Technical-economic cost modeling as a technology management tool

A case study of membranes for PEM fuel cells

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Abstract

Purpose – The purpose of this paper is to show how technical-economical cost modeling can help in steering research and development to target key production cost elements of new products based on emerging technologies.

Design/methodology/approach – The authors demonstrate the development and use of a technical-economic cost model (TCM) of the proton exchange membrane (PEM) in fuel cells to steer research to produce more economical and reliable products. A TCM is developed to depict how the production cost per unit varies depending on the different fabrication methods, production rate limitations, material selection, labor distribution, energy consumption, financial parameters and the target production volume. By using such an approach in the design, research time and resources can be saved by prioritizing R&D and production scale-up options at an early stage.

Findings – The results of this study show the importance of applying technical-economic cost model (TCM) techniques on early stage research projects to steer the development for resolving key problematic figures. As a case study, a cost analysis platform has been established to apply this technique by analyzing different manufacturing and R&D options for producing durable PEM fuel cells. The projected manufacturing cost of the PEM is found to be lower than previously estimated and the enhanced durability does not significantly impact this production cost.

Originality/value – Production is an important factor in informing NPD targets and R&D direction. And yet it is difficult to estimate scaled up production cost for prototype products and components in the R&D lab. Technical-economic cost models (TCM) are a tool to assist decision-making in technology portfolio management and NPD.

Keywords Transportation, Cost modeling, Fuel cells, Process cost model, Proton exchange membrane, Technical-economic cost model

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1. Introduction

Production is an important factor in informing new product development (NPD) targets and R&D directions. And yet it is difficult to estimate scaled up production cost for prototype products and components in the R&D lab. Technical-economic cost models (TCM) are a tool to assist decision-making in technology portfolio management and NPD. TCM involves modeling the key technical limitations of a process (often in terms of limiting production rate), estimating equipment and labor costs of scaled up production processes over a range of production volumes, and running informed scenarios for all key input variables. Through comparing such cost estimates against those of incumbent products and components, better information about viable target markets is available earlier in the development process. Thus, TCM acts as a technology management tool at the interface of manufacturing and R&D.

To illustrate this method, we describe the TCM analysis of a current R&D effort to advance the functionality and affordability of fuel cells for automotive applications. Currently fuel cells are too expensive for widespread commercialization and need to be replaced too often to be viable in automotive applications. One of the key elements in the proton exchange membrane (PEM) fuel cell systems that affect both durability and cost is the membrane. The cost of membranes in PEM fuel cells represents one of the major costs of the fuel cell system in low production volumes (James *et al.*, 2010). This cost drops in large production volumes, but still represents a considerable percentage of the total net power cost. In addition, degradation of membranes is the major cause for early failures and reduced durability and reliability of the fuel cell stack (Macauley *et al.*, 2013; Goulet *et al.*, 2013). Thus, optimizing membranes for cost and durability is essential to make fuel cell technology competitive in power generation and transportation.

The methodology to establish the unit cost of alternative membranes is based on studying the manufacturing and preliminary material cost as a function of production volume (Maine and Ashby, 2002). The production cost should be compared with similar existing solutions to establish a scale for its market acceptance. In our study, we explore the cost of new emerging membrane technologies and compare with basic existing membrane cost. In addition, we use target costs determined by the US Department of Energy (DOE) for a similar production method for comparison purposes.

1.1 Existing cost analysis techniques

Ahmad *et al.* (2011) argue that production plants are more competitive when their organization embraces a learning-based technology strategy. To create and adapt such a technology strategy, some type of cost analysis must be undertaken. However, cost analysis methodologies can range from back-of-the-envelope estimates to fully integrated predictive tools, which are suitable for different purposes.

Although not quite back-of-the-envelope, the first methodology we review is on that side of the spectrum. Target costing methodology is defined as a structured approach to determine the cost at which a company aims to produce a new product (Gopalakrishnan *et al.*, 2007). In the target cost methodology, the analysis starts with determining the selling price and the desired profitability over the expected life cycle of the product. From these known targets, along with the specified functionality and quality of the proposed product, the analysis works backward to determine a target production cost (Cooper, 2002). Although useful, this methodology does not reflect actual production cost and thus is of limited use for novel products. For novel processes and products, especially those with ongoing R&D to improve performance parameters, links between cost component estimates, functional attributes and production parameters are essential (Field *et al.*, 2007).

Another key cost analysis technique widely used is the cost analysis approach design for manufacture and assembly (DFMA) technique as presented by Boothroyd and Dewhurst (Marcinkoski *et al.*, 2011). As in the present case study, DFMA has been used to predict the cost of membranes for PEM fuel cells (James *et al.*, 2010). However, DFMA is not adequate to assess and guide early stage product research as it does not link process rate limiting steps with both potential R&D outcomes and production cost elements. DFMA focuses on cost, quality, serviceability and time to market. This methodology is most useful once technological advances have already been incorporated into a prototype product.

In contrast, TCM is meant to steer research to produce more economical and reliable novel products. TCM is a critical tool to bridge the gap from R&D to manufacturing because a TCM depicts the linkage between production cost per unit and a range of design, R&D, and production variables. Research time and resources can be saved by prioritizing R&D and production scale-up options at an early stage. TCM reduces NPD uncertainty by improving the linkage between production cost estimates, process variables, and achievable R&D goals. Improving NPD success rates can provide substantial economic benefit to companies and can be a source of competitive advantage (Cooper *et al.*, 2004). In addition, overly conservative predictive techniques, such as estimates which unduly penalize uncertainty, supress innovation (Christensen *et al.*, 2008).

Very few of the models in the literature consider the interdependencies among the factors used in the evaluation technique (Ordoobadi, 2012). Neither of the wide spread costing approaches of target costing and DFMA accounts for these interdependencies. Based on the literature, such interdependency was observed in the model developed by Sarkis *et al.* (2007) for agile virtual enterprise partner selection and in the technique developed by Anand and Kodali (2009) for decisions regarding the implementation of lean manufacturing systems. But these techniques are however not suitable to evaluate novel products with ongoing R&D. A TCM approach explicitly considers this interdependency among factors as described in Section 2.2. Such an approach can create an evaluation method for researchers and managers that consider the relation within the selection criteria as well as between the alternatives and the criteria (Ordoobadi, 2012).

