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End-of-life Management of Solid Oxide Fuel Cells

by

Eileen Wright

A Doctoral Thesis
Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

Wolfson School of Mechanical and Manufacturing Engineering

October 2011

Loughborough University

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

Eileen Wright (Signed)

17th November 2011 (Date)

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Finally I would like to acknowledge the patience shown by my friends and family in encouraging me to pursue and complete this research. In particular I am grateful to my Mum and Dad for the good start they have given me in life, and for backing up their encouragement to me to “do my best” with practical support and love.

I dedicate this thesis to my husband Gary for being with me throughout, and to my daughter Esther who has kept me smiling.

Synopsis

This thesis reports on research undertaken to investigate the end-of-life management of solid oxide fuel cells (SOFC), through the definition of a framework and the development of a multi-criteria evaluation methodology which together support comparison of alternative end-of-life scenarios. The primary objective of this research is to develop an understanding of the challenges and opportunities arising during the end-of-life phase of the technology, such that any conflicts with end-of-life requirements might be addressed and opportunities for optimising the end-of-life phase fully exploited.

The research contributions can be considered in four principal parts. The first part comprises a review of SOFC technology and its place in future sustainable energy scenarios, alongside a review of a growing body of legislation which embodies concepts such as Extended Producer Responsibility and Integrated Product Policy. When considered in the context of the life cycle assessment literature, which clearly points to a lack of knowledge regarding the end-of-life phase of the SOFC life cycle, this review concludes that the requirement for effective end-of-life management of SOFC products is an essential consideration prior to the widespread adoption of commercial products.

The second part of the research defines a framework for end-of-life management of SOFCs, which supports clarification of the challenges presented by the SOFC stack waste stream, as well as identifying a systematic approach for addressing these challenges through the development of alternative end-of-life management scenarios. The framework identifies a need to evaluate the effectiveness of these end-of-life scenarios according to three performance criteria: legislative compliance; environmental impact; and economic impact.

The third part of the research is concerned with the development of a multi-criteria evaluation methodology, which combines conventional evaluation methods such as life cycle assessment and cost-benefit analysis, with a novel risk assessment tool for evaluating compliance with current and future legislation. A decision support tool builds on existing multi-criteria decision making methods to provide a comparative performance indicator for identification of an end-of-life scenario demonstrating low risk of non-compliance with future legislation; low environmental impact; and a low cost-benefit ratio.

Finally, the validity of the framework for end-of-life management is tested through the completion of two case studies. These case studies demonstrate the flexibility of the framework in supporting a reactive end-of-life management approach, whereby end-of-life management is constrained by characteristics of the product design, and a proactive approach, whereby the impact of design modification on the end-of-life phase is explored.

In summary, the research clearly highlights the significance of the end-of-life stage of the SOFC life cycle. On the one hand, failure to manage end-of-life products effectively risks undermining the environmental credentials of the technology and is likely to lead to the loss of a high-value, resource-rich material stream. On the other hand, the early consideration of aspects identified in the research, especially while opportunities remain to influence final product design, represents a real opportunity for optimising the end-of-life management of SOFC products in such a way as to fully realise their potential as a clean and efficient power generation solution for the future.

ABBREVIATIONS

ADP	:	Abiotic Depletion Potential
AFC	:	Alkaline Fuel Cell
AP	:	Acidification Potential
APU	:	Auxiliary Power Unit
CBA	:	Cost-Benefit Analysis
CBR	:	Cost-Benefit Ratio
CHP	:	Combined Heat and Power
CML	:	Centre of Environmental Science, Leiden University
E^2LM	:	Environmental, Economic and Legislative impact Model for end-of-life management
EDIP	:	Environmental Design of Industrial Products
ELV	:	End-of-life Vehicles
EOL	:	End-of-life
EP	:	Eutrophication Potential
EPR	:	Extended Producer Responsibility
GWP	:	Global Warming Potential
HSE	:	Health, Safety and Environment
IKP	:	Institut für Kunststoffkunde und Kunststoffprüfung (Institute for Polymer Testing and Polymer Science), University of Stuttgart
IPP	:	Integrated Product Policy
ISO	:	International Standards Organisation
LCA	:	Life Cycle Assessment
LSC	:	Strontium-doped Lanthanum Chromate
LSM	:	Strontium-doped Lanthanum Manganite
MCFC	:	Molten Carbonate Fuel Cell
NETL	:	National Energy Technologies Laboratory
ODP	:	Ozone Depletion Potential
OECD	:	Organisation for Economic Cooperation and Development

