19-670 / 24-680

Quantitative Entrepreneurship

12V Fuel Cell

Report 4: Final Report

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1. Executive Summary

Hydrogen fuel cell technology represents a promising clean alternative for electricity generation. Though many applications are limited due to high material costs like platinum catalysts, current research at Carnegie Mellon University focuses on producing platinum group metal (PGM) free catalysts to reduce the overall production costs. This analysis examines the feasibility of producing a hydrogen fuel cell battery charger for maritime applications, a market estimated at $32M/year. Focusing on the manufacturing process to produce these fuel cells, the analysis compared a few decision variables, as they contributed to key portions of the overall production costs[1], including: cell area, catalyst loading, catalyst type, and automation level. Additionally, a market survey was conducted to analyze user preferences in regards to boat battery chargers. The survey gave users a randomized choice between discrete levels of four main product attributes: charger type, amperage, price, and recharging costs.

This analysis suggests that the boat battery charger market would not be a very profitable market for a hydrogen fuel cell battery charger. However, if one were to pursue this technology in this market, the best option would be to produce a 5 Amps portable fuel cell battery charger. At 5A, the production model estimates a unit cost of $346 (+/- $35) using the platinum free catalyst or $351 (+/-$35) using the platinum catalyst. At a unit cost around $350, the market analysis shows profit maximization at a price of ~$450. At this price, we estimate gaining a 2.2% (+/- 0.7%) market penetration. This equates to approximately $1.5M in revenue and $340,000 in profit. These market estimates are based on extrapolated values due to low initial production cost estimates and a simulated market analysis based on the low production costs. The Pt-free catalyst did not result in significant cost savings due to its performance leading to increases in other fuel cell component costs. While this analysis shows limited profit potential within the boat battery charger market, further cost reductions and further market studies could result in the development of the product for a more lucrative market segment.

2. Introduction

Product Description:

A hydrogen fuel cell is a device that directly converts chemical energy into electrical power with no local pollutant by-product except water. The main components of a fuel cell are two electrode structures consisting of a gas diffusion layers, a catalyst layer and an electrolyte later. The multi-layered electrode structure, also referred to as the Membrane Electrode Assembly (MEA) is enclosed on both sides by sealing gaskets and bipolar plates (Figure 1 in appendix).

Figure 1: Boat Charger

The product presented herein aims to extend the life of deep-cycle batteries for long boating expeditions by means of a Proton Exchange Membrane (PEM) fuel cell. Competitive products, such as those offered by Minn Kota, Promariner, Marinco, or NPower, require the use of an external power source, typically standard plug-in electricity. The portability and clean energy factors would differentiate a fuel cell charger among the competition. Other product attributes considered by customers include: charger type (on-board or portable), amperage (time to

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[1] The most significant contributors are further referred to as cost drivers.

charge), and recharging costs. The production analysis focuses on the fuel cell area, catalyst material, catalyst loading, and stacking assembly equipment needed to create an assembled fuel cell stack. The demand analysis studies the fuel cell charging unit as a whole, rather than focusing only on the fuel cell technology.

Production Process Description:

The scope of this analysis spans the catalyst coating process to the stacking process of the MEAs. To simplify the manufacturing process, the catalyst slurry, gas diffusion layers, membrane, and bipolar plates will be considered as material inputs to the process model. The manufacturing and assembly of a fuel cell is described by figure 6 in the Appendix. The production process begins with feeding the raw catalyst material along with the membrane film into the coating machine, which mixes and evenly deposits the slurry onto the both sides of the membrane film, creating the anode and cathode catalysts (Carlson et. al.). This step includes the catalyst type and loading variables. The catalyst type falls into two categories, those that contain platinum, and those that do not.

After coating, the membrane moves on to drying. To prevent a potential bottleneck, we decided upon using an oven drying approach (Carlson, Saunders). When sufficiently dry, the catalyst deposited membrane is then combined with the Gas Diffusion Layers (GDL). This is typically performed by means of a roll-to-roll hot lamination press (Carlson et al). Next, the membrane is cut into the desired dimensions using a slitting machine. Finally the individual cells are stacked with bipolar plates using an assembly-stacking machine. We have the option here to use a manual or semi-automatic stacking machine.

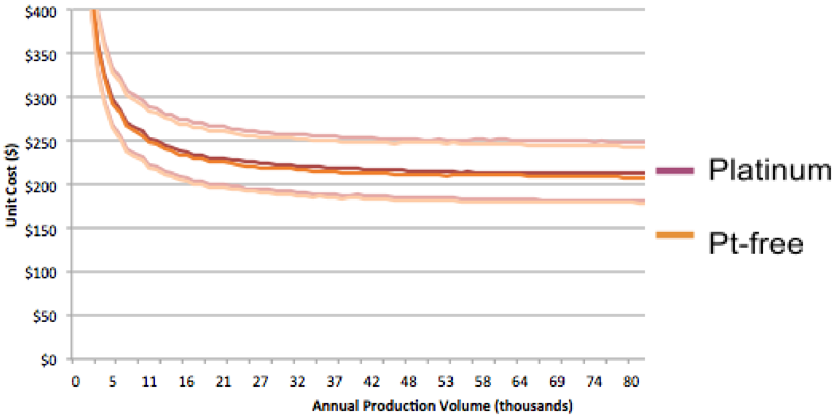
Key Decisions:

To best model the production process of the MEA stack assemblies, five key production factors were focused on. These factors, known as decision variables, consisted of: price, cell area, catalyst loading, catalyst type, and automation. The general relationships (positive, negative, or non-monotonic) between process and product variables can be seen in the model relationship table shown in Figure 3 in the appendix. The underlying price of the manufacturing process will ultimately drive the profitability of the venture. Cell area, catalyst loading, and catalyst type all play a critical role in the performance of the fuel cell. This will affect aspects like the durability, efficiency, and the amperage of the final product. In addition, as will be seen later in the analysis, the material costs are the dominating factor in driving the price of production. These three variables are the biggest contributors to material used in the production process. Finally, choosing between manual or automated processes directly impacts the way in which the production process is performed as well as the associated costs.

3. Production Analysis

A process-based cost model (PBCM) studying the production of fuel cell stacks using the five main process steps (coating, drying, laminating, slitting, and stacking) was created to quantify the effects of the decision variables on the unit cost. One limitation of this process is that it studies the fuel cell stack only, neglecting hydrogen canister production and final product packaging, although a rough parametric estimate from James et al (2014) is added at the end to simulate the packaging. A unit is defined as a 60W fuel cell stack of 17 cells of 10 cm^2 each that would operate at 12V/5A. The levels of decision variables and equations used to create the model can be seen in Appendix Tables 2-9. Drop-down menus allowed for the selection of discrete decision variables: Pt-free v. Pt catalyst and manual v. semi-automatic stacking.

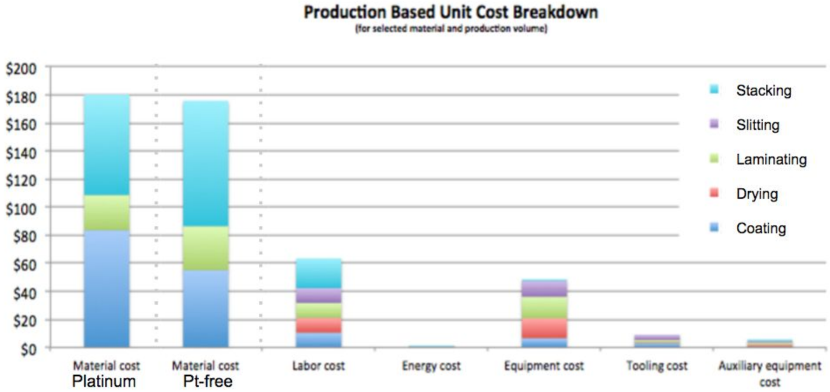
Figure 2: Unit Cost Curve for Pt and Pt-free Fuel Cell Production



The base case analyzed with this model utilizes an annual production volume of 3,440 based on optimized profit. At this production volume, the platinum option yields a unit cost of $351 +/- $35 and the platinum free option yields a unit cost of $346 +/- $35 (see Tables 10 and 11 for detailed unit cost breakdown). The largest cost components are shown below and in Figure 3:

Material Cost **(51%)**	Labor Cost **(18%)**	Equipment Cost **(14%)**
Catalyst, Bipolar Plates	Stacking (Step 5)	Drying, Laminating, Slitting

Figure 3: Unit Cost Breakdown for Pt and Pt-free Fuel Cells



Material costs are the most significant cost driver. Given that all the material costs are calculated per unit area, the most effective way of reducing the material cost is to improve the catalyst performance, which directly affects the fuel cell efficiency and cell area. The bipolar plates have the potential to cost much less, given they are a relatively low-value low-tech component made of stainless steel, but they are made-to-order depending on the size and design of a fuel cell. The lower bound shown in Figure 4 reflects the potential availability of mass-produced custom bipolar plates. In comparison, the other materials are already produced in bulk powder, sheets, or rolls, and have less potential for cost reduction, but could still drop with industry maturation and high-volume large-scale fuel cell production[2].

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[2] In our model, we set the lower bound for material prices from those found in James et al (2014), which analyzed automotive fuel cell production between a range of annual production volumes of 1000 units/yr to 500,000 units/yr was examined. However, given that an automotive fuel cell contains 100x the cell area of our product, their lower bound on production of 1000 units/year is equivalent to purchasing approximately 1M units worth in surface area of fuel cell components for our product. This indicates how much fuel cell industry maturation, external to our model, drives material costs for our product.

If the Pt-free and platinum-based catalysts were functioning at the same efficiency, there would be cost savings of approximately $40 (+/- $35) per unit (see Appendix Figure 8 for detailed description). Ultimately, it appears that the platinum-free catalyst will only provide non-negligible cost savings once the technology matures and has comparable performance (see Appendix Figure 8) or if catalyst cost is a larger fraction of total costs like in larger fuel cells (James et al, 2014).

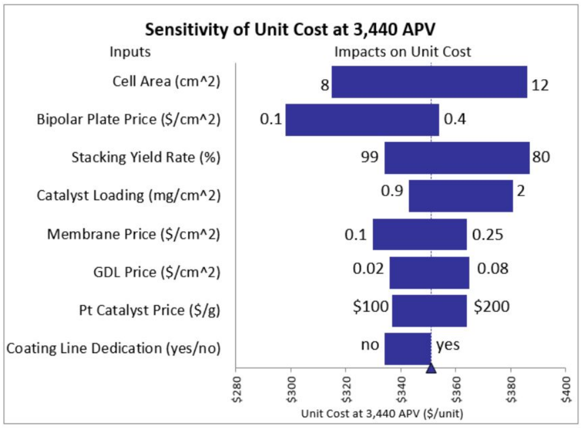

Figure 4: Production Sensitivity

4. Demand Analysis

A randomized choice-based conjoint survey was created to study the demand and willingness to pay for various attributes. Each survey question (sample question in appendix, figure 11), of fifteen total questions, included three theoretical chargers to select from given four attributes. A "none" option was not included because in general all boat owners must purchase a battery charger if they own a boat, with the small exception of boat owners who are part of boating communities that have public access chargers. The randomized approach was utilized to ensure that interaction effects could be captured with the survey responses. In particular, preferences for charger cost could correlate to the cost per recharge.