1.2 Technical-economic cost modeling as a tool for technology management

Technical-economic cost modeling (TCM) was introduced to link estimates of production scale-up costs to product specifications, production conditions, and technical uncertainties in emerging materials-based processes (Clark *et al.*, 1997). TCM has been used most widely to assess the potential of new materials and production methods in the automotive sector (Han, 1994; Fuchs *et al.*, 2006; Maine and Ashby, 2002). TCM is generally used to guide scale-up decisions about a lab scale production process. The process is segmented into stages, cost information about inputs and production equipment is gathered or estimated, and limitations in production rate factors are established. Standard accounting measures of fixed and variable costs are used to represent the production costs over a range of production volumes and across informed scenarios about future input costs and technological advances (Maine and Ashby, 2000).

The related process-based cost modeling framework introduced by Field *et al.* (2007) is represented in Figure 1. It postulates that cost can be regarded as a function of technical factors, such as cycle time, downtime, reject rate, equipment and tooling requirements, or the material used (Nadeau *et al.*, 2010). Understanding the effect of these underlying technical cost drivers can provide insight for managers and engineers as to what process improvements are most critical to lower production costs (Fuchs *et al.*, 2006).

1.3 Case study: fuel cell membranes

As a background to the case study, a fuel cell is a device that uses a continuous supply of hydrogen and air to produce electricity, heat, and water through an internal electrochemical process. The proton exchange membrane fuel cell (PEMFC) is predominantly used by the automotive fuel cell industry. As shown in Figure 2,

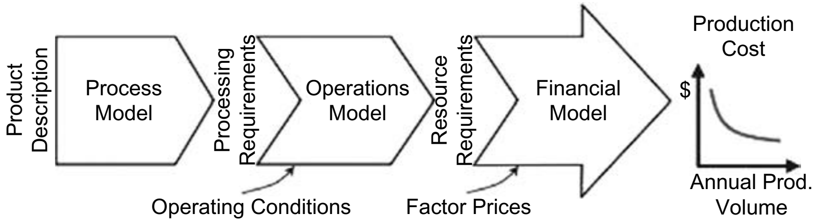

Figure 1.
Process-based cost modeling framework

Source: Field *et al.* (2007)

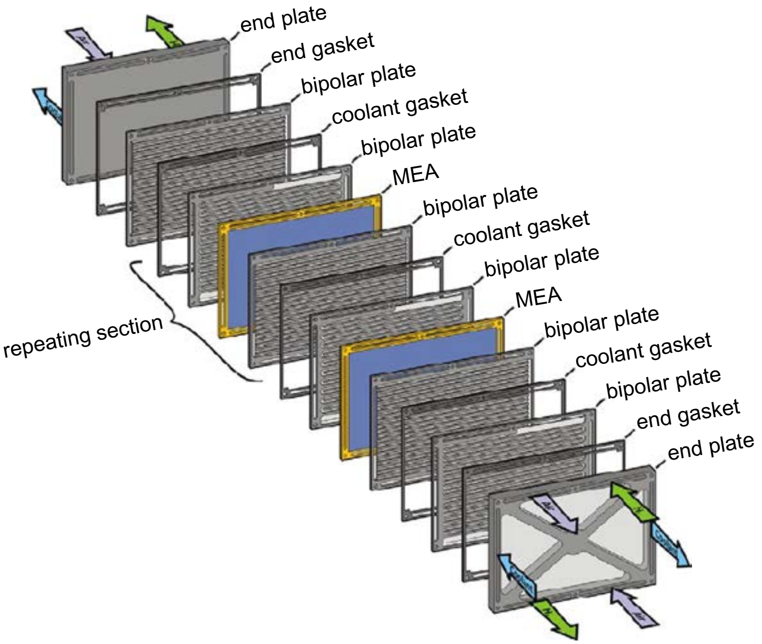

Figure 2.
Proton exchange membrane fuel cell essential components

Source: James *et al.* (2010)

the core of the PEMFC is the membrane electrode assembly (MEA), which contains two electrodes (anode and cathode) separated by a proton-conducting membrane. The role of the membrane is to physically separate the electrodes while also conducting the protons formed by hydrogen oxidation on the anode across to the cathode where they react with oxygen to form water. The electrons generated are passed through an external load, e.g. an electric motor in the case of a fuel cell vehicle, where the electric power produced by the fuel cell is consumed. The voltage output from a single fuel cell is usually less than one volt. To increase the voltage, several fuel cells are connected in series in a stack configuration. In the automotive industry, fuel cell stacks commonly comprise more than 200 individual cells.

1.4 PEM fuel cells for transportation

Fuel cell systems have to reach a certain price target to be a competitive solution for power generation in different sectors. Currently, transportation has been dominated by fossil fuel-based internal combustion engines, which are responsible for 27 percent of CO_2 emission in the USA. According to the US Department of Energy (DOE), by using fuel cells in light duty vehicles, transportation will be less reliant on gasoline consumption as well as crude oil imports and may reduce up to 85 percent of CO_2 emission from the transportation sector (Hydrogen Bus Alliance, 2011).

As for any new technology, government policies struggle to adopt and implement regulations to cover its purpose in a complex market. For this reason, the DOE has had a decade-long partnership with the US Council for Automotive Research, called FreedomCAR, established to study the use of fuel cells in vehicles (National Research Council, 2010). In 2011, most of the major automotive OEMs around the world signed a joint statement about their commitment to start commercializing fuel cell vehicles by 2015. Based on this commitment, it is estimated that over 670,000 fuel cell light duty vehicles will be sold by 2020 and the market related to public transportation, mainly transit buses, will increase at a rate of 30 percent every year after 2014 (*Hydrogen and Fuel Cells: Essential Components of the "New Energy Economy"*, 2011).

The membrane employed in the proton exchange membrane (PEM) fuel cell systems for automotive applications is known to create serious constraints for both durability and cost. According to Direct Technologies Inc. (DTI), the cost of membranes in PEM fuel cells represents the major cost of the fuel cell system in low production volumes (James *et al.*, 2010). This relative cost drops in large production volumes, but still represents a considerable percentage of the total cost of the fuel cell stack. In addition, degradation of membranes through both chemical (Macauley *et al.*, 2013) and mechanical (Goulet *et al.*, 2013) degradation mechanisms is the main limitation for lifetime and reliability under automotive operating conditions and duty cycles. Thus, optimizing membranes for cost and durability is essential to make fuel cell technology competitive for widespread adoption in transportation systems.