PAFC : Phosphoric Acid Fuel Cell

PEMFC : Proton Exchange Membrane Fuel Cell

POCP : Photochemical Ozone Creation Potential

RA : Risk Assessment

SOFC : Solid Oxide Fuel Cell

SECA : Solid State Energy Conversion Alliance

TRACI : Tool for the Reduction and Assessment of Chemical and other environmental Impacts

WEEE : Waste Electrical and Electronic Equipment

WSM : Weighted Sum Method

YSZ : Yttria-Stabilised Zirconia

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CHAPTER 1 INTRODUCTION

The generation and supply of electrical power has become a fundamental requirement for human society. Recent history has demonstrated that insecurities related to the provision of this requirement can lead to significant economic and political turbulence. With increasing demands on the earth's resources arising from growing human consumption, and a developing understanding of the detrimental impacts of fossil fuel combustion on the environment, it is clear that existing power generation technologies and behaviours must change towards more sustainable solutions.

Fuel cells are power generation devices which demonstrate high efficiency with regard to the conversion of chemical energy to electrical energy. The principle of their operation has been understood since the early 19th century (Grove, 1839); however their use has historically been limited to specialist applications, such as space travel, where high costs have not been prohibitive to their adoption. In more recent decades, the drive to make the technology viable in a wider market has been the primary focus of development activities, with efforts from both academia and industry. Much of the motivation for this drive towards commercialisation has arisen from the environmental benefits anticipated from the widespread utilisation of fuel cells in power generation applications.

Fuel cells are suited to a broad range of stationary and mobile applications, and several types of the technology have been developed, as summarised in Table 1.1. The distinction between different fuel cell types lies primarily in the electrolyte material. This in turn has a direct impact on the temperature at which efficient operation is achieved and, as such, is influential in determining the most suitable application for the technology. The research reported in this thesis is concerned specifically with solid oxide fuel cell (SOFC) technology which is primarily suited to stationary power generation applications. Figure 1.1 shows the 1 MW SOFC system under development at Rolls-Royce Fuel Cell Systems Limited (Rolls-Royce Plc, 2007) and illustrates how fuel cells can be combined with conventional technologies to provide electricity to the consumer.

Table 1.1: Summary of different fuel cell types and their defining characteristics (adapted from Haile, 2003)

Type of fuel cell	Electrolyte material	Operating temperature (°C)	Fuel	Principal applications
PEMFC: Proton exchange membrane	Fluorinated polymers (solid)	70 – 110	Hydrogen, methanol	Automotive industry, space travel, other portable applications
AFC: Alkaline	Potassium hydroxide (liquid)	100 – 250	Hydrogen	Automotive industry, space travel
PAFC: Phosphoric acid	Phosphoric acid (liquid)	150 – 250	Hydrogen	Stationary power generation
MCFC: Molten carbonate	Lithium/sodium/ potassium carbonate (liquid)	500 – 700	Hydrogen, hydrocarbons, carbon monoxide	Stationary power generation
SOFC: Solid oxide	Stabilised zirconia (solid)	700 – 1000	Hydrogen, hydrocarbons, carbon monoxide	Stationary power generation, auxiliary power units

Typically, a stationary SOFC system is made up of various sub-assemblies. Individual fuel cell components are combined in a sub-assembly known as the SOFC stack, and it is in this sub-assembly that the fuel cell technology converts inputs of fuel and air into electrical power. An example of a module of the fuel cell stack used within the Rolls-Royce Fuel Cell Systems design is illustrated in Figure 1.2. The integrated-planar SOFC stack is modular in design, to allow flexibility in the overall power-generating capacity of the system. Additional sub-assemblies required for the delivery of electrical power include fuel processing equipment and electrical systems for controlling the supply of power to the customer. In addition, hybrid systems such