The possible amperage set included 5 amps, 10 amps, and 20 amps. The price levels included $100, $200 and $300. The market demonstrates a general range of $100 to $400 with $200 being approximately the middle value. The recharging cost attribute includes $0.10, $1, and $5 levels, and corresponds to the cost of electricity or hydrogen to power a single charge.

The survey respondents represented the market relatively well. In order to qualify for the survey, the survey taker was required to be a boat owner and be 18 years of age or older. There were 101 complete responses. Geographically, the respondents were primarily from coastal states with a bias towards the east coast, however there was representation of many states (see map in Appendix Figure 12). These results also show a good spread across boating use, current charger type, frequency of recharge, and frequency of boating.

The choice model uses a simple logit model specification, while the utility functional form is a combination of linear (price) and partworth utilities, with discrete levels for charger type, amperage, and recharging cost. Figure 6 illustrates the willingness to pay for the proposed fuel cell product. From the left side of the graph, the chart depicts the impact each of the attributes (price, charger type, amperage and recharging cost)—along with their respective levels—have on the willingness to pay for the three available options (fuel cell, portable plug-in, on-board plug-in). The demand analysis in Figure 13 shows that, on average, people are more likely to choose the On-Board charger then switch to the Fuel Cell Charger option. Similarly, customers are more likely to choose the Portable Charger option than the fuel cell option. The negative values indicate that consumers are likely to spend more money for either of the plug-in options than for the fuel cell option.

The charging attribute (amperage) showed significant importance amongst the survey takers. The results in figure 5 show that potential customers are more likely to spend money on switching from 5-amp charger to 20-amp charger, than both a 10-amp charger to 20-amp charger, or a 5-amp charger to 10-amp charger. As was the case with the charger type attribute, the cost of charging the fuel cell (in $/charge) had a negative impact on the willingness to pay. The analysis shows that potential customers are very unlikely to switch from either of the plug-in options to the fuel cell charger when considering the hydrogen refill cost. On average, customers are more likely to opt for charging either the portable or onboard charger at 0.1$/charge (based on the cost of electricity), than either of the assumed costs of hydrogen; $1 for the low estimate and $5 for the high estimate (both estimates include the cost of hydrogen itself, the cost of an amortized metal hydride canister and the cost of delivery).

The choice model suggests that the charging costs, $/charge, is one of the important attributes that negatively impacted the fuel cell charger option. Potential buyers showed a strong preference for the plug-in chargers over the fuel cell charger. The rated amperage of the charger had positive willingness-to-pay, explained by potential customers being more likely to spend money on the extra amps. While the relationship is not linear[3], a linear approximation would amount to a willingness to pay for each additional amp of $20 (+/-$5).

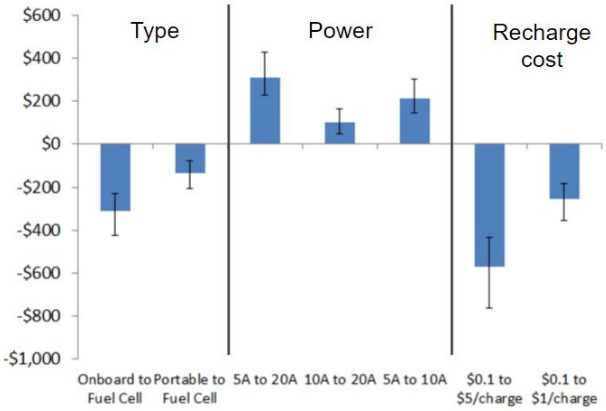

Figure 5: Customer Willingness to Pay

The simulated market scenario options are shown in Table 10. The first choice option is the fuel cell charger with the following attributes: portable, 5A, $450 price, and $1 cost to charge (assuming readily-available hydrogen supplied via metal hydride hydrogen tank which lasts 100 uses). The second choices is the Minn Kota A option: portable, 5A, $110 price, and $0.10 cost per charge, assuming it uses a standard wall outlet. The third choices is the Minn Kota B option: onboard, 10A, $250 price, and $0.10 cost per charge, assuming it uses a standard wall outlet.

The simulated market scenario results are shown in Figure 13. As can be seen, the proposed fuel cell charger product captures 2% (with a 95% credible interval between 1% to 4%) of the market share, while the portable and on-board plug-in chargers capture 29% and 69% of the market share respectively. We assume a reference market size of 160,000 units per year, corresponding to the number of new powerboats purchased in the US annually (National Marine Association, 2016). This is roughly equivalent to $16-48M per year. This assumes that people buying a new boat will need to buy a charger, and that it is a mandatory, not optional, accessory. One interesting finding from market segmentation based on current charger type (portable, on-board) was that consumers have a strong distaste for change. Figures 14 and 15

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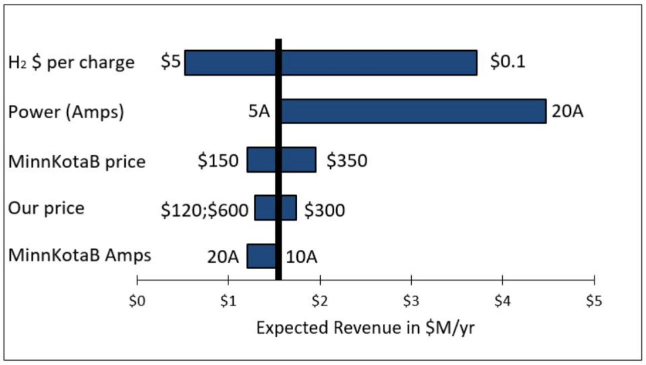
[3] 5A to 10A with higher WTP than 10A to 20A

show the market scenarios for current charger type. Users that currently use a portable charger have a strong preference for purchasing a portable plug in charger, while users that use an on-board plug in charger have a strong preference for an on-board plug in charger. Therefore, penetrating this market with a new product may be difficult based on consumer's preference to purchasing the same product that had previously been using.

As shown in Figure 6, the cost of hydrogen and the product power rating were the two most significant uncertainties and decisions affecting the expected market share and revenue for our product. A lower bound on hydrogen cost would approximately double demand while a higher hydrogen cost would halve demand. A 20A product could triple the expected the revenue. Alternative offerings by competitors could also reduce revenue, though they are already dominant in the simulated market scenario.

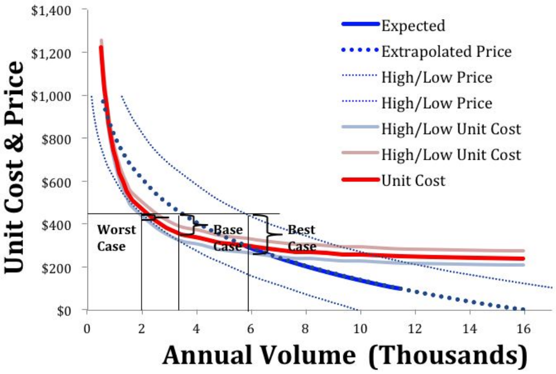
Figure 6: Attribute Sensitivity



5. Integrated Analysis

To maximize profit[4], we selected a selling price of $450 to gain a 2.2% expected market share. Figure 7 illustrates price and unit cost vs. annual production volume. This graph combines the unit cost of a fuel cell at specific annual production volumes, shown in red, with the expected demand and price estimates from the simulated market share analysis, shown in blue. The uncertainty for the unit cost curve accounts for variation in material costs mostly, while the uncertainty in the demand curve represents the 95% credible interval. The difference between the two curves shows the region within our solution space at which a specific production volume and unit cost will allow us to price the fuel cell to yield the most profit.

Figure 7: Price and Unit Cost vs. Volume



There are three conclusions that can be ascertained from Figure 7. The first relates to the base case. As labeled in the figure, we can expect to maximize profit by pricing the fuel cell at $450. This corresponds to a production volume of approximately 3400 and a production cost of $350. The uncertainty bounds tell us the best case (the most we can expect to profit for a low production cost at a specific volume) and worst case (the least we can expect to profit at a low cost at a specific volume) for our fuel cell product. Optimistically (best case), at a production volume of approximately 5800 and a unit cost of $268, we can expect a profit of $182 (~$1.05M

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[4] Our profit estimates are based on extrapolated costs (as opposed to the expected costs, as described in the the survey results and simulated market analysis), since our initial approximations of the fuel cell production costs were low. Our revised production model significantly increased production cost, from $150 to $350. As a result, in order to show results where our product can be profitable, we based our estimates on the extrapolated region of the expected demand curve.

annual profit), while the pessimistic scenario (worst case) shows that at a production volume of ~2000 and cost of approximately $450, our profit is almost $0.

Figure 9 shows the simulated profit at a specific annual production volume. From this graph we can identify the production volume where our profit can be maximized. As can be seen, at a production volume of 3450 (base case), the figure shows that the expected profit is approximately $340,000. Optimistically (best case), the product can be expected to generate a profit of approximately $1.3M, while the pessimistic case (worst case)shows that we are losing $317,000. Similarly, figure 8 shows the profitability of the fuel cell charger in terms of the price of the product. By charging $450 for the fuel cell, the expected profit is approximately $340,000 in the base case scenario, while the best case shows profits of up to $1.3M and the pessimistic outlook shows negative profit.

Figure 8: Profit vs. Price

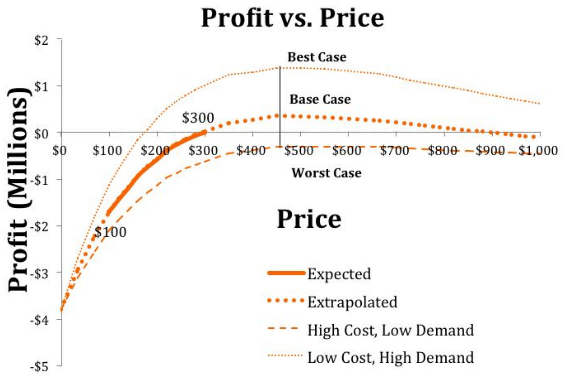
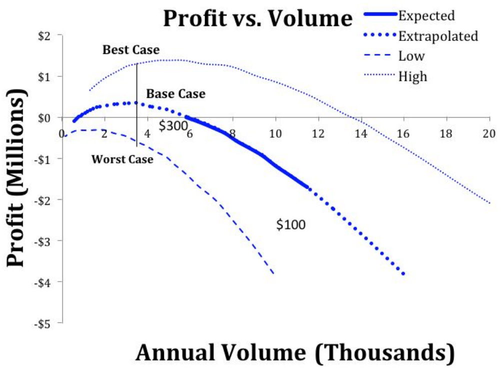


Figure 9: Profit vs. Volume



Key Decisions:

The design decision to produce and sell a fuel cell at a 5A rating had the most impact on profitability. This decision affected both production cost and market demand. Although the demand model indicated that consumers would be willing to pay $300 more for 20A than a 5A product, or if the price remained the same, simulated market share would grow 2-3x, the production model revealed that unit cost would grow almost 4x, reflecting the 4x increase in required cell area and materials. The profitability of a 20A product would be highly negative (-$7M), and therefore, we recommend producing a 5A product.