In order to fulfill automotive industry requirements, the membrane needs to demonstrate stability greater than 5,500 h under normal operating conditions and meet the price target of $30/kW for fuel cell production by 2015. In addition to the targets defined for cars, according to the hydrogen bus alliance, membranes need to demonstrate 20,000 h under normal operating conditions for buses (Hydrogen Bus Alliance, 2011).

1.5 Existing fuel cell cost analysis

The primary cost analysis to date on fuel cell manufacturing and production scale up has been conducted by the consulting firm Direct Technology Inc. (DTI). Their focus has been on the entire fuel cell, which led to oversimplifying of membrane R&D decisions. We believe that the cost analysis described in DTI targets a general audience of government agencies, investors and generalists in the fuel cell research market. Although useful for guiding high level investment decisions, it carries very conservative market values and is not detailed enough to guide component level R&D decisions.

Other existing cost analysis related to PEM fuel cells show different study scenarios and also provide verification of the DTI cost analysis using self-developed cost models. One of these studies, presented by Bar-On *et al.* (2002), shows a verification of the DTI study within 10 percent. However, they have assessed technologies and production methods that are well developed and have not assessed new input materials options nor new innovations to enhance the durability of PEM fuel cells. In contrast, our cost analysis is established to provide a cost estimate per production volume for possible membrane solutions which are in an early R&D phase. It is important to understand cost implications at an early research stage to target parameters affecting the overall cost of the product and to prioritize lower cost solutions.

1.6 The manufacturing technology management problem

The production of proton exchange membranes for fuel cell applications has been dominated by Ion Power of Du Pont, which developed and manufacture Nafion® polymer. In the 1970s, Du Pont developed a perfluorosulfonic acid membrane that showed a considerable improvement in the performance and lifetime compared to other membranes and electrolytes used for the same purpose at the time. This type of membrane became the standard in the PEMFC industry and still is the major player in the membrane supply chain. It also became a suitable reference material for new membrane research and developments are because of its long trusted performance record. Other companies such as FuMA-Tech, Dow Chemical Company, 3M and Asahi Glass have presented alternatives to replace the Nafion® with advanced perfluorosulfonic acid membranes with shorter functional side chains and a higher ratio of SO_3H to CF_2 groups, but the industry is still dominated by the Nafion® type membranes.

Over the past 40 years, Nafion® perfluorosulfonic ionomer (PFSI) and membranes have been subjected to several modifications and improvements in regards to their thickness, ion exchange capacity and/or equivalent weight which are used interchangeably. Over these years, several types of commercialized Nafion® membranes were presented. Gore production techniques have been used to produce adequate membranes using the dominant material for PEM Nafion® in the form of polymers. This product is available in the form of resin and needs to be pre-treated and applied on a porous material such as ePTFE before it becomes a proton exchange membrane.

In addition, the membrane structure needs to be protected without compromising its electrochemical characteristics. A solution developed at the Illinois Institute of Technology proposes to integrate regenerative free-radical scavengers such as cerium oxide (CeO_2) to protect the structure of the membrane and avoid oxidation (Danilczuk *et al.*, 2009). At the same time, it purports to conserve its efficiency in producing currents and resisting high temperature.

Thousands of publications are dedicated to study the structure, properties, and performance of these membranes, but only a few investigate their market cost. Today, this industry is facing an interesting dilemma on how to reduce the cost of the PEM while improving its durability and performance. Research has been trying to overcome this issue by studying different alternatives; however, a proven low-cost membrane has not yet emerged. From our observation of the research in this field, we noticed the importance of establishing a cost analysis platform that can assess the production scenarios of new membrane candidates expected to meet the performance and durability targets, predict the cost of the product, and determine the key parameters in the production that effect the overall cost. Using this tool, researchers can steer their R&D in order to target the problematic factors. In our present case study, the Gore membrane production type and the potential of adding durability additives to the mix are evaluated to understand the effect on the overall cost.

2. Methodology

In this paper, we demonstrate a methodology for management of the R&D/production interface. A cost analysis platform has been established in order to investigate the scaled up production cost of different types of membranes and potential additives. The methodology to establish the unit cost of the modified membrane is based on studying the manufacturing and preliminary material cost as a function of production volume (Maine and Ashby, 2002). The production cost is compared with similar existing solutions to establish a scale for its market acceptance. In our study, we explore the new solution cost and compare it to basic existing membrane cost. The cost analysis approach is first described, including key parameters. Next, the assumptions and key inputs of this PEM fuel cell membrane TCM analysis are described.

2.1 Case study selection

We demonstrate the TCM approach on a case study of fuel cell innovation. A case study approach is appropriate when there is an exemplar (Yin, 2002). Fuel cells are a notable example of a superior technological and environmental solution which is not adopted in high volume applications due to production economics. Two components in fuel cells are acknowledged as the cost limiting components – membranes and catalysts. In this paper we focus on the former.

2.2 Cost analysis approach

The costing methodology used for this analysis follows the technical-economic cost analysis methodology (Section 1.1). As shown in Figure 3, this costing methodology takes in consideration parameters affecting production such as direct material costs, manufacturing costs, assembly costs, mark-up and others. These parameters are interlinked directly or indirectly. Capturing this interaction is what gives TCM an advantage compared to the other existing cost analysis. Similar technical-economic cost modeling methods also informed our research (James *et al.*, 2010; Maine and Ashby, 2002).