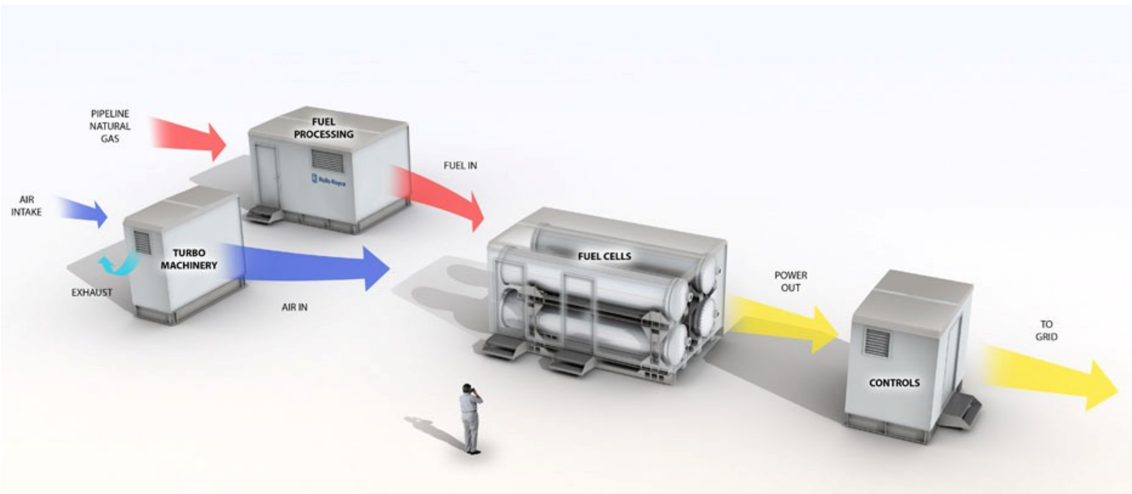


Figure 1.1: Schematic view of a stationary SOFC system, illustrating the integration of conventional technologies and fuel, air and power flows.

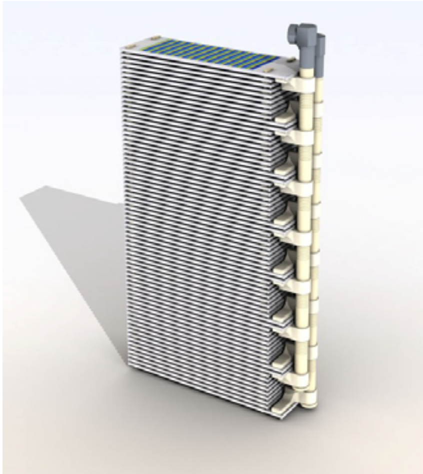


Figure 1.2: Illustration of a module from a SOFC stack assembly. The module consists of an assembly of flat ceramic tubes, each of approximately 30 cm in length. A module of this size could be expected to have a power-generating capacity of 2.5 – 3 kW.

as that illustrated in Figure 1.1 can incorporate small gas turbines which utilise waste heat from the SOFC stack thus increasing overall efficiencies.

SOFC technology has not yet reached commercial maturity, and systems such as that illustrated in Figure 1.1 are still in the early stages of product development. Design targets indicate that a large stationary system would be expected to have a lifetime of approximately 20 – 25 years, whereas the SOFC stack would be expected to have an operating lifetime of 40,000 hours (approximately 5 years) (Karakoussis *et al.*, 2001; Hawkes *et al.,* 2006; Thijssen *et al.,* 2010). Therefore it should be anticipated that the complete SOFC stack assembly will require replacement three or four times throughout the lifetime of the SOFC system. The SOFC stack will therefore contribute substantially to the total waste generated by a large stationary SOFC plant throughout its operational lifetime.

The concept of Extended Producer Responsibility (EPR) has developed in response to increasing levels of consumerism in society. The concept identifies that product designers and manufacturers have a responsibility to consider the impacts of their products across the complete product life cycle, including impacts arising from the management of products in the end-of-life stage. End-of-life vehicles and waste electrical and electronic equipment are currently targeted by legislation encompassing the EPR principal. The legislation establishes requirements for aspects such as collection of end-of-life products from consumers (product recovery), removal of components containing hazardous substances (de-pollution) and treatment of wastes. Recycling targets have been established, with the responsibility falling on the product manufacturer to ensure that these targets can be achieved.

Against this legislative background, it is essential that the end-of-life management of all new products, including SOFC technology, is considered prior to commercialisation. It appears likely that the scope of EPR-based legislation will increase to encompass a much broader range of product-types. Failure to be able to comply with such requirements may be detrimental to the acceptance and adoption of this new power-generation technology. In addition to EPR-based legislation, more traditional waste management and landfill legislation encompasses requirements concerning the transportation, processing and safe disposal of wastes, especially where hazardous substances are present.

Consideration of end-of-life management requirements prior to commercialisation of SOFC technology not only supports legislative compliance, but also offers opportunities to ensure that the environmental impacts of the technology are minimised. In addition, effective end-of-life management of a product can also positively affect its life cycle costs. In severe cases, specific additional costs may be introduced in the form of fines arising from non-compliance, or in the form of financial liability for environmental damage. More commonly, unnecessary costs may be introduced through poor organisation of end-of-life logistics, or through the selection of costly and/or inappropriate end-of-life processing routes. In the case of products containing valuable materials, the implementation of effective recycling processes may also result in the recovery of a proportion of the original material costs.