The use of platinum catalyst compared to the Pt-free catalyst under development did not affect profitability significantly. The weaker performance of the Pt-free catalyst necessitated a 20% increase in cell area and the increased requirement of other fuel cell components cancelled out the savings due to the reduced cost of catalyst. In terms of demand, a Pt-free product may also have downsides, due to reduced durability and higher consumption of hydrogen compared to the conventional Pt-based fuel cell. Therefore, we recommend using platinum for this product.[5]

A more mature fuel cell industry and hydrogen market would also change the potential for profitability of our product. Based on assumptions in James et al (2014) for costing of

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[5] The cost of the catalyst for larger fuel cells, such as those modelled in James et al (2014) for automotive applications, are much more dominant, whereas the cost of the catalyst in our product with power rating between 60-240W was rivalled by the costs of other fuel cell components. Therefore, the Pt-free catalyst may be more effective in reducing the total cost for other larger fuel cell products.

automotive-scale fuel cell components and on a lower bound for hydrogen cost based on energy content and fully efficient production, distribution, and storage, we expect an annual profit in the order of $1-3M, significantly higher than in the base case.

Our analysis is limited to a steady-state production and sales scenario and does not account for potential delays and lags due to factory start-up and commissioning, and time needed to scale up product distribution, marketing, and consumer familiarity. The availability of appropriate hydrogen canisters would also need to be timed with our product's availability.

Realistically, the results may represent an overly optimistic scenario, due to the results capturing profitability under specific and idealized conditions. This analysis does not account for perturbations caused by dynamically changing market sizes, customer preferences, material prices, manufacturing technologies, nor changes in competitor pricing (Michalek & Whitefoot, 2016). This analysis does not account for out-of-scope production costs associated with advertising or legal costs (Michalek & Whitefoot, 2016). The survey on which this analysis was based did not model attributes such as product aesthetics and reliability, which could vary perception and valuation. Additionally, the context in which the survey was designed may not match true market behavior in the market, and as such, the results may not reflect the true demand or willingness to pay.

6. Final Recommendations and Conclusions

Based on the above analysis, a decision to pursue the boat battery charger market with a hydrogen fuel cell powered charger should target a 12V, 5A charger priced at $450. This product could expect to capture approximately 2% of the charger market leading to $300,000 of profit. We find this to be a limited opportunity for profitability, based on a negative customer valuation of the fuel cell charger compared to current chargers and high material costs.

We recommend a platinum-based catalyst over the PGM-free catalyst. Though use of PGM-free catalyst gives a $5 per unit savings in manufacturing costs, use of PGM-free based catalyst remains highly uncertain comparatively, particularly due to its current unavailability for large-scale production. Additionally, uncertainty of the performance and durability of the PGM-free catalyst may limit the product's appeal and consumer demand.

This analysis relies on extrapolated price data from the market survey results. Future market studies should be conducted to better determine customer price preferences over revised price ranges. Additional uncertainty remains over exact production equipment prices and parameters. New production analyses should be conducted considering industry trends and vertical integration to provide insight into potentially more profitable lines of business. These include in-house bipolar plate production, production and sales of MEAs with excess machine capacity, or outsourcing of catalyst and MEA production to focus on assembly only.

Improving catalyst and overall fuel cell performance represents the biggest opportunity for improving profitability, via reduction in required cell area and material costs. Improved performance would also allow for a higher amperage and more desireable product to be produced. The current technology would be insufficient to warrant further pursuit of the boat battery charger market. Other market opportunities in which clean energy and portability are driving factors should be studied in further detail.

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Retail volume of the recreational boating market, 2001-2014. Statista. https://www.statista.com/statistics/209293/retail-volume-of-the-recreational-boating-market/

Appendix:

Figure 1: Membrane electrode assembly breakdown [6]

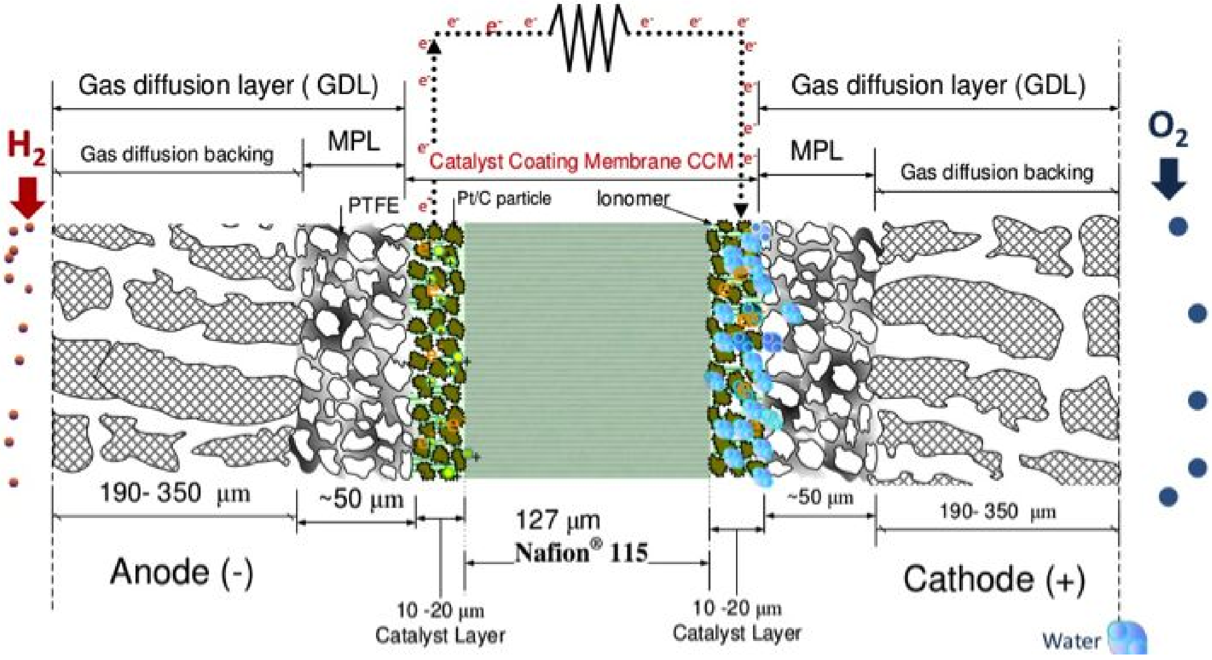


Figure 2: Process flow diagram for the fuel cell manufacturing process

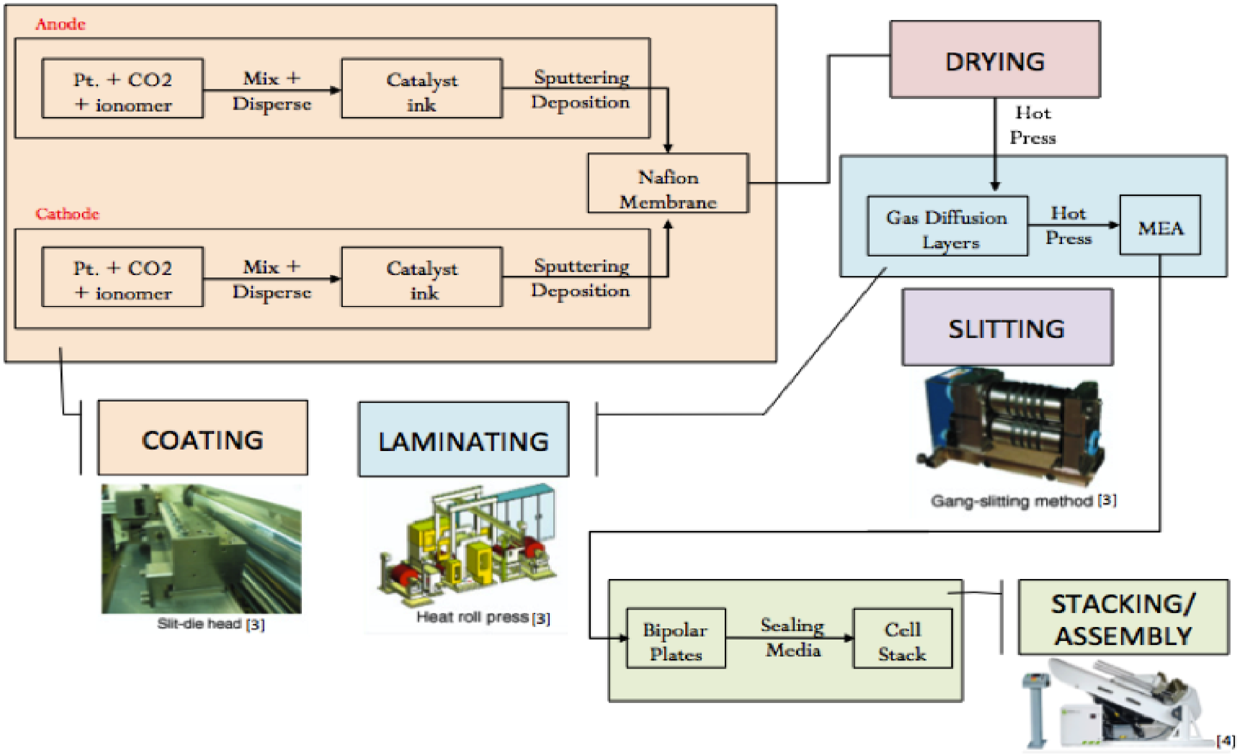
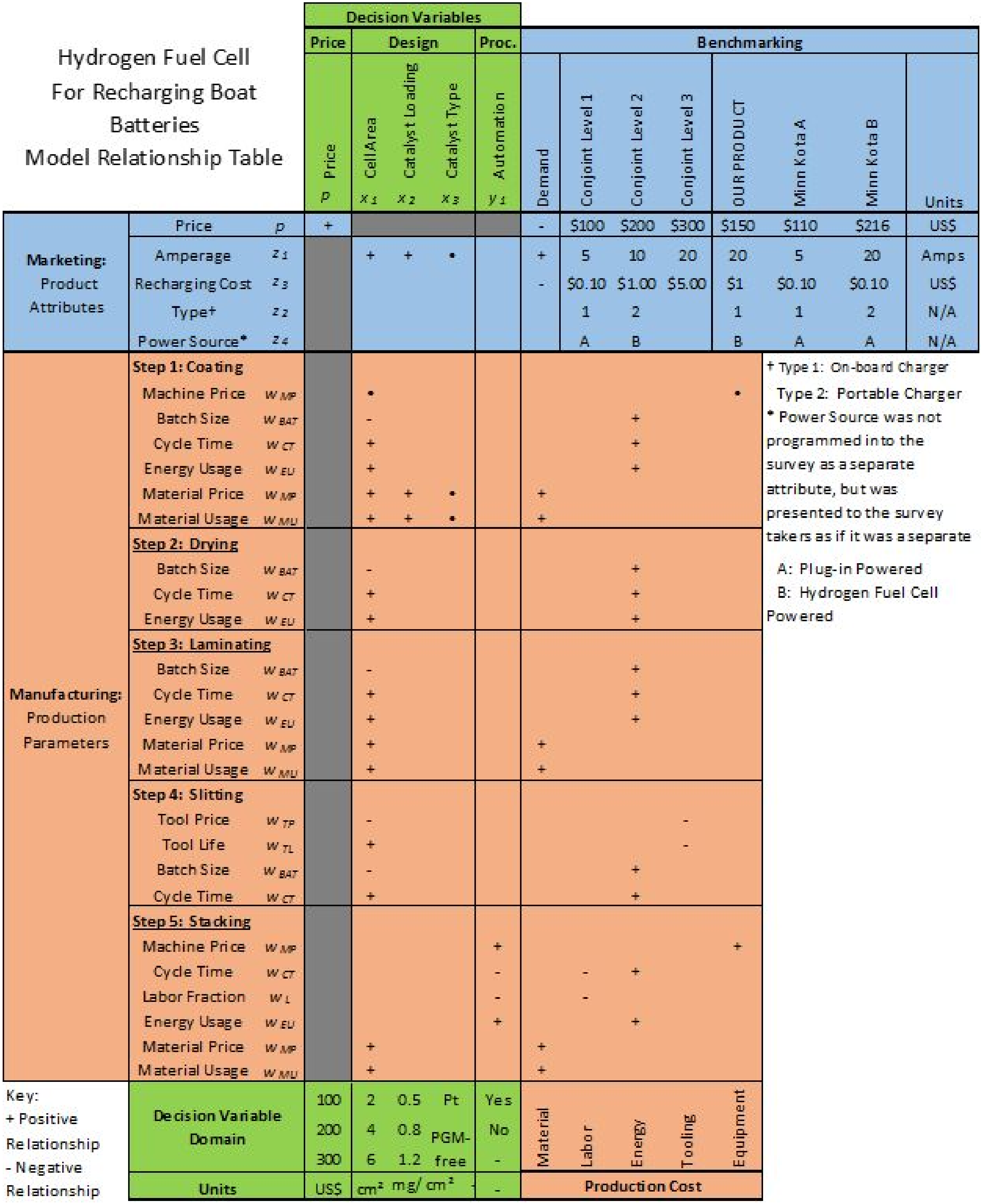