The TCM analysis was set up using Microsoft Excel with Visual Basic coding; it was organized to accommodate several production scenarios, additional parameters when needed and break down output results. Each production step has its own variables related to production and volume; financial parameters are linked to production steps;

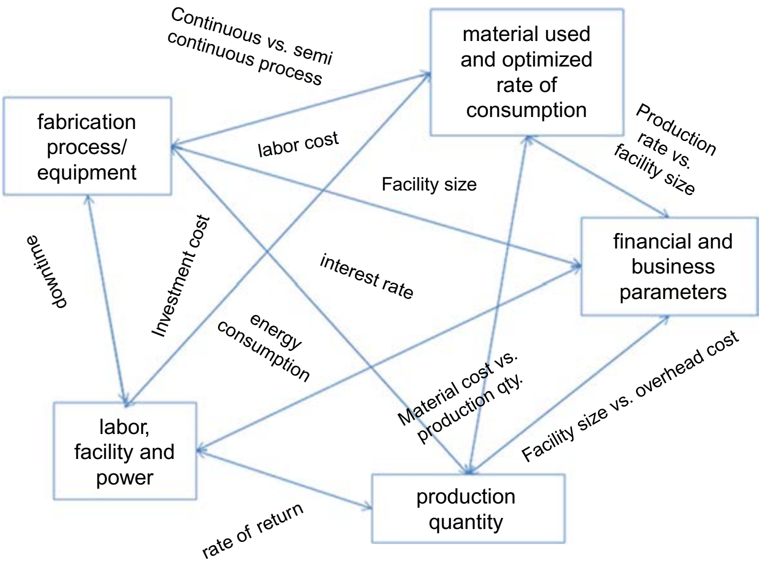

Figure 3.
Cost analysis approach and parameters

materials used are linked to production steps as admitted into the process. Outputs are separated into variable costs that include material cost, labor cost and energy cost; then fixed cost based on equipment cost, building cost, and working capital.

Material cost is generated either from historical values, quotations or market expert assumptions. The manufacturing costs are a combination of the steps necessary to transform the initial material into the desired final product. This includes but is not limited to machines, labors, energy consumed, space utilized, and financial cost. Two key parameters in the manufacturing section are production time versus production volume. They are interrelated by the production cycle time which represents the production quantity per time unit. This value depends on machine, labor and facility capacity. Along the same concept of the manufacturing costs, the assembly cost covers what it takes to assemble the different components in a final consumed product. At the end, the mark-up covers the profit, administration cost and R&D cost.

2.3 Assumptions and inputs

Here the key inputs and assumptions are presented with the logic behind them. Several parameters govern the final unit cost of the production; these parameters for our case study were defined using common manufacturing practices, inputs from industry leaders, and from the literature. Table I summarises key assumptions and inputs.

The nature of the product in question, PEM fuel cells, led us to investigate both existing low volume production processes and potential high volume production processes. We chose to analyze the Gore manufacturing process because this process is applicable for continuous production and it is flexible in terms of adding special chemicals to improve the characteristics of the membrane. In addition, and similar to DTI-based material, we are using Nafion® and ePTFE for the primary structure of the membrane.

Items	Description	Value
Manufacturing process	Plant cost	Function of production ($15M for 2,280,000 m^2 production capacity)
	Tool replacement	Function of production ($10,000 for every 300,000 m^2)
	Maintenance	5 percent of the total capital cost
	Man hour consideration	Man hour is linked to production volume on a base of $60/h
Financial description	Interest rate	6 percent interest rate
	Expected payback	Ten years
Material description	Material type	Nafion® ionomer, additives, and ePTFE
	Material cost	Varies with production volume as shown in Table II
	Scrap rate	Base assumption of 50 percent but varies with production volume
Production volume	Line speed	5 m/min
	Fuel cell stack	13.2 m^2/fuel cell system of 80 kW net
	Production time	Based on 8 h/day production and could be increased depending on different scenarios
	Mark-up	Depends on overall production scenario of the fuel cell

Table I. Summary of key assumptions and inputs

2.3.1 Definition of the manufacturing process. As described by James *et al.* (2010), the Gore manufacturing process consists of eight different steps all dependent on each other. It commences with the unwinding step of the ePTFE roll and proceeds through dipping in an ionomer bath to drying in an oven. The latter two steps are repeated again and the process is completed by the hydration and air drying steps.

The investment cost of manufacturing equipments was based on DTI estimates of $15M. The size of the manufacturing facility was based on our estimation for similar production lines, requiring space to produce 2,280,000 m^2 of annual production. The cost of replacement tools was related to production quantities: in our approach, we used an average of $10,000 for new tools for every 300,000 m^2 of production. Another 5 percent of maintenance on the total capital cost was considered. The capital cost, which is a significant portion of the total manufacturing cost, was related to a payback period of ten years with an interest rate.

On the other hand, labor was related to hours of production versus the lump sum cost of fixed individuals needed to operate the plant regardless of the production volume. Our reasoning behind this observation is based on a maximum 8 h/day production target. If production volume increases, over time shifts will be required, therefore more production hours will be paid. Hourly wages were considered equal to $60, which is an average cost that covers the overhead fees related to work safety, medical coverage, insurance, and other costs.

2.3.2 Financial description. The interest rate was considered to be 6 percent as a conservative estimate, and the payback period was based on the expected lifetime of the machines which is ten years. Other factors such as capital recovery rate, opportunity cost of capital rate, auxiliary equipment cost, and overhead are presently neglected.

2.3.3 Material description. In the case of fuel cell membranes, the material inputs are key technical components to be assessed. For the objective of durability, chemical additives are added to the ink mixture with the Nafion® ionomer and the production process is adjusted accordingly. Based on the present scenario, CeO_2 was used as the primary additive in the Nafion® basin. Several cases were considered based on the CeO_2 loading in the Nafion® as reported by Danilczuk *et al.* (2009). The scrap rate was assumed to be 50 percent which should cover any waste from material dissipation in production, maintenance of equipment, cleaning, and cutting loss. This rate was also suggested by DTI (Trogadas *et al.*, 2008; James *et al.*, 2010).

Two sources for the material cost were considered. The first source was based on DTI's cost analysis work showing a change in the Nafion® cost from $2,000/kg for low production target to $120/kg for high production volume, as shown in Figure 4. The second material cost source considered here was Ion Power. We were quoted prices ranging from $3.00/g to $4.30/g for Nafion® NR50 1100 EW Polymer Beads, depending on volume purchased, as depicted in Table II.

By using linear interpolation, the decreasing trend of cost with volume was approximated as shown in Figure 4. For the purpose of our research we used realistic values based on accurate market pricing from market leaders based on individual quotations. Our inputs for material cost are summarised in Table II.