The end-of-life waste arising from the SOFC stack assembly requires attention, since this represents a novel technology for which no specific waste management infrastructure exists. In addition, the comparatively short life-span of the SOFC stack means that the generation of end-of-life waste from this assembly will occur throughout the lifetime of the SOFC system. The research assertion presented by this thesis is that prior to commercialisation of SOFC technology, the challenges and opportunities arising at the end-of-life phase must be identified and addressed.

The research reported in this thesis therefore aims to develop a framework to support decision making with respect to end-of-life management of the SOFC stack assembly. The framework will provide a structured approach to support identification of alternative end-of-life management scenarios and evaluation of their performance, in terms of legislative compliance, environmental impact and economic performance. This is to be achieved through:

1) Characterisation of existing SOFC stack concepts in terms of their design and material characteristics.
2) Identification of alternative end-of-life management scenarios for SOFC stack assemblies based on viable processes and technologies.
3) Construction of an evaluation methodology which supports the identification of compliant, environmentally responsible and economically viable solutions for end-of-life management of SOFC stacks.

An outline of the thesis structure is shown in Figure 1.3. The thesis can be considered in three sections, namely the research background and overview; theoretical research, model development and case studies; and the research conclusions.

The research background and overview consists of five chapters. Following this introduction, the research context and scope are defined in Chapter 2. This definition of the research is supported by a literature review, which focuses on SOFC technology in Chapter 3, and various aspects relating to requirements and evaluation methods for end-of-life management in Chapter 4. Chapter 5 provides a brief review of common research methodologies and explains the methodological approach adopted within the thesis.

The middle section of the thesis documents the theoretical research, model development and case studies performed in order to address the research aims and objectives. In Chapter 6 a framework for end-of-life management of SOFC stacks is presented. This framework has three principal parts within it. The first requires the characterisation of SOFC products, in terms of their design and materials selection, and the findings from this research are reported in Chapter 7. In Chapter 8 alternative end-of-life management scenarios for the SOFC stack are developed, supporting the second part of the framework. Chapter 9 presents the evaluation methodology used in the third stage of the framework, and in Chapter 10 the application of the framework is demonstrated through case studies.

The final section of the thesis presents the conclusions from the research. Chapter 11 provides a discussion of the research findings and assesses the outcomes of the research against the stated objectives. This discussion is summarised in a number of final conclusions presented in Chapter 12, in which opportunities for further development of the research are also identified.

Additional calculations and data to support the case studies are included in the appendices, along with two conference papers and one journal paper which have been published, based on different aspects of the research reported in the thesis.