Figure 3: Model Relationships Table for 12V Fuel Cell Marine Battery Charger System



Hydrogen Fuel Cell
For Recharging Boat
Batteries
Model Relationship Table

			Decision Variables					Benchmarking							
			Price	Design			Proc.								
			Price p	Cell Area x_1	Catalyst Loading x_2	Catalyst Type x_3	Automation y_1	Demand	Conjoint Level 1	Conjoint Level 2	Conjoint Level 3	OUR PRODUCT	Minn Kota A	Minn Kota B	Units
	Price	p	+					-	\$100	\$200	\$300	\$150	\$110	\$216	US\$
Marketing: Product Attributes	Amperage	z_1		+	+	•		+	5	10	20	20	5	20	Amps
	Recharging Cost	z_3						-	\$0.10	\$1.00	\$5.00	\$1	\$0.10	\$0.10	US\$
	Type†	z_2							1	2		1	1	2	N/A
	Power Source*	z_4							A	B		B	A	A	N/A
Manufacturing: Production Parameters	**Step 1: Coating**														
	Machine Price	w_{MP}		•								•			
	Batch Size	w_{BAT}		-						+					
	Cycle Time	w_{CT}		+						+					
	Energy Usage	w_{EU}		+						+					
	Material Price	w_{MP}		+	+	•		+							
	Material Usage	w_{MU}		+	+	•		+							
	Step 2: Drying														
	Batch Size	w_{BAT}		-						+					
	Cycle Time	w_{CT}		+						+					
	Energy Usage	w_{EU}		+						+					
	Step 3: Laminating														
	Batch Size	w_{BAT}		-						+					
	Cycle Time	w_{CT}		+						+					
	Energy Usage	w_{EU}		+						+					
	Material Price	w_{MP}		+				+							
	Material Usage	w_{MU}		+				+							
	Step 4: Slitting														
	Tool Price	w_{TP}		-							-				
	Tool Life	w_{TL}		+							-				
	Batch Size	w_{BAT}		-						+					
	Cycle Time	w_{CT}		+						+					
	Step 5: Stacking														
	Machine Price	w_{MP}					+					+			
	Cycle Time	w_{CT}					-		-	+					
	Labor Fraction	w_L					-		-						
	Energy Usage	w_{EU}					+			+					
	Material Price	w_{MP}		+				+							
	Material Usage	w_{MU}		+				+							
Key: + Positive Relationship - Negative Relationship	**Decision Variable Domain**		100	2	0.5	Pt	Yes	Material	Labor	Energy	Tooling	Equipment			
			200	4	0.8	PGM-free	No								
			300	6	1.2		-								
	Units		US\$	cm²	mg/ cm²	-	-	**Production Cost**							

† Type 1: On-board Charger
Type 2: Portable Charger
* Power Source was not programmed into the survey as a separate attribute, but was presented to the survey takers as if it was a separate

A: Plug-in Powered
B: Hydrogen Fuel Cell Powered

Table 1: Major regional competitors

North America	Europe	Asia-Pacific
Pro Charging System	Tecmate (Belgium)	Daeyang Electric Co. (Korea)
Professional Mariner	Mastervolt (Netherlands)	
Marinco	C-Tek (Sweden)	
Sterling Power Products	Sterling Power Products (UK)	
Deltran Corporation	Cristec (France)	
NOCO Genius	Pb Batteries (UK)	
Schumacher Electric Corp.		
Clore Automotive		
VDC Electronics		
Sears DieHard		
Minn Kota		

Table 2: PBCM Parameter Bounds

Process Parameter	Var.	Base Case	Low Bound	Upper Bound	Source
Cell Area (Platinum) (Platinum Free)	CA	40.34 cm^2 50.43 cm^2	33.61 cm^2 40.34 cm^2	48.41 cm^2 60.52 cm^2	Calculated, Litster
Platinum Catalyst Cost	$p_{c,pt}$	\$150/g	\$100/g	\$200/g	Fuel Cell Store.com[6] Litster
Catalyst Loading (Pt)	CL_{pt}	1.13 mg/cm^2	.9 mg/cm^2	1.97 mg/cm^2	Litster; James et al (2014)
Catalyst Loading (Pt-free)	CL_{ptfree}	4.5 mg/cm^2	3.6 mg/cm^2	5.4 mg/cm^2	Calculated, Litster
Pt-free Catalyst Cost	$p_{c,ptfree}$	\$0.30/g	\$0.20/g	\$0.50/g	Team 3
Bipolar Plate Cost	p_{bp}	\$0.38/cm^2	\$0.20/cm^2	\$0.40/cm^2	James et al (2014)
GDL Cost	p_{gdl}	\$0.05/cm^2	\$0.02/cm^2	\$0.08/cm^2	Litster, James et al (2014)

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[6] http://fuelcellstore.com/fuel-cell-components/catalyst

Stacking Batch Size	$n_{5,bat}$	1	--	10	Assumption
Stacking Yield Rate	y_5	90%	80%	99%	Assumption
Membrane Cost	p_{mem}	$\$0.34/\mathrm{cm}^2$	$\$0.10/\mathrm{cm}^2$	$\$0.40/\mathrm{cm}^2$	Fuel Cell Store, Litster, James et al
Stacking Cycle Time	$t_{5,cyc}$	0.6hr	0.2hr	0.8hr	James, Brian D. (2009)
Cells per Stack	NCELL	18	--	--	Calculated
Discount Rate	DR	10%	--	--	Assumption
Days per Year*	DPY	260 days	--	--	Assumption
Scheduled Maintenance*	MT	5 days	--	--	Educated Assumption
Unplanned Maintenance*	UD	5 days	--	--	Assumption
Shift Time*	HPS	8 hrs	--	--	Assumption
No. Shifts*	NS	1	--	--	Assumption
Paid Breaks	PB	0 hrs	--	--	Assumption
Unpaid Breaks	UB	1 hr	--	--	Assumption
Direct Wage	p_{emp}	$\$20$	$\$15$	$\$50$	BLS.gov[7]
Electricity Price	p_{elec}	$\$0.14$	--	--	BLS.gov[8]
Building Unit Rate	p_{buil}	$\$1.74/\mathrm{ft}^2$	--	--	Market Watch[9]
Assembly Cost	Φ_{asb}	50% material and labour cost per unit	--	--	Assumption, based on James et al (2014) for large-scale production
Overhead Ratio	Φ_{ov}	10%	--	--	Assumed

* designates parameter that was tested arbitrarily and had no statistically significant impact on the unit cost (result of generally low machine usage)

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[7] http://www.bls.gov/regions/southeast/news-release/averageenergyprices_atlanta.htm

[8] http://www.bls.gov/regions/southeast/news-release/averageenergyprices_atlanta.htm

[9] http://www.marketwatch.com/story/heres-how-much-your-company-pays-to-rent-office-space-2015-05-27

Table 3: Material Input Parameters

Step	Material	Cost	Amount in Final	Bounds (if applicable)	Source
1	Catalyst (pt)	$150/g	Loading * Cell Area * No. Cells	[$100,$200]	Fuel Cell Store[2]
	Catalyst (pt-free)	$0.30	Loading * Cell Area * No. Cells	[$0.15,$0.50]	Group 3
	Nafion Membrane	$0.34/cm^2	Cell Area * No. Cells	[$0.10, $0.40]	Fuel Cells Etc.[10] Lowerbound from James et al (2014)
3	Gas Diffusion Layer	$\$0.05/\text{cm}^2$	2 * Cell Area * No. Cells	[$0.02, $0.08]	Fuel Cells Etc.[5] Lowerbound from James et al (2014)
5	Bipolar Plates	$\$0.38/\text{cm}^2$	Cell Area * No. Cells	[$0.10, $0.40]	Fuel Cell Store[2] Lowerbound from James et al (2014)
	Fastener	$0.13/ea	6	-	McMaster-Carr[11]

Table 4: Step 1 Machine Parameters (Coating)

Parameter	Machine 1 (Sono-tek Flexicoat)	Machine 2 (Coatema Verticoater)	Bounds (if applicable)	Source
Machine Cost	$122,000	$1,500,000	$1M-2M	Quote from Sono-tek
Machine Lifetime	8 years	8 years	-	assumed
Setup Time	.5 hours	0.5 hours	-	assumed
Cycle Time	1 hour	1 hour	-	assumed
Yield Rate	100%	100%	-	assumed
Tooling Cost	$5000	$3000	-	Sono-tek; James

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[10] http://fuelcellsetc.com/products-services/membrane-electrode-assemblies/

[11] http://www.mcmaster.com/#standard-rubber-sheets/=14jmr0v

				et al (2014)
Tooling Lifetime	1 year	1 year	-	assumed
Scrap	15%	5%	3%-15%	Sono-tek; James et al (2014)
Energy Usage	10kW	55kW	**-**	Sono-tek; James et al (2014)

Table 5: Step 2 Machine Parameters (Drying)

Parameter	**Base Case**	**Bounds (if applicable)**	**Source**
Machine Cost	$300,000	$250,000 - $350,000	TIAX document (2005)
Fractional Labor Use	-		
Cycle Time	1 hr	Up to 24-36 hrs for air drying	Brian Mcfall, thelamco
Loading/Unloading	-		
Batch size	89,000 fuel cells/roll	+/- 5%	calculated
Machine Lifetime	10 years		assumed
Tooling Cost	$1000	$800 - $1200	Brian Mcfall, thelamco
Tools/line	2		assumed
Tool Lifetime	3 years		Brian Mcfall, thelamco

Table 6: Step 3 Machine Parameters (Laminating)

Parameter	**Base Case**	**Bounds (if applicable)**	**Source**
Machine Cost	$150,000	[150K, $191K]	TIAX document (2005)
Fractional Labor Use	20%	[15%, 25%]	TIAX document (2005) and Brian Mcfall, thelamco

Cycle Time	40 ft/min	[40 ft/min, 80 ft/min]	TIAX document (2005)
Loading/Unloading	8 min	[7 min - 15min]	Brian Mcfall, thelamco
Batch size	3529 FC/Batch	-	Calculated
Machine Lifetime	25 years	40 years max	Brian Mcfall, thelamco
Tooling Cost	$5000	$4000- S6000	Brian Mcfall, thelamco
Tool Lifetime	15years	10 years - 20 years	Brian Mcfall, thelamco
Tools/Lines	1	-	Calculated

