r$, subtracted by the activation cost, A. There is also an option to switch again after activation, W_A, so the net gain is $p_A/r-c/r-A+W_A$. This is discounted by the factor $E[e^{-rT_{LA}}]$, whose interpretation follows from the paragraph above.

Eq. (1.3) contains the similar relationship for W_A. The ship is laid up when p_L is hit. If it were to remain laid-up, the gain would be $c/r-L-p_L/r$ as the net present operating cost c/r is saved, the exit cost L is paid, and the expected, discounted freight income p_L/r is also lost. Right after exit, the situation of Eq. (1.2) has returned, so the value of further switching options equals W_L. The total gain, $c/r-L-p_L/r+W_L$, is discounted by $E[e^{-rT_{LA}}]$ for the same reason as above.

Two characteristics of the geometric Brownian process (and many similar processes) prove to be convenient: it is a continuous process with no memory in the sense that the distribution of future values (freight rates) is determined entirely by the current value. This implies that the discount factors can be written as functions of the startpoint and endpoint, so $E[e^{-rT_{0L}}]$, $E[e^{-rT_{LA}}]$ and $E[e^{-rT_{AL}}]$ can be written as $Q(p_0,p_A)$, $Q(p_L,p_A)$ and $Q(p_A,p_L)$, where Q is specific function. The model as visualized in Fig. 1.

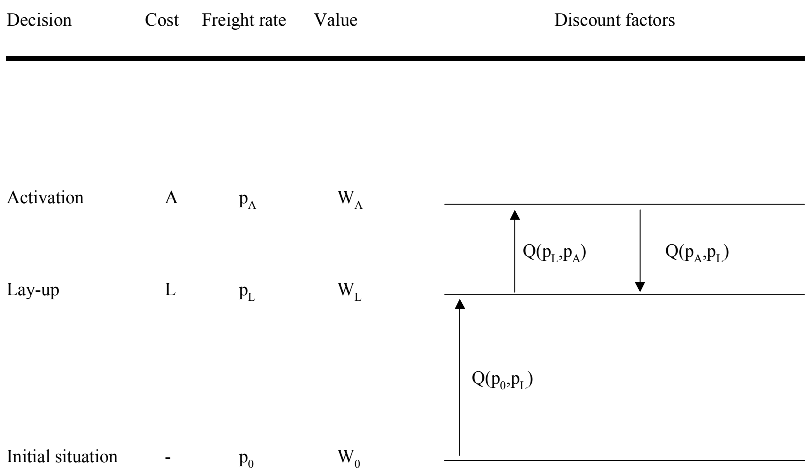

Fig. 1. The entry-exit model.

The discount factors for the geometric Brownian process of this paper can be shown to be:

(1.4) $Q(p_0, p_L) = (p_0 / p_L)^b$

(1.5) $Q(p_L, p_A) = (p_L / p_A)^b$

(1.6) $Q(p_A, p_L) = (p_L / p_A)^{b-1}$

where $b = \frac{1}{2}(1 + \sqrt{1 + 8r/s^2})$. (Similar formulas holds for all positive endpoints: the ratio of the endpoints is powered to b if the motion is upward, and to b–1 if the motion is downward.) The initial value of the decision policy, W_0, is found by solving the system (1.1-3) with respect to W_0, W_L and W_A, and inserting (1.4-6). The following expression is obtained:

$$(1.7) \quad W_0 = (p_0 / p_A)^b \frac{(p_A / r - c / r - A + (p_L / p_A)^{b-1}(c / r - L - p_L / r))}{1 - (p_L / p_A)^{2b-1}}$$

The maximum of W0 with respect to pL and pA give the optimal policy. No closed-form solution exists, but numerical analysis can be used to determine the optimal thresholds as well as the optimal W_0. The latter is used in the text when quantifying losses of flexibility.

Appendix 2: The entry-exit-scrapping model

The optimal policy of the entry-exit-scrapping model can be derived by similar procedures as in Appendix 1. The model with no switching restrictions is illustrated in Fig. 2.