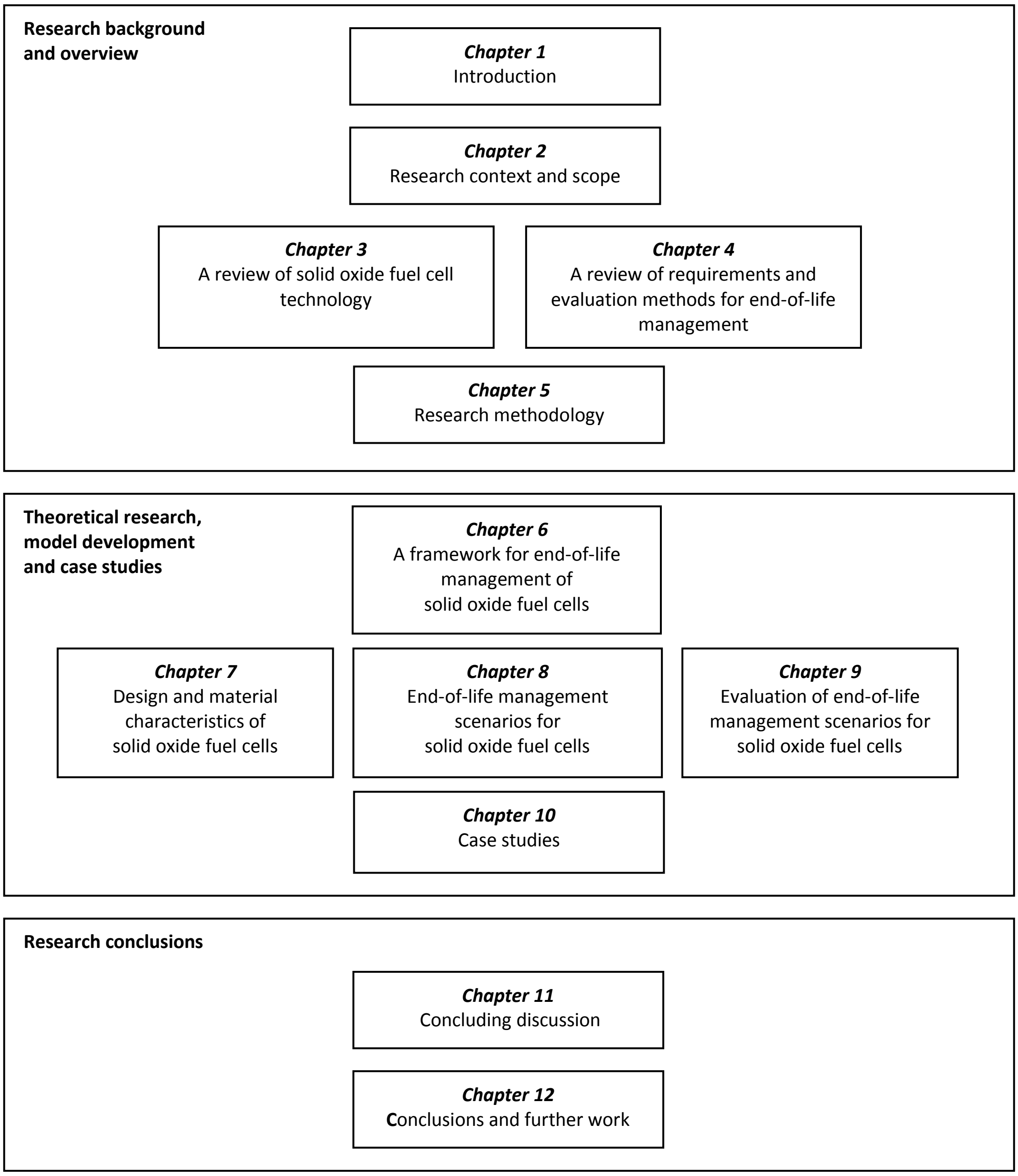


Figure 1.3: Thesis structure

CHAPTER 2 RESEARCH CONTEXT AND SCOPE

2.1 Introduction

This chapter identifies the context of the research reported in the thesis. The underlying research assertion is stated, and from this a general research aim is derived. Several objectives are developed in support of the research aim, and for each of the objectives the scope of the research is described.

2.2 Research context

The predicted environmental benefits of SOFCs in comparison with conventional power generation technologies have provided a substantial driving force for continued investment in their development. As such, their environmental performance has been the subject of academic interest, and various studies have endeavoured to investigate the likely environmental impacts arising across some or all of the life cycle. However, from an initial reading of publications reporting these studies, a prevailing theme indicates an absence of knowledge regarding the end-of-life phase. Several specific quotes have been identified, which span almost fifteen years of research into SOFC technology, and which demonstrate the lack of progress in this area.

One of the first publications reporting on the environmental performance of SOFCs was published in 1996 by Zapp, who wrote:

> *"Even after successful operation, dismantling of the unit remains an important part of the entire cycle life. Prevention and reduction and reuse of waste products are key elements in the material management that has to be planned before introducing a new technology. For SOFC technology, little is known about handling waste products; some problems however, are already known…The increasing interest in waste management will yield a higher demand for research in the field of dismantling SOFC."* (Zapp, 1996)

Five years later, researchers at Imperial College, London, commented on a weakness in their life cycle assessment study of the technology:

> *"This study assumed that there is no recycling of process waste. Thus, a worst case scenario has been produced. End-of-life material recovery and reuse or recycling will be important in reducing the burdens associated with materials supply. However, the current state of development of the industry means that end-of-life options have so far*

> *been given little consideration, and little data is available. It was therefore inappropriate to define explicit recycling scenarios for this study, and further examination of the opportunities are warranted. It is clear however, that recycling of key materials can be expected to significantly reduce the environmental burden associated with materials supply."* (Karakoussis *et al*., 2001)

Similarly, in 2005, Barrato reported a similar challenge in conducting a complete life cycle assessment study of SOFCs:

> *"There are no data available regarding future end-of-life management scenarios and so for the purpose of this study the potential for reuse and recycling of individual cells has not been studied."* (Baratto *et al*., 2005)

The most recent life cycle assessment studies of SOFC products available in the literature have not included any detail regarding the end-of-life phase within their scope (Strazza *et al.,* 2010; Pehnt, 2008).

This demonstrated absence of prior knowledge regarding the end-of-life management of SOFC technology provides the context and supports a case for the research reported in this thesis, which has been conducted against a backdrop of a legislative framework increasingly concerned with the management of wastes from end-of-life products.