Table 7: Step 4 Machine Parameters (Slitting)

Parameter	Base Case	Bounds (if applicable)	Source
Machine Cost	$3,000,000	[$1 mil, $5 mil]	Todd, Roll Razor
Machine Lifetime	15 yrs	[10 yrs, 20 yrs]	Todd, Roll Razor
Setup Time	12 min	--	Roll Razor
Cycle Time	24 mins	--	Roll Razor
Yield Rate	90%	--	Roll Razor
Tooling Cost	$1,000	[$500, $2000]	Todd, Roll Razor
Tooling Lifetime	1 month	--	Roll Razor
Yield	95%	[90%, 100%]	Assumption: The edges of each roll will be cut off and since the slitting machine removes all materials in the laminated MEA and is processed as **sheets** rather than individual **units**. What technically is scrap is approximated as a fractional yield to simplify equations.
Scrap	0%	--	
Energy Usage	2.80kW	--	Roll Razor

Table 8: Step 5 Machine Parameters (Stacking)

Parameter	Manual	Semi-Auto	Source
Machine Cost	$11,060	$810,171	James, Brain, D. (2009)
Fractional Labor Use	100%	25%	James, Brain, D. (2009)
Cycle Time	24 minutes	9.3 minutes	James, Brain, D. (2009)
Loading/Unloading	26 minutes	-- minutes	Assumption
Batch size	1	10	Assumption
Machine Lifetime	15 yrs	15 yrs	James, Brain, D. (2009)
Dedicated Labor	1	10	Non dedicated, calculated
Dedicated Machinery	1	56	calculated

Table 9: PBCM Equations

General	Annual Paid Time	$APT = DPY * NS(HPS - UB)$
	Line Time Available	$LTA = (DPY - UD - MT) * NS(HPS - UB - PB)$
	Effective Production Volume	$EPV_i = \frac{APV}{y_1 \cdot y_2 \cdots y_n}$; n [i,N]
	Line Time Required	$LTR = \frac{EPV(t_{cyc} + t_{load} + t_{unload})}{BA}$
	Lines Required	$n_{lines} = \left[\frac{LTR}{LTA}\right]$ *roundup iff dedicated*
	Material Consumption	$u_{mat} = \frac{u_{n,mat} \times EPV}{(1-s)}$
	Laborers Required	$Ceiling[\Phi_i^{LB} t_i^{REQ} / t_i^{AVL}]$
	Energy Consumption	$u_{uk}^{EG} = q_i(t_i^{CYC} w_{ik}^{RUN} + t_i^{SET} w_{ik}^{IDL})$
	Primary Equipment Required	$u_i^{EQ} = n_i^L$
	Tools Required	$u_i^{TL} = Ceiling[n_i^L n_i^{TPL}]$
	Material Cost	$C^{MA} = \sum_{i=1}^{m} \sum_{k \varepsilon M} p_k^{MA} u_{ik}^{MA}$

	Labor Cost	$C^{LB} = \sum_{i=1}^{n} p^{LB} u_i^{LB} (t^{OP} n^{SH} (t^{SH} - t^{UB})$
	Equipment Cost	$C^{EQ} = \sum_{i=1}^{n} p_i^{EQ} u_i^{EQ} \frac{r(1+r)^{t^{eq}}}{(1+r)^{t^{EQ}}-1}$
	Auxiliary Equipment Cost	$C^{AX} = \Phi^{AX} C^{EQ}$
	Energy Cost	$C^{EG} = \sum_{i=1}^{m} \sum_{k \varepsilon M} p_k^{EG} u_{ik}^{EG}$
	Building Cost	$C^{BL} = p^{BL} \sum_{i=1}^{n} A_i n_i^{L} \frac{r(1+r)^{t^{BL}}}{(1+r)^{t^{BL}}-1}$
	Overhead Cost	$C^{OH} = \Phi^{OH} (C^{EQ} + C^{AX} + C^{TL} + C^{BL} + C^{MT})$
	Maintenance Cost	$C^{MT} = p^{MT} (t^{MT} n^{SH} (t^{SH} - t^{UB}) + \sum_{i=1}^{n} t_i^{MT})$
Specific	Batch Size	$BA = \frac{V_{roll} \times W_{roll}}{N_{cell} \times CA}$
	Amount in Final Product	$u_{n,mat} = C_{mat} \times N_{cells}$
	Assembly Cost	$C^{AS} = \sum_{i=1}^{m} \sum_{k \varepsilon M} p_k^{AS} u_{ik}^{AS}$

Figure 4: Membrane electrode assembly breakdown of the fuel cell along with key decision variables highlighted in yellow (Odetola et al. 2016)

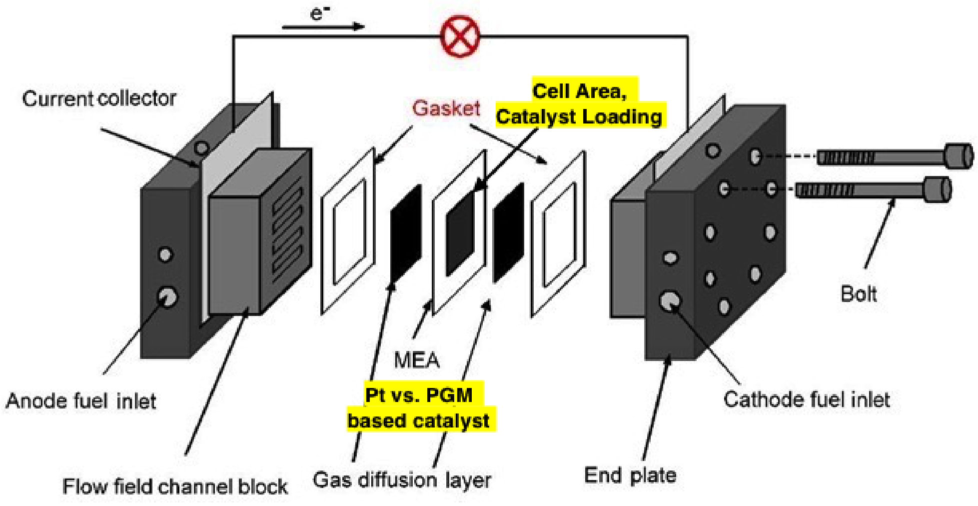
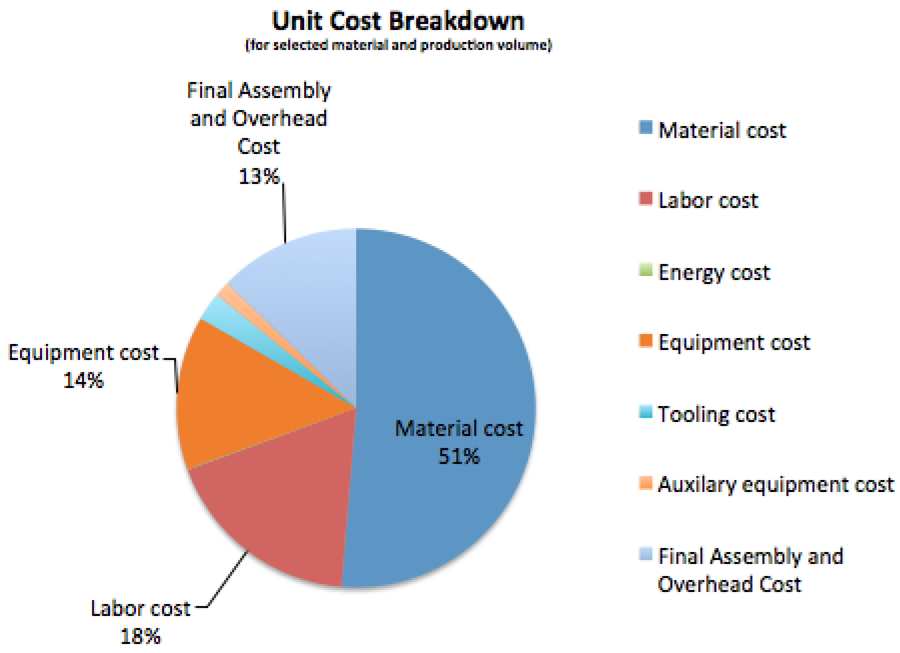


Figure 5: Unit Cost Breakdown by Cost Type

5(a)



5(b)

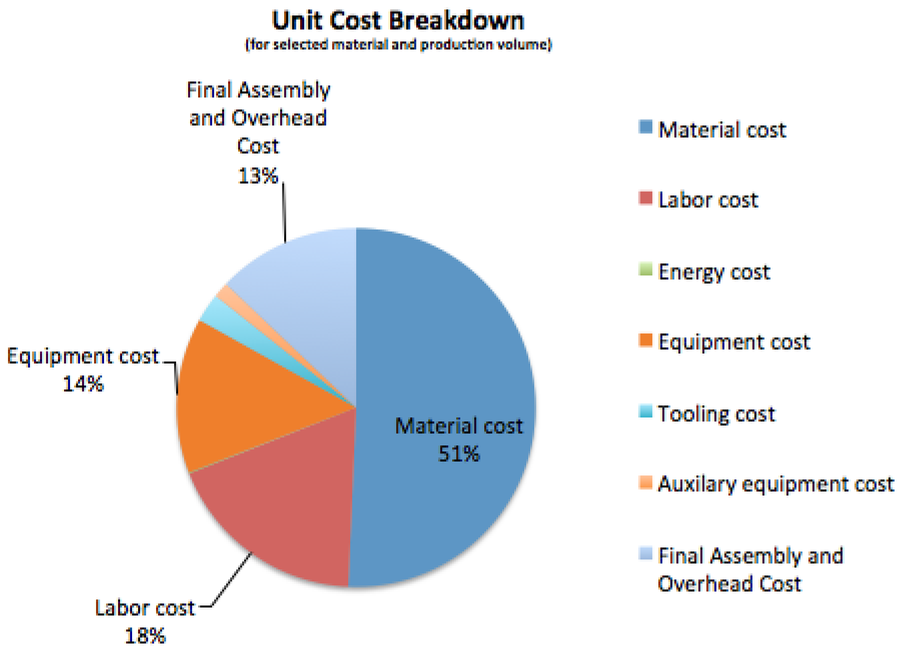
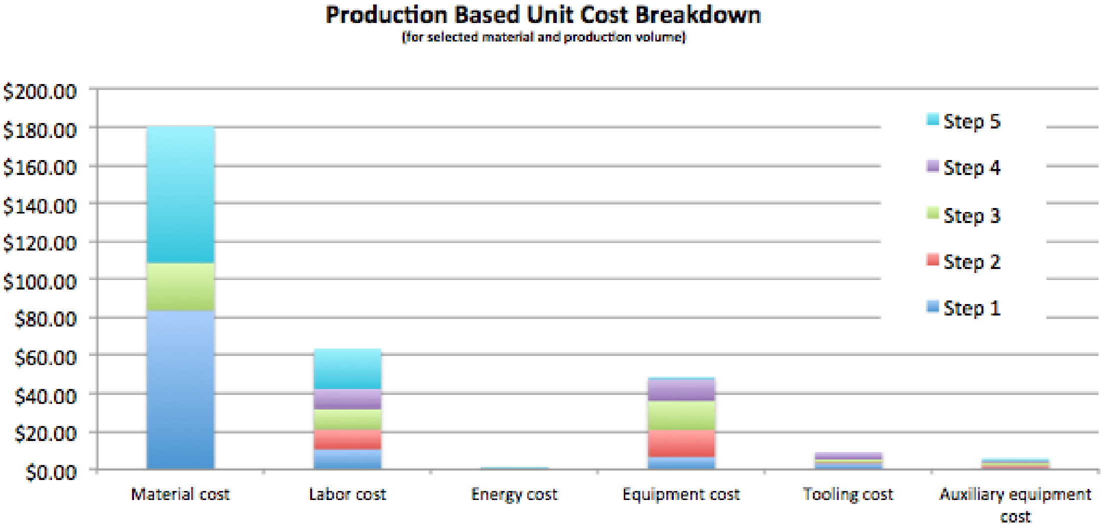