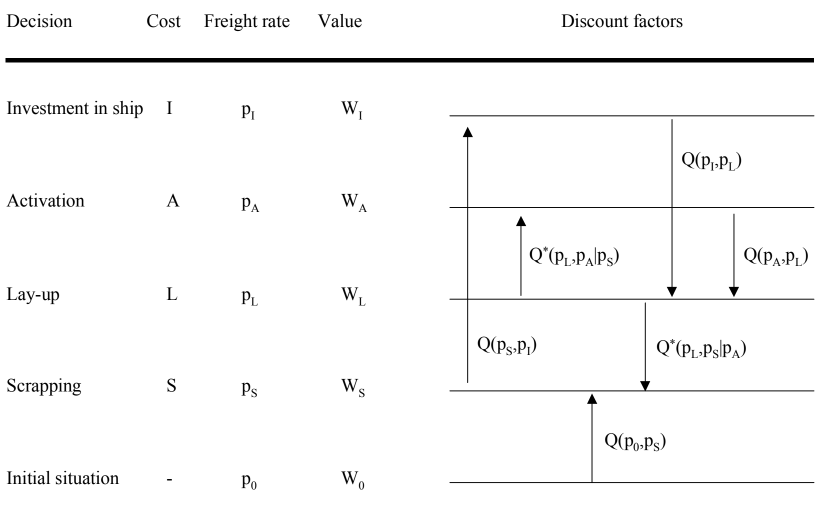

Fig. 2. The entry-exit-scrapping model.

Four investment thresholds (p_S, p_L, p_H, p_I) characterize a decision policy, whose value is determined by the following equations:

$$(2.1) \quad W_0 = Q(p_0, p_S)W_S$$

$$(2.2) \quad W_S = Q(p_S, p_I)\left(p_I / r - c / r - I + W_I\right)$$

(2.3) $W_I = Q(p_I, p_L)\left(c/r - L - p_L/r - m/r + W_L\right)$

(2.4) $W_L = Q^*(p_L, p_A \mid p_S)\left(p_A/r - A - c/r + m/r + W_A\right) + Q^*(p_L, p_S \mid p_A)\left(m/r - S + W_S\right)$

(2.5 $W_A = Q(p_A, p_L)\left(c/r - L - p_L/r - m/r + W_L\right)$

This equation system is similar to that of Appendix 1, and need not be explained in depth. For example, Eq. (2.3) states the value of the policy right after the ship has been acquired at freight rate p_I. This is similar to Eq. (1.2), except for the mothballing cost, m, which is subtracted whereas lay-up was free in the previous model. The main new element is Eq. (2.4), which states the value right after lay-up at p_L. It is not clear whether the freight rate then decreases to p_S (implying scrapping) before or after it hits p_A (implying activation). The conditional discount factors $Q^*(p_L,p_A|p_S)$ and $Q^*(p_L,p_S|p_A)$ account for this. The first one is the expected discount factor when moving from p_L to p_A conditional on not hitting p_S. The second one is the similar discount factor when moving from p_L to p_S conditional on not hitting p_A. These discount factors can be shown to be:

(2.6) $$Q^*(p_L, p_A \mid p_S) = \frac{(p_L/p_A)^b - (p_S/p_L)^{b-1}(p_S/p_A)^b}{1-(p_S/p_H)^{2b-1}}$$

(2.7) $$Q^*(p_L, p_S \mid p_A) = \frac{(p_S/p_L)^{b-1} - (p_S/p_A)^{b-1}(p_L/p_A)^b}{1-(p_S/p_A)^{2b-1}}$$

where $0 \le p_S \le p_L \le p_A$, and $p_S < p_A$. By solving the system (2.1-5) and inserting (2.6-2.7), an analytical expression for W_0 is obtained. The optimal policy and the value of the ship follow from maximization of W_0 with respect to p_S, p_L, p_A and p_I. The formula for W_0 is omitted as it is lengthy, and as a software package is needed anyway to determine the maximum.

When lay-up is restricted, the investment decisions are the same as without the restriction up until the end of the lay-up period. The equations (2.1-3) remain, but the following equations replace (2.4-5):

(2.8) $W_L = Q^*(p_L, p_A \mid p_S)\left(p_A/r - A - \alpha c/r + m/r + W_A\right) + Q^*(p_L, p_S \mid p_A)\left(m/r - S + W_S\right)$

(2.9) $W_A = Q(p_A, p_L)\left(\alpha c/r - p_X/r - S + W_X\right)$

(2.10) $W_X = Q(p_X, p_I)\left(p_I / r - c / r - I + W_I\right)$

Eq. (2.8) coincides with Eq. (2.4) except for the parameter α, which accounts for a possible operating cost increase after lay-up. (The numbers used are α=1.00 and α=1.03.) Eq. (2.9) applies right after the lay-up period, so scrapping when the freight rate hits p_X must be the next event. At that time the operating cost αc is saved, and the revenue flow starting at p_X is lost. The net gain is discounted and reduced by the scrap cost, S, while the remaining option value, W_X, is added. The latter, given by Eq. (2.9), coincides with Eq. (2.2) except for the initial price. The optimal policy is determined as usual, by solving (2.1-3; 2.8-10) for W_0, W_S, W_I, W_L, W_A, W_X, and then maximizing with respect to p_S, p_X, p_L, p_A and p_I.