2.3 Research assertion

In a world where the supply of energy is of fundamental importance, SOFC technology provides environmental benefits including increased fuel efficiencies and reduced emissions (Hart and Hormandinger, 1998; Bauen and Hart, 2000; Stambouli and Traversa, 2002). These benefits support compliance with global legislative targets regarding global warming, air pollution and the implementation of alternative power generation technologies in preference to combustion-based processes. However, despite these positive aspects, other global legislative trends should not be overlooked, especially those encompassing requirements for management of waste from end-of-life products. These various different measures may direct or constrain end-of-life solutions.

The environmental benefits of SOFC technology are apparent, but for SOFC products to be regarded as truly environmental products there is a requirement to ensure that environmental impacts are minimised across the complete product life cycle. In particular, the management of end-of-life SOFC stacks, a high volume and potentially hazardous waste stream, must be conducted in a responsible manner to ensure minimisation of environmental impacts arising from the treatment of toxic substances. Given the immature nature of the technology and the many technical challenges facing designers, a balance of proactive and reactive approaches to minimising these impacts must be adopted.

Effective end-of-life management may provide design flexibility by reducing life cycle costs. If revenue can be recovered through recycling activities, then additional cost margins may be available in the initial design and materials selection stages. This may be particularly effective in a product service systems model, where ownership of the product remains with the original manufacturer, and the customer pays for the power generated by the SOFC system.

The assertion underlying the research reported in this thesis is that an in depth understanding of the end-of-life management of SOFC technology must be developed, prior to widespread commercialisation. Failure to adequately address potential future legislative requirements may provide substantial setbacks to market penetration, while environmentally irresponsible actions would threaten the integrity of the technology. At the same time, opportunities for recovering value through effective end-of-life management may play an important role in helping the technology achieve cost targets required for entry into a competitive market.

2.4 Research aims and objectives

In line with the assertion presented above, the aim of the research is to explore the opportunities and challenges arising during end-of-life management of solid oxide fuel cells in order to support the development of end-of-life management solutions which demonstrate legislative compliance, reduced environmental impact and where possible provide economic benefit.

In order to achieve this aim, the following objectives have been identified:

1. To review the current status of SOFC technology and to identify relevant end-of-life management requirements including those arising from legislation, and methods for evaluating end-of-life performance, from published literature.
2. To develop a framework for end-of-life management of SOFC stacks, that supports evaluation of alternative scenarios against a number of performance criteria.
3. To propose alternative end-of-life scenarios for SOFC stacks, based on their design and material characteristics.
4. To develop a methodology for evaluating the risk of non-compliance with current and future legislation.

5. To apply life cycle assessment and cost-benefit analysis methodologies to the evaluation of alternative end-of-life management scenarios for SOFC stacks.
6. To develop a method for integrating the outputs from compliance, environmental and economic assessments into a single performance parameter, in order to support decision making.
7. To test the framework for end-of-life management of SOFC stacks using a case study approach.

2.5 Research scope

The scope of the research is in line with the objectives presented in Section 2.4, and is described in the following sections.

2.5.1 Review of the current status of SOFC technology and relevant end-of-life management requirements and evaluation methods

A review of SOFC technology will be conducted to identify alternative design concepts and the current status of the technology with regard to commercialisation. Opportunities for the application of SOFC technology in future energy scenarios will be reviewed in order to develop an understanding of the potential scale of the end-of-life SOFC stack waste stream.

In order to ensure that the research considers all relevant aspects of end-of-life management, a comprehensive review of the literature will be conducted. Particular attention will be given to legislation identified as being of relevance to end-of-life management, in order that legislative requirements can be clearly identified. Studies relating to the end-of-life management of other products will be reviewed in order to ensure that the research is established in an appropriate academic context and that existing knowledge can be exploited. The benefits and limitations of existing evaluation tools will be explored in order to identify and select suitable evaluation methods for application in the current research.

2.5.2 Development of a framework for end-of-life management of SOFC stacks

A framework for end-of-life management of SOFC stacks will be developed to provide a structured approach by which opportunities and challenges arising at this stage of the product life cycle can be explored. The framework will allow alternative end-of-life scenarios to be evaluated in terms of their legislative compliance, environmental impact and economic performance. While it is recognised that these three performance metrics provide useful indicators of the viability of alternative end-of-life scenarios, the framework should also support the combination of all three evaluation outcomes into a single performance metric.