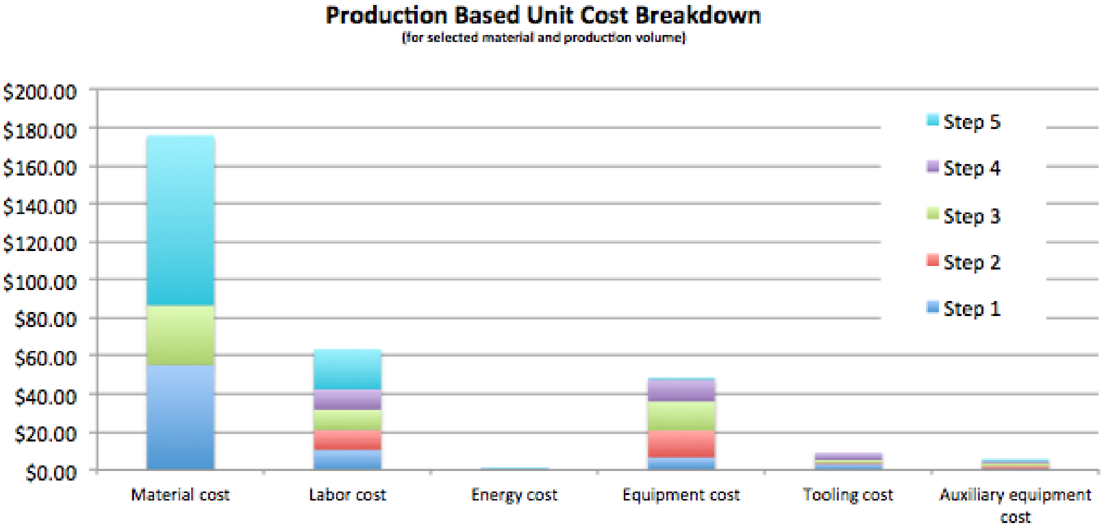
Figure 5(a) shows a unit cost breakdown given the base case scenario (annual production volume of 3,440, platinum catalyst, 10cm^2 cell area). The unit cost is approximately $351 (+/- $35). Figure 5(b) shows the same cost breakdown for a platinum-free catalyst fuel cell assembly with APV of 3,440 and cell area of 12cm^2 (same power output as Pt comparison). The unit cost is approximately $346 (+/- $35).

Figure 6: Base Case Unit Cost Breakdown by Step & Cost Type

6(a)



6(b)

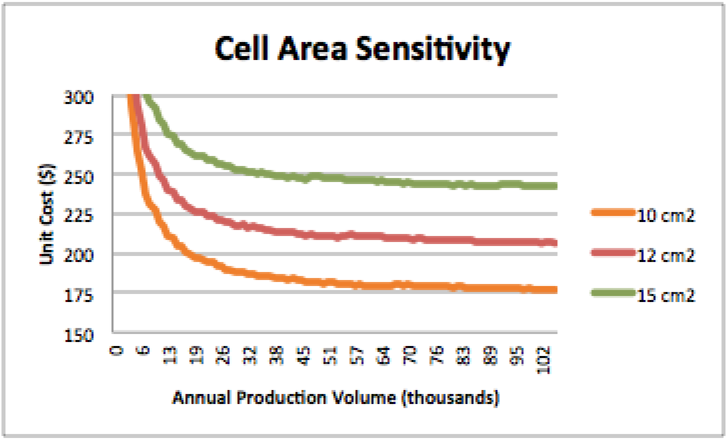


Both of these figures assume an annual production volume of 3,440 units being produced. Figure 3(a) uses a platinum catalyst and a cell area of 10cm^2 and Figure 3(b) uses a platinum free catalyst and 12cm^2 cell area.

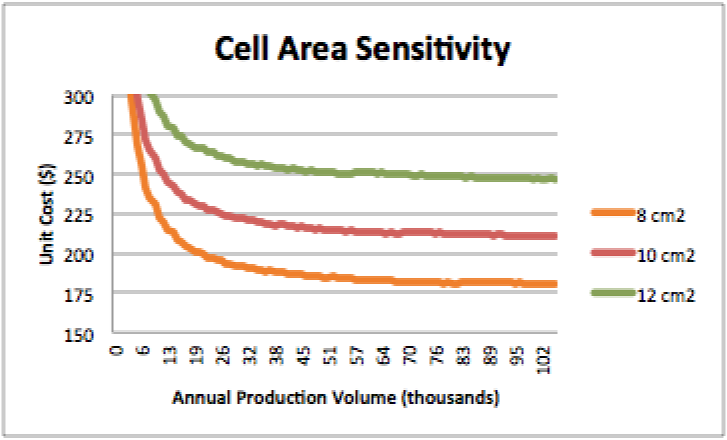
These figures clearly demonstrate that material costs are the driving factor, with the step 1 materials (catalyst and membrane) being more significant in the platinum catalyst case than in the pt-free case. The comparison of the figures also shows the increase in step 5 (bipolar plates) cost with the pt-free configuration.

Figure 7: Unit Cost Curves for Decision Variable Visualization

7(a) Cell Area Sensitivity for Pt-Free Catalyst



7(b) Cell Area Sensitivity for Pt Catalyst



7(c) Catalyst Type Sensitivity

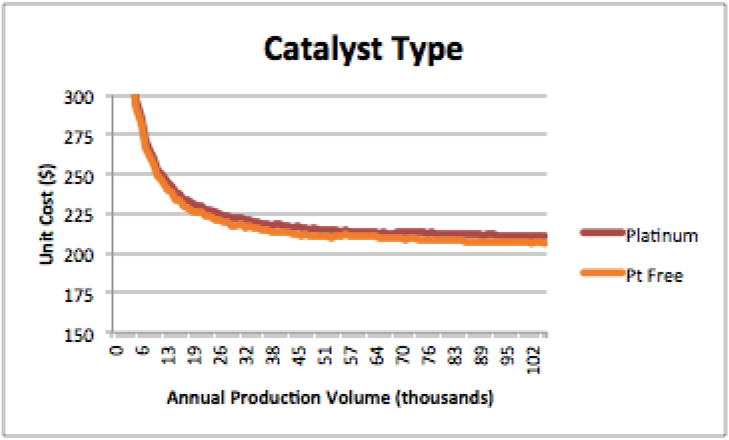
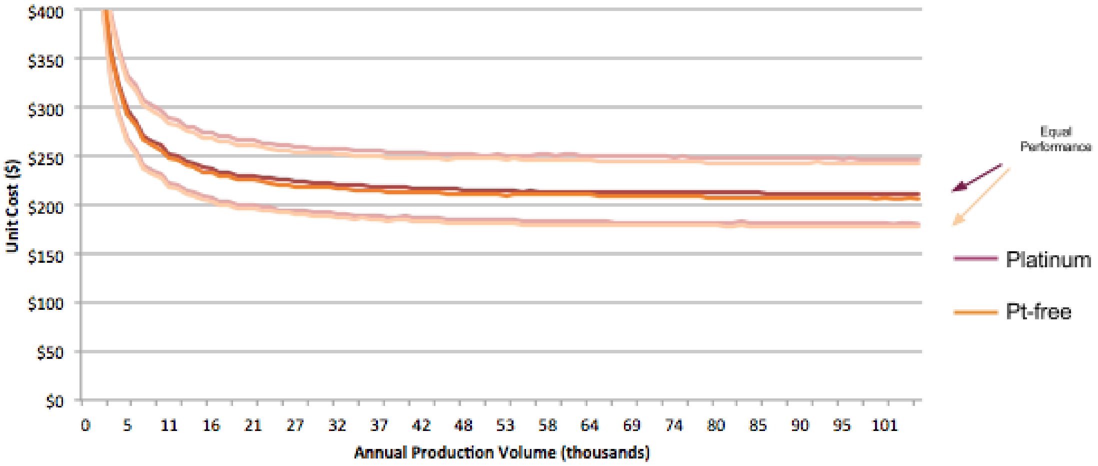


Figure 7 shows various cost curves for the base case (3,440 annual production volume). Figure 7(a) isolates the effects of cell area for a platinum free cell. Figure 7(b) isolates the effects of cell area for a platinum cell. Figure 7(c) isolates the different catalyst types.

Figure 8: Unit Cost Curve



The above plots show the unit cost versus annual production volume. The plant reaches minimum capacity between 30,000 (within 5% of asymptotic unit cost value) and 76,000 (within 1% of asymptotic unit cost value). The pale colored lines indicate +/- 20% efficiency of the catalyst. The base case efficiencies are 40% and 60% for platinum free and platinum, respectively. Thus, the lower orange line and the middle dark purple line represent the platinum and platinum free functioning at the same efficiency. Figure 8 demonstrates that there is a similar uncertainty between the two catalysts. The uncertainty results mainly from the variation in efficiency of the cells of up to 20% (varies due to temperature, platinum content, humidity, etc.) (Litster).

Table 10: Unit Cost Breakdown for Platinum Cell

UNIT COST SUMMARY	Step 1	Step 2	Step 3	Step 4	Step 5	Additional Costs*	TOTAL
Material cost	$83.66	$0.00	$25.08	$0.00	$71.47		$180.21
Labor cost	$10.58	$10.58	$10.58	$10.58	$21.16		$63.49
Energy cost	$0.00	$0.00	$0.18	$0.00	$0.09		$0.27
Equipment cost	$6.65	$14.19	$15.29	$11.47	$1.04		$48.64
Tooling cost	$3.12	$0.58	$1.60	$3.68	$0.00		$8.98
Auxiliary equipment cost	$0.66	$1.42	$1.53	$1.15	$0.10		$4.86
Total Variable Cost	$94.25	$10.58	$35.83	$10.58	$92.72	$31.24	$243.97
Total Fixed Cost	$10.44	$16.20	$18.42	$16.29	$1.15	$13.49	$75.98
TOTAL COST	$104.68	$26.78	$54.25	$26.87	$93.87	$44.73	**$351.19**

Table 11: Unit Cost Breakdown for Platinum Free Cell

UNIT COST SUMMARY	Step 1	Step 2	Step 3	Step 4	Step 5	Additional Costs*	TOTAL
Material cost	$55.19	$0.00	$31.35	$0.00	$89.34		$175.88
Labor cost	$10.58	$10.58	$10.58	$10.58	$21.16		$63.49
Energy cost	$0.00	$0.00	$0.22	$0.00	$0.09		$0.32
Equipment cost	$6.65	$14.19	$15.29	$11.47	$1.04		$48.64
Tooling cost	$3.12	$0.58	$1.60	$3.68	$0.00		$8.98
Auxiliary equipment cost	$0.66	$1.42	$1.53	$1.15	$0.10		$4.86
Total Variable Cost	$65.78	$10.58	$42.15	$10.58	$110.59	$31.24	$239.68
Total Fixed Cost	$10.44	$16.20	$18.42	$16.29	$1.15	$13.49	$75.98
TOTAL COST	$76.21	$26.78	$60.56	$26.87	$111.74	$44.73	**$346.90**

* Additional costs includes post-stacking electronics assembly, overhead, building rental, and maintenance cost projections.