2.3.4 Production volume. We assumed that the platform is set up based on 5 m/min line speed with a maximum production capacity based on 24 h/day and 352 days/year with 10 percent downtime. The equipment of the facility is based on a final product width of 1 m. Therefore, the total capacity of the facility can reach about 2,280,000 m^2 per year. The standard fuel cell stack considered was specified by DOE as 80 kW net.

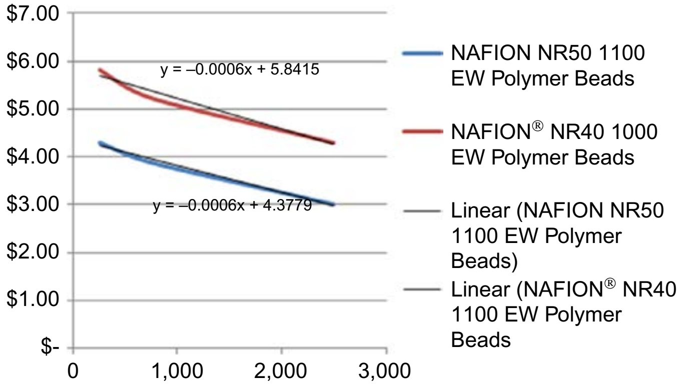

Figure 4.
Nafion® cost variation with production volume based on Ion Power

Type	Quantity	Unit	Cost ($/unit)
ePTFE base material	Fixed	m^2	$5.00
Additives (CeO_2 in this case study)	Fixed	g	$4.00
Nafion® NR50 1100 EW Polymer Beads	200-499	g	$4.30
	500-999	g	$3.88
	1,000-5,000	g	$3.00
Nafion® NR40 1000 EW Polymer Beads	200-499	g	$5.80
	500-999	g	$5.22
	1,000-5,000	g	$4.30

Table II.
Cost of material based on market quotations

DTI considers about 13.2 m^2 for each stack. Therefore, the plant we are setting up in the analysis will provide membranes for 172,800 fuel cell stacks per year. For higher production levels, an additional production line is recommended.

2.3.5 Mark-up. For our TCM analysis, we have not accounted for product mark-up. However, different levels of mark-up will be added to the product cost depending on where the final assembly is performed. For instance, if the entire manufacturing and assembly are co-located in one factory, the overhead cost will be less and therefore the mark-up cost will be reduced. However, in cases where the production volume is not large enough to absorb the cost of a manufacturing facility, assembly factories use sub facilities to provide their supplies. These facilities may eventually become a specialized supplier for one product for several assembly lines. In our case, ideally, it would be useful to consider one facility to produce membranes for several fuel cell assemblies for different automotive suppliers. This setup will reduce cost and limit competition on other aspects, especially if the membrane production is meeting the cost and performance requirements.

3. Results and discussion

The main findings of the fuel cell membrane case study are presented in this section using the TCM methodology. We have used several scenarios of membrane production and compare their results. The use of our TCM results to guide NPD and R&D decisions is then discussed.

3.1 Analysis

We arrived at cost estimates for the high volume production of fuel cell membrane of between \$39/m^2 and \$46/m^2 dependent on the quantity of durability additives required. We determined that membrane cost was predominantly impacted by input decisions on material selection, durability additives, annual production volume and fabrication process. For the purpose of this article we are presenting these four key observations to reflect the importance of cost analysis in steering early stage research.

3.1.1 Importance of input material cost in this product. In Figure 5, we depict how the input material cost used to fabricate the membrane will vary depending on production volume and product composition scenario as described above. This graph shows that the material cost in the four production scenarios is following the initial trend of material cost depending on production volume, as described in Section 2. As shown in Figure 5, the material cost will be between \$33/m^2 and \$40/m^2 for high production volumes, depending on the additives concentration. However, this variation is miniscule in its effect on total unit production cost, as it goes from about \$254/m^2 for the highest concentration of CeO_2 to \$242/m^2 in the lowest concentration based on 5,000 m^2 total production volume. For the highest production volume, the variation is more significant but still not the limiting feature in cost reduction.

3.1.2 Effect of membrane stability additives. In Figure 6, we analyzed the variation of the overall cost of the four membranes additive concentrations modeled on a spectrum of production volume. Because of the fixed cost amortisation over the production volume, we observed that the cost on small production volume is very similar in all cases. This means that the amount of additives makes essentially no difference to membrane cost at low production volumes. However, at the larger production volumes where the material cost dominates, we are observing about 5 percent increase in cost at low additive concentrations up to a 20 percent increase for the highest case (3 percent of CeO_2) on average.

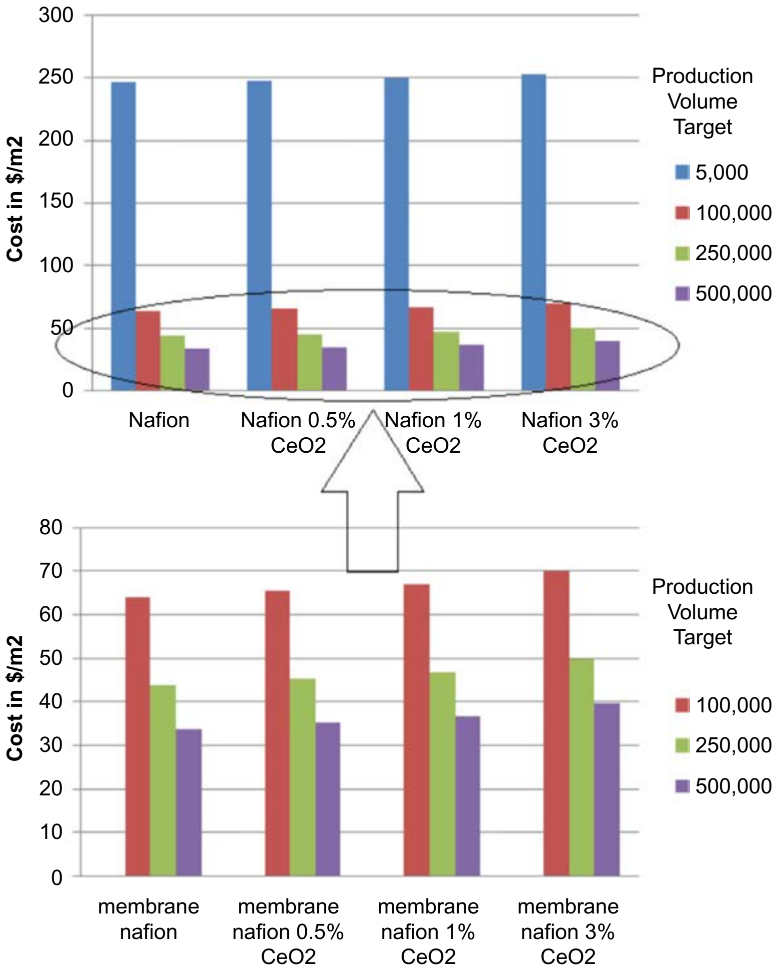

Figure 5.
Total material cost depending on production volume and additive concentration