2.5.3 Definition of existing SOFC concepts in terms of design and material characteristics and proposal of suitable alternative end-of-life scenarios

The opportunities and challenges arising during end-of-life management are primarily defined by the design and material characteristics of the product. Three different SOFC concepts will be analysed and evaluated in order to explore the general relationships between design, materials selection and end-of-life management. A detailed analysis of the design and material characteristics of the integrated-planar SOFC concept under development at Rolls-Royce Fuel Cell Systems will be conducted to support development of alternative end-of-life scenarios. Alternative end-of-life scenarios will be proposed, based primarily on known waste management technologies and infrastructures.

2.5.4 Development of a methodology for evaluating legislative compliance

SOFC technology has not yet reached commercial maturity, and within the timescales between market penetration and the generation of significant volumes of end-of-life SOFC stacks it is likely that observed trends in the development of end-of-life legislation will continue. A risk-based method is proposed as an appropriate approach to evaluate legislative compliance. A methodology will be developed which can be used to evaluate the risk of end-of-life management scenarios failing to comply with future legislative requirements.

2.5.5 Application of life cycle assessment and cost-benefit analysis within the framework

Existing tools for the evaluation of environmental impact and economic performance will be adopted for application in the framework for end-of-life management of SOFC stacks. A streamlined life cycle assessment methodology will be used to evaluate the environmental impact of alternative end-of-life scenarios; a model will be constructed to represent the relevant end-of-life processes, and data requirements will be identified. Similarly a parametric cost model will be generated to allow evaluation of the cost-benefit ratio for alternative end-of-life scenarios. Economic data required as input to the model will be defined.

2.5.6 Development of a methodology to support multi-criteria decision making

Although the results from the individual compliance, environmental and economic evaluation methods will be useful in identifying the viability of alternative end-of-life scenarios, it is anticipated that a further evaluation methodology will be needed to allow the three individual performance scores to be combined into a single factor, to support an effective and simple decision support tool.

2.5.7 Demonstration of the framework through case studies

In order to assess the validity of the framework for end-of-life management of SOFC stacks, and the evaluation methods adopted, the framework will be applied in two case studies. These case studies will use a combination of data from industrial trials and the literature to evaluate alternative end-of-life scenarios for the integrated-planar SOFC concept. Legislative compliance, environmental impact and economic performance will be evaluated independently and then combined into a single performance parameter. The results from the case studies, together with any general observations regarding the application of the framework, will be used to identify the benefits and limitations of the methods employed. Opportunities for improving the framework may be identified based on the implementation experience generated during the case studies, as well as the results obtained.

2.6 Summary

In this chapter the context of the research has been identified, and the research assertion stated. Objectives have been defined, in support of the research aim, and these objectives have been used to generate the scope of the research. The following two chapters address the first research objective. Chapter 3 presents a review of SOFC technology, and Chapter 4 reviews relevant legislative requirements and evaluation methods for end-of-life management.

CHAPTER 3 A REVIEW OF SOLID OXIDE FUEL CELL TECHNOLOGY

3.1 Introduction

This chapter presents a review of SOFC technology, to provide background to the research and to identify current knowledge regarding aspects of the technology most relevant to the research. The chapter begins with a review of electricity generation, in relation to global energy requirements, and considers the place of fuel cell technology within potential future energy scenarios. SOFC technology is then reviewed in terms of technical aspects relating to design and function, and the current commercial status is explored. Finally, previous studies evaluating the environmental performance of the technology life cycle are reviewed.

3.2 Energy supply: challenges and opportunities

Power generation and energy supply can be viewed as one of the greatest issues of the twenty-first century. As economic development extends across the world, greater demands for energy arise. At the same time, human impact on the environment is coming under increasing scrutiny, with fossil fuel consumption and concerns regarding the emission of greenhouse gases informing the global political and economic climate. It is clear that this conflict will only be resolved through the development of new technologies for electricity generation, along with the adoption of new approaches for effective distribution and reduced consumption of this resource (Ghoniem, 2011).