Figure 9: Process flow diagram for the fuel cell manufacturing process

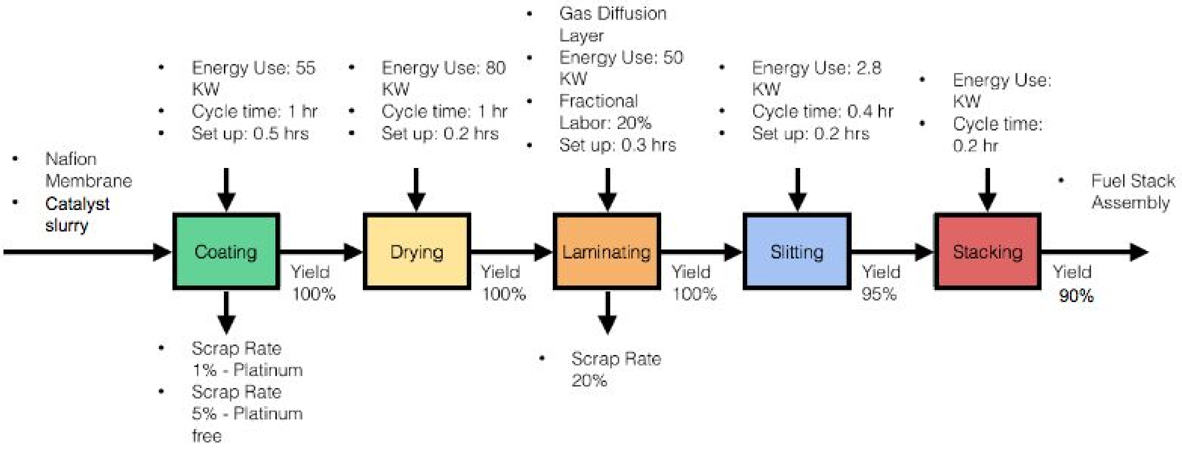
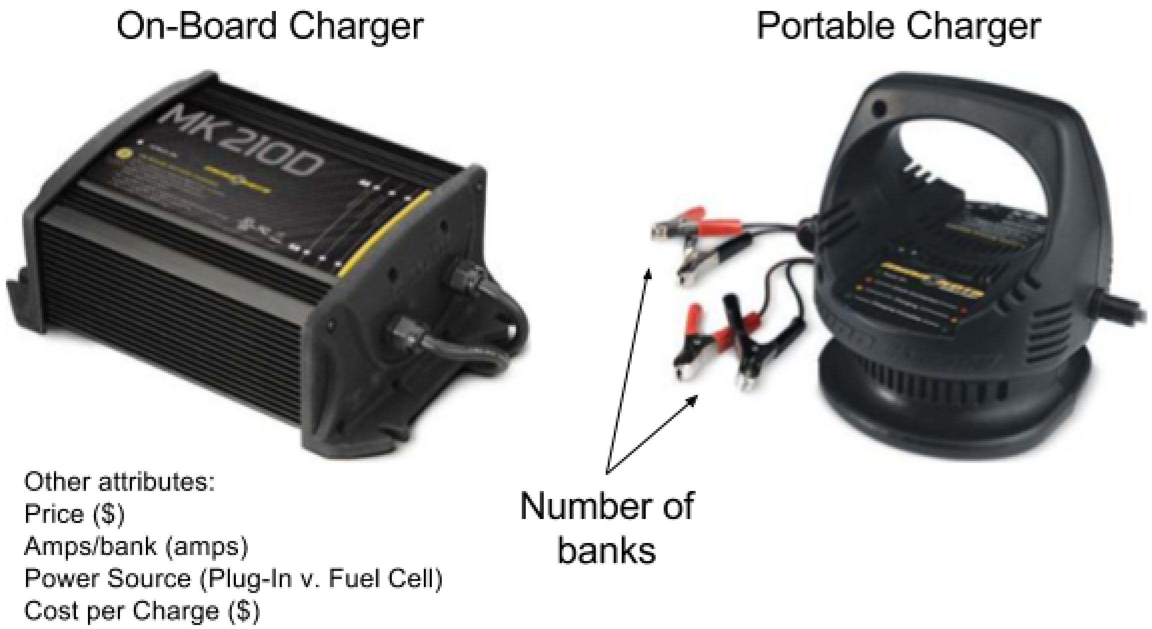
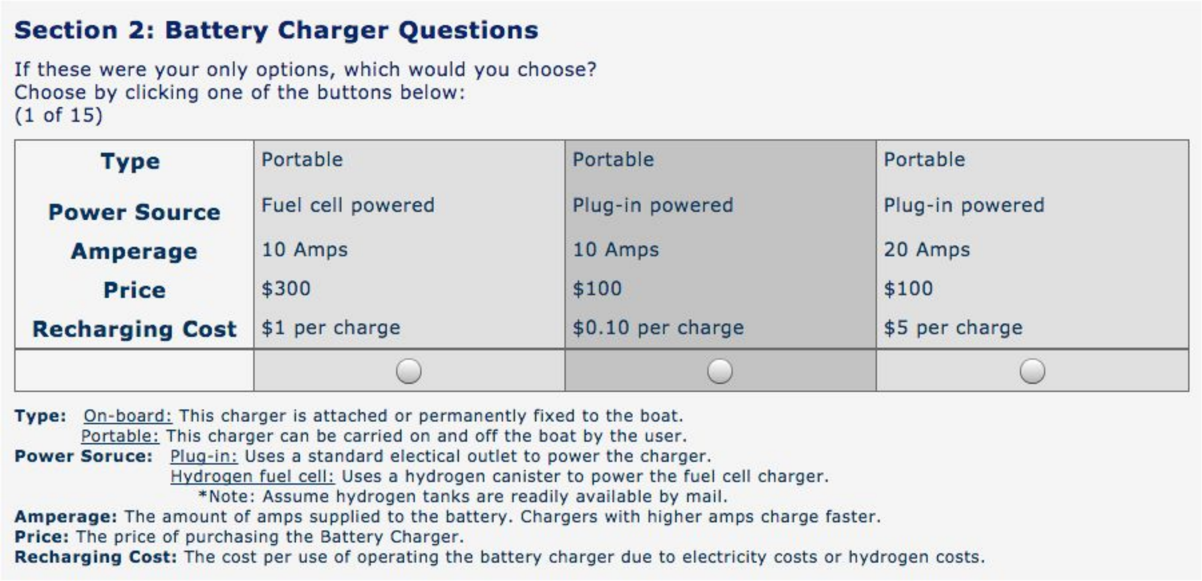


Figure 10: Fuel Cell Charger



Minn Kota MK-210D (2 Bank) On-Board Battery Charger Pictured
http://mk.factoryoutletstore.com/details/36625/minn-kota-210d.html?category_id=20873&catalogitemid=38148
Minn Kota MK 210P (2 Bank) Portable Charger pictured
http://mk.factoryoutletstore.com/details/43827/1822110.html?category_id=20874

Figure 11: Sample Survey Question



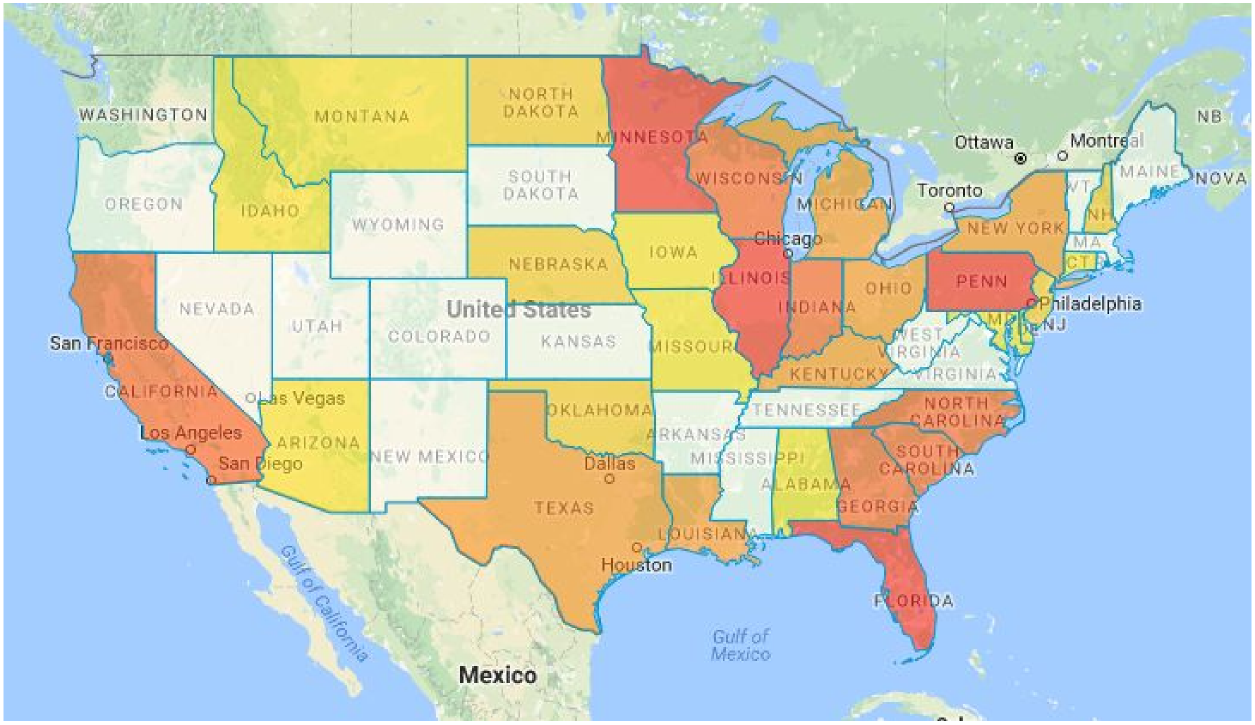
Section 2: Battery Charger Questions

If these were your only options, which would you choose?
Choose by clicking one of the buttons below:
(1 of 15)

Type	Portable	Portable	Portable
Power Source	Fuel cell powered	Plug-in powered	Plug-in powered
Amperage	10 Amps	10 Amps	20 Amps
Price	$300	$100	$100
Recharging Cost	$1 per charge	$0.10 per charge	$5 per charge
	○	○	○

Type: On-board: This charger is attached or permanently fixed to the boat.
Portable: This charger can be carried on and off the boat by the user.
Power Soruce: Plug-in: Uses a standard electical outlet to power the charger.
Hydrogen fuel cell: Uses a hydrogen canister to power the fuel cell charger.
*Note: Assume hydrogen tanks are readily available by mail.
Amperage: The amount of amps supplied to the battery. Chargers with higher amps charge faster.
Price: The price of purchasing the Battery Charger.
Recharging Cost: The cost per use of operating the battery charger due to electricity costs or hydrogen costs.