3.1.3 Observation of production cost in low and high production volumes. In addition, it can be observed in Figure 6 that fixed cost, represented by machine cost, factory setup, etc. dominates the overall cost of the final product for low production volumes. That led us to explore the effect of batch production.

3.1.4 Observation of different fabrication processes scenarios. The obtained membrane costs associated with manual batch production and continuous roll-to-roll production are presented in Figure 7 as a function of production volume. In this case, Nafion® without additive was considered.

Results show that the batch plant process is lower cost up to annual production volumes of around 25,000 m^2. However, batch production is significantly more labor intensive than continuous production based on automated processes. Moreover, batch production commonly results in more human error and increased scrap rate, although the capital cost is considerably lower.

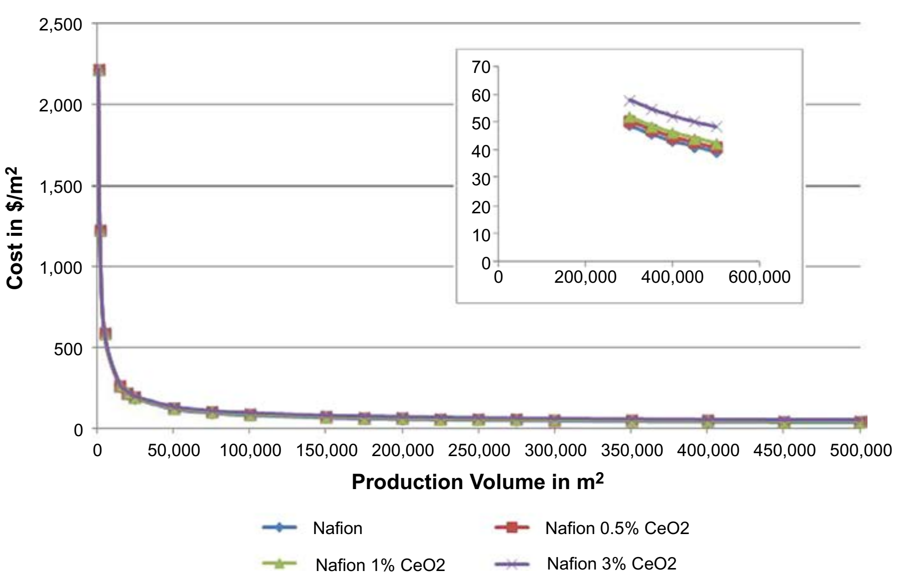

Figure 6.
Comparison of the total cost for the different membrane additive concentrations as a function of production volume

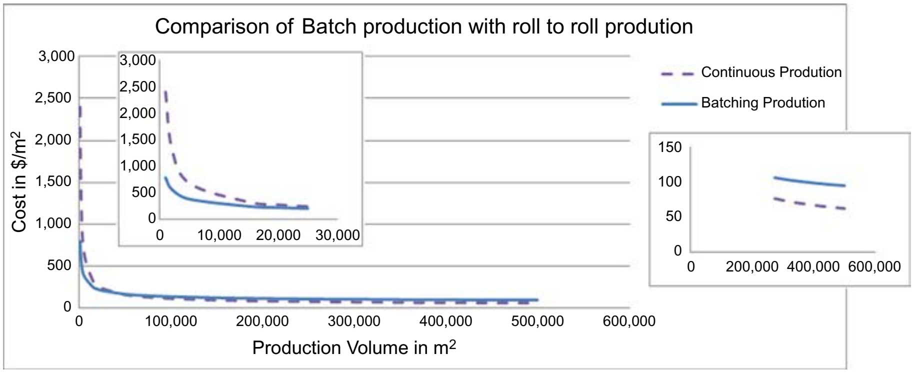

Figure 7.
Cost of batch production compared to continuous roll-to-roll production

3.1.5 Sensitivity analysis. We conducted a sensitivity analysis to assess the impact of changes to input variables and assumptions. We examined a range of scenarios, informed by R&D objectives, fluctuating commodity prices, uncertainty related to input variables, and competitor activity. Table III indicates the level of uncertainty associated with each of the input variables into the TCM. In the far right column, Table III also indicates the sensitivity of our cost model output to fluctuation of that variable within a plausible range. As indicated in Table III, the cost model output is highly sensitive to changes in the input assumptions on Nafion® polymer pellet cost. The cost model output is moderately sensitive to production line speed and to scrap rate. At low production volumes, the cost model output is moderately sensitive to plant cost and production time; however, the TCM is not sensitive to these variables at higher production volumes. There is low sensitivity of the cost model to all of the other input variables.

Table III.
Sensitivity of analysis to input variables

Items	Description	Value	Uncertainty	Sensitivity
Manufacturing process	Plant cost	\$15M for 2,280,000 m^2 production capacity	Low	Low (except at low volumes)
	Tool replacement	Cost of \$10,000 for every 300,000 m^2	Low	Low
	Maintenance	5 percent of maintenance on the total capital cost	Low	Low
	Man hour consideration	\$60/h	Low	Low
Financial description	Interest rate	6 percent interest rate	Low-medium	Low
	Expected payback	Ten years	Low	Low
Material description	Nafion® NM40	\$4.30/g (above 1 kg)	Medium	High
	Nafion® NM50	\$3/g (above 1 kg)	Medium	High
	CeO_2 additives	\$4/g	Medium	Low
	Amount of additive required	0.5-3%	Medium	Low
	ePTFE	\$5/m^2	Low	Low
	Scrap rate	50 percent but varies with production volume	Medium	Medium
Production volume	Line speed	5 m/min	Medium-high	Medium
	Fuel cell stack	13.2 m^2/fuel cell system of 80 kW net	Low	Low
	Production time	8 h/day	Medium	Low (except at low volumes)

The base material cost with the additives has a significant effect on the overall cost especially when it comes to high production volume where the manufacturing set up cost is divided across a larger number of units. However, when production volume is low, manufacturing set up becomes the governing cost factor for the production, as shown in Section 3.1.3.