3.2.1 Energy supply and demand

Figure 3.1 illustrates the historic growth in electricity generation, between 1971 and 2008 (International Energy Agency, 2010). These figures indicate an increase in electricity generation of over 300% over a thirty-year period. The regional breakdown of electricity generation has also changed during this time period, and these geographic changes provide some explanation for the growth in global demand. In 1973, member countries of the Organisation for Economic Co-operation and Development (OECD) were responsible for approximately 73% of global electricity generation: by 2008 this value had decreased to 53%. During the same period, the industrialisation of the developing world is clearly demonstrated by the relative increase in power generation in China, India and Latin America. Between 1973 and 2008 China's electricity generation increased from 2.9% of the global total to 17.3%. For the rest of Asia, growth was more moderate, but still substantial, with an increase from 2.6%

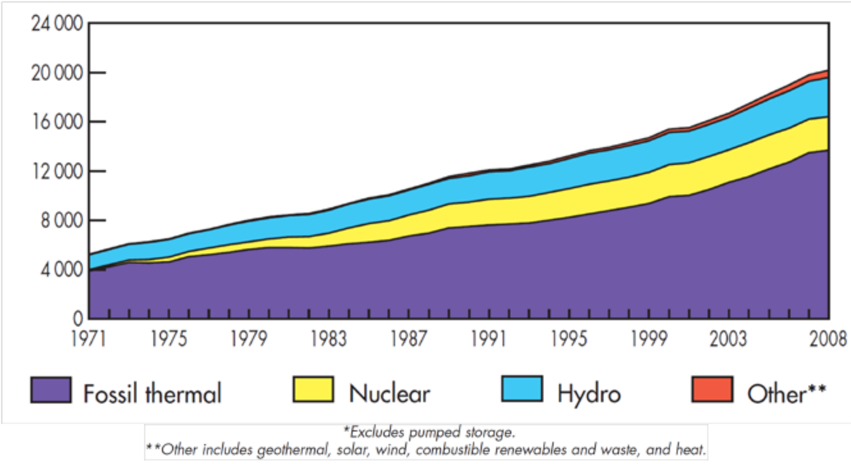


Figure 3.1: Evolution from 1971 to 2008 of world electricity generation* by fuel (TWh)

Figure extracted from Key World Energy Statistics 2010 © OECD/IEA, 2010

of global production in 1973 to 9.1% in 2008. The proportion of global electricity production attributed to Latin America during the same period doubled, increasing from 2.6% to 5.3% (International Energy Agency, 2010).

As well as documenting growth, Figure 3.1 also shows the breakdown in electricity generation technologies employed between 1971 and 2008. It is clear that thermal power generation remains the dominant source, with fossil fuels providing two thirds of global electricity in 2008. However, this represents a relative decrease from 1973, when three quarters of global electricity production was dependent on fossil fuels. This decrease in fossil fuel dependence coincides with the growth of the nuclear power industry since the 1970s. Although the generation of electricity using renewable technologies has increased by almost five times during the last four decades, this source of electricity remains marginal, providing only 2.8% of the world's electricity generated in 2008 (International Energy Agency, 2010).

These observed trends in electricity generation are set to continue, with the Department of Energy forecasting an increase in global electricity generation of 87% between 2007 and 2035, with countries outside of the OECD becoming responsible for around 61% of total production. Growth in electricity generation is forecast to continue to outstrip growth in total energy consumption, as has been the case since 1990 (Energy Information Administration, 2010).

These statistics demonstrate the fact that electrical power is a commodity on which economic growth is founded, and that the security of future supply is fundamental to the stability of society. The challenges of maintaining adequate supply, especially in the light of forecasted demand, are many: finite resources of fossil fuels and their geographical distribution in the earth's surface limit long-term dependence on conventional thermal power generation technologies, and introduce economic and geo-political insecurities; the correlation between the combustion of fossil fuels and the release of carbon dioxide into the atmosphere presents a requirement to favour carbon-free electricity generation; concerns surrounding nuclear proliferation and the capital costs associated with the installation of new nuclear power plants potentially restrict access to this alternative technology; existing electricity grid systems in the developed world are increasingly under strain to provide uninterrupted supply, and are likely, eventually, to fail under increased load, while much of the developing world has no access to centralised electricity networks.

These challenges indicate that novel approaches are required if human behaviour is to maintain its dependence on electricity. Novel approaches to electricity supply, as well as the implementation of alternative electricity generation technologies, are required. The concept of distributed power generation is reviewed in the following section, as an approach to electricity supply which moves away from conventional centralised power plants. In section 3.3 the use of SOFC technology as an alternative means of stationary power generation in future energy scenarios is reviewed and discussed.

3.2.2 Distributed power generation

Distributed power generation is a term used to cover a broad range of definitions, and can be interchanged with terms such as "embedded generation", "dispersed generation", and "decentralised generation" (Ackermann *et al.*, 2001). Ackermann *et al.* (2001) discuss various inconsistencies in what is meant by the term, however, in general, it can be assumed that distributed power generation means generation of electricity with the focus on meeting local demand (Kaundinya *et al.*, 2009). In contrast to conventional electricity networks in which large centralised plants, usually based on fossil fuel or nuclear conversion technologies, are