Figure 12: Heat Map of Survey Respondents



White states had zero respondents, yellow states had one ranging up to 8 or more in the darkest red states.

Table 12: Utility coefficient estimates (β) with standard errors (σ)

Attribute	Level	β	σ
Charger Type	*On-board, Plug-in*	0.5686	0.053009433
	Portable, Plug-in	-0.04209	0.053851648
Charger Rating	*5 Amps*	-0.61651	0.058395205
	10 Amps	0.13203	0.053103672
Price	*Price $*	-0.00361	0.000470322
Charging Cost	*$0.10 per charge*	0.97372	0.056302753
	$1 per charge	0.06735	0.053162295

Table 13: Utility Function Equation & Definition

$$v = \beta_1 x_1 + \left[\beta_{21} y_{21} + \beta_{22} y_{22} - (\beta_{21} + \beta_{22}) y_{23}\right] + \left[\beta_{31} y_{31} + \beta_{32} y_{32} - (\beta_{31} + \beta_{32}) y_{33}\right] + \\ + \left[\beta_{41} y_{41} + \beta_{42} y_{42} - (\beta_{41} + \beta_{42}) y_{43}\right]$$

Price	---	1
Charger Type	On-board, plug-in	21
	Portable, plug-in	22
	Portable, fuel cell	23
Amperage	5 amps	31
	10 amps	32
	20 amps	33
Recharging cost	$0.10 per charge	41
	$1 per charge	42
	$5 per charge	43

Figure 13: Base Case Market Scenario SImulated Share

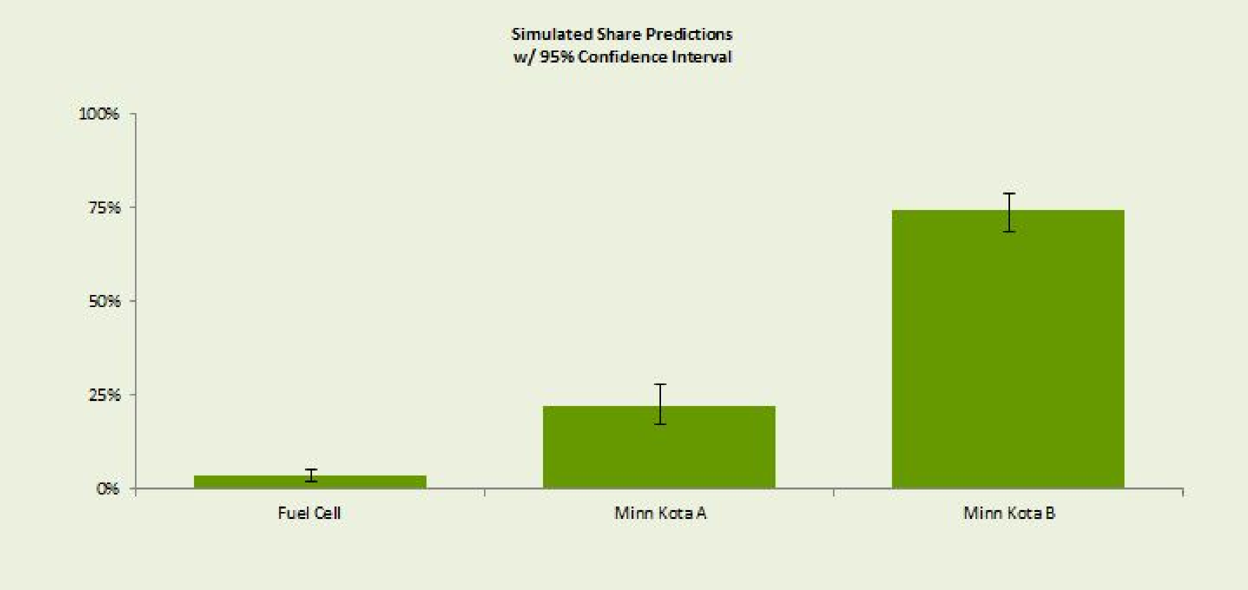


Figure 14: Onboard Charger Market Scenario SImulated Share

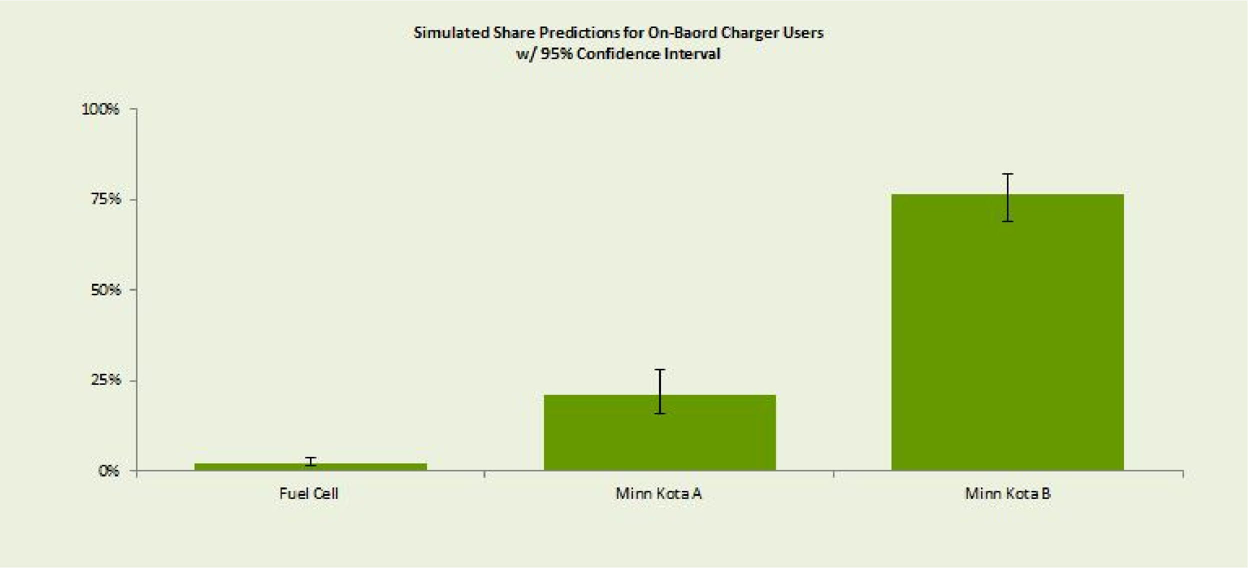


Figure 15: Portable Charger Market Scenario

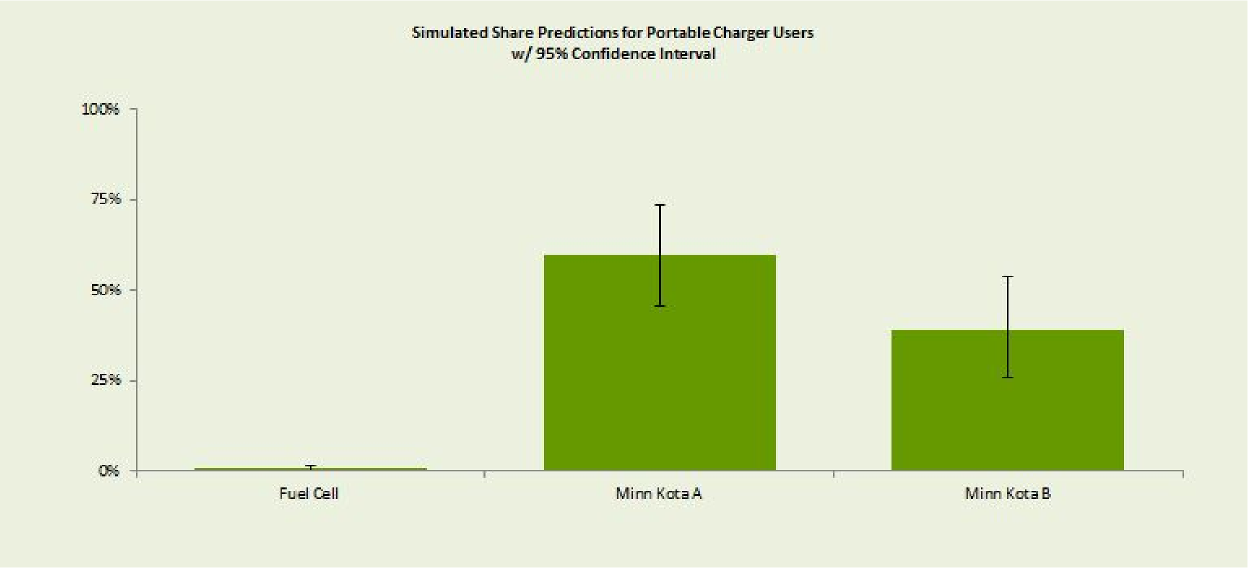


Figure 16: Willingness to Pay

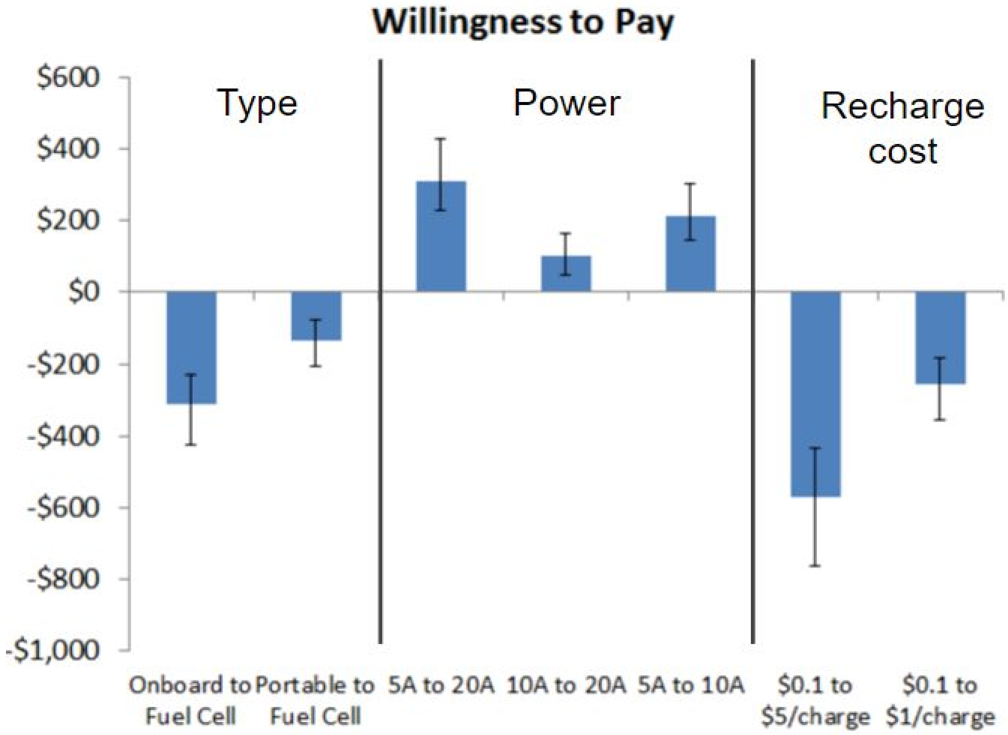


Table 10: Simulated Market Scenario Options

	Type	Price	Amperage	Cost per Recharge
Fuel Cell Charger	Portable, fuel cell	$450	5 amps	$1
Minn Kota A	Portable, plug-in	$110	5 amps	$0.10
Minn Kota B	On-board, plug-in	$250	10 amps	$0.10