Because of the high sensitivity of the TCM output to input polymer pellet costs, we did further scenario analysis on this variable. We assessed current membrane alternatives, and the current cost of their input polymeric material. Fumion® materials and other existing fluorinated polymers are cheaper than the Nafion® polymers as an input material. Fumion® materials are produced using a similar approach, extrusion type, dispersion cast and Gore manufacturing process, which means they have the potential to be a lower cost alternative to Nafion®. However, they do not currently have a durability, performance or lifetime record comparable to Nafion®.

We explored a sensitivity analysis on the material cost by replacing the Nafion® polymers by Fumion® polymers. This material is based on a perfluorosulfonic acid ionomer material produced by FuMA-Tech; it could be also used in the Gore manufacturing process and it has also the capacity to accept additives to improve its stability. The prices are shown in Table IV. For the purpose of this sensitivity analysis, we kept the same characteristics as per the original Gore Nafion® membrane production.

The results, shown in Figures 8 and 9 are based on the Fumion® cost. The membrane production costs have lowered dramatically, to between \$7.5/m^2 and \$7.7/m^2 dependant on annual production volume and percentage of durability additives included (Figure 9). The variation in cost is dominated this time by the manufacturing cost. The cost of the base material is no longer the dominant cost. In such case, researchers will be focusing more on optimizing the production cost and evaluating differently the use of additives. Along with the reduction in overall cost, the threshold production volume which batch production is most economical is raised from 25,000 m^2 (Figure 7) to about 150,000 m^2 (Figure 10).

Fumapem® membranes and other existing fluorinated membranes are also available commercially, and are currently cheaper than Nafion® membranes, but in this sensitivity analysis we have seen the additional cost advantage that could be achieved by manufacturing fuel cell membranes from Fumion® polymers. Neither the currently available Fumapem® membranes nor membranes fabricated utilizing Fumion® polymers as an input material are drop-in replacements for Nafion®, as they have no major durability, performance or lifetime record as compared to Nafion®.

3.2 Discussion

The value of TCM for technology management is demonstrated by linking different aspects of production to unit cost, over a range of scenarios which incorporate

	Fumion® FLNA-905	Fumion® FLNA-1005
Density (g/cm^3)	1.00	1.00
\$/g from 0 to 100 g	\$0.98	\$1.04
\$/g from 100 to 250 g	\$0.73	\$0.81
\$/g from 250 to 500 g	\$0.62	\$0.69

Source: *Technical Data Sheet – Fumion® FL Dispersion*, available at: www.fumatech.com/EN/Onlineshop/Fumion-Polymer-Ionomeres/Ionomerloesungen-in-Isopropanol-Wasser/

Table IV. Price range of the Fumion® polymer

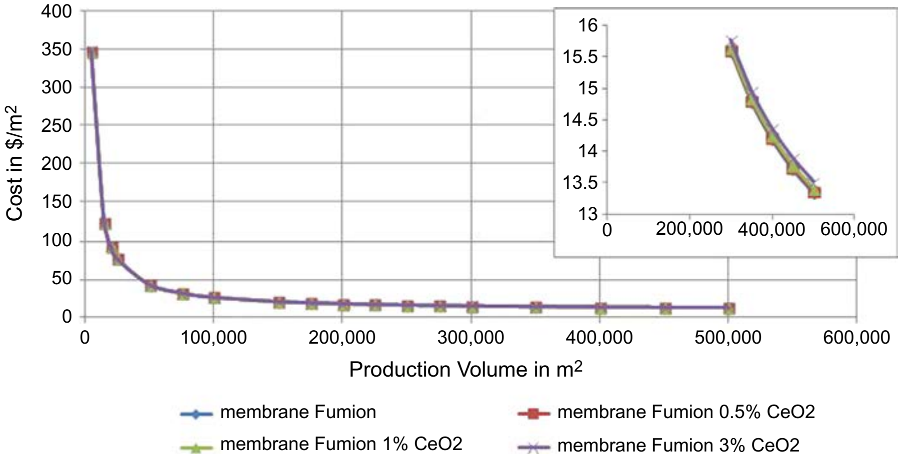

Figure 8. Production cost with Fumion® ionomer pellets

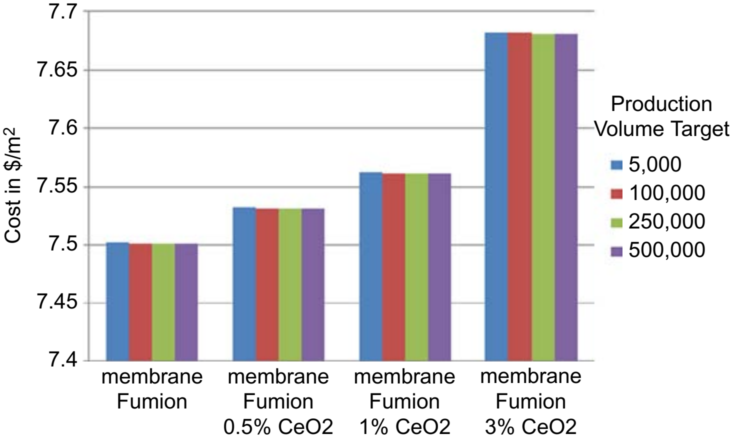

Figure 9.
Material cost with Fumion® polymers and additives' effect on cost

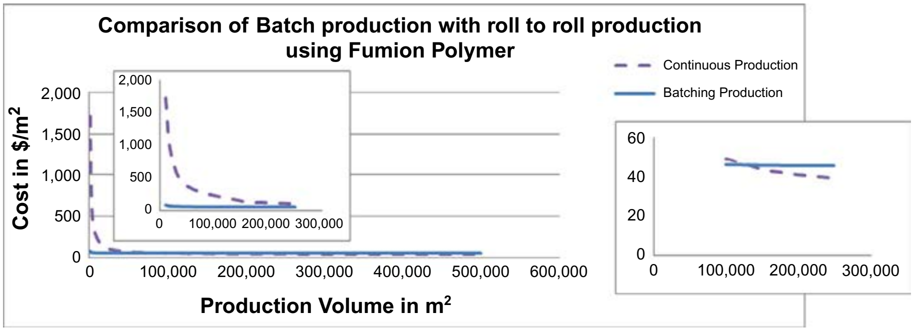

Figure 10.
Sensitivity analysis using production scenario

feasible R&D goals. By such linkage, TCM reveals the components, inputs and production processes which most greatly impact cost under various scenarios. This knowledge allows for a strategic prioritization of development efforts.

The TCM methodology, as opposed to the target costing and DFMA techniques previously discussed, is suitable for evaluating the viability and R&D priorities of novel products which rely on evolving R&D. As the decision to proceed with the development of a novel production process involves high capital investment (Cooper, 2001; Maine *et al.*, 2005), a tool which increases the chances of NPD success is highly valuable.

In our case study of the technology management of fuel cell membrane innovation, we demonstrate the guidance provided by the TCM methodology. We know already that PEM fuel cells are not viable for large-scale commercialization for transportation applications currently because of their cost and durability, and that membrane cost and durability are limiting factors. Through TCM, we investigate the cost impact of currently proposed R&D initiatives to improve membrane durability. By assessing the input cost, production rate and production cost at different production volumes, we determined that durability additives were not affecting the unit cost significantly. Thus, efforts to enhance membrane durability through additives to Nafion® should be prioritized and considered essentially cost neutral.

Next, we focussed on the aspects of the materials, inputs and process parameters which could reduce the cost of the membrane and thus PEM fuel cells. First, Nafion® pellets were found to be such a dominant cost component across production volumes that evaluation of alternative materials, such as Fumion® polymers from Fumatech, should be a priority. Although deviating from the Nafion® standard is considered a risk, it is likely a worthwhile risk, considering the dramatic unit cost implications: our analysis indicates that the switch in input material may result in a fivefold reduction of production costs. Second, increasing the production rate of the membrane production process is a priority, as it will reduce the unit cost of membrane by amortising production equipment over more units. The trade-off between membrane durability and production rate should be further investigated. Third, efforts should be made to reduce the scrap rate, which currently is significant in membrane costs.

We feel that this case study demonstrates the value of using the TCM methodology to prioritize R&D efforts and assess the viability of production scale-up. However, this case study is somewhat unusual as Nafion® was such a key component of the membrane cost, and overshadowed the other input variables and cost components at all except for small production volumes. The main challenges in applying TCM to this case study were:

- understanding the batch and continuous process options and what limitations were inherent; and
- assessing the way that durability additives would be incorporated into the continuous process.

Fuel cells currently provide an environmentally desirable transit option at a higher price than internal combustion engines. R&D targeted at higher durability and lower cost fuel cells can narrow the existing viability gap. There is also a role for policy initiatives to facilitate widespread adoption of fuel cells. Creating new legislation to encourage the utilization of environmentally progressive fuel cells vehicles by providing tax incentives or subsidies to consumers can bring the production volume of such vehicles to a higher level, consequently making them more economical over time. Fuel cell designers and manufacturers have a role to play in advocating such a governmental intervention, by communicating the technological advances in performance and durability, and by modeling the impact of such advances on production and market cost. Fuel cell costing scenarios should include such legislation.

4. Conclusion

A cost analysis platform has been established to analyze different manufacturing and R&D options for producing durable (PEM) fuel cells. This techno-economical cost model takes into consideration the different fabrication methods, material selection, labor distribution, energy consumption, financial parameters and the target production volume. The TCM depicts how the production cost per unit varies depending on all the above cited parameters on different levels depending on the production volume. This platform enables the efficient exploration of each potential design solution and identification of the key factors for each design. By using such an approach in the design, research time and resources can be saved by prioritizing R&D and production scale-up options at an early stage.

We find TCM to provide valuable guidance to R&D objectives and on production scale-up decisions. In the discussed case study, we provide advice on the use of TCM as a technology management tool for decision makers at the R&D manufacturing interface. Other cost analysis such as DFMA and target costing failed to incorporate a complete observation that allows researchers to scrutinize influential parameters to be focused on or resolved. Target costing begins with the price consumers will accept and works backward to allowable production costs, but provides no linkage to actual process conditions or input costs. DFMA does assess input costs, but does not link to process variables or to production rate limitations.

Our case study provides useful guidance for technology management. While the science and technology of additives to the Nafion® to improve the reliability of the membrane are at a relatively early stage: the results demonstrate that the effect of additive on the production cost is small. Therefore, such durability research is to be prioritized and should be considered essentially cost neutral.

In order to meet the reliability required while achieving the cost target, research should focus on the following goals. First, finding and validating an alternative to Nafion® ionomer should be a top priority, as it is the biggest cost in the membrane fabrication. Our analysis indicates that the development of an alternative input material, such as FuMA-Tech's Fumion® polymer, could result in up to a fivefold reduction of membrane production costs. Thus, research into the enhancement of durability and performance of Fumion® membranes is recommended. Second, optimizing membrane production lines will be important to increase production rate capacity and decrease scrap rates. Third, further research into simultaneously increasing membrane durability and enabling faster production process speeds is recommended.

In this study, we demonstrated that cost estimation is an important part of developing a novel product such as durable PEM fuel cells for transportation applications. Such an approach can guide the decision to scale up a process for commercial applications. Most notably, TCM assists in guiding R&D by identifying the critical items that need to be resolved in order to reach certain targets in cost and performance. The TCM methodology is useful for technology managers making decisions about the viability of and R&D priority for novel processes embodied in mass produced products. TCM is only as valuable as the inputs and informed scenario analysis with which it is employed: thus, further research on strategic technology decision making and how it links to cost analysis could provide a more comprehensive methodology for technology managers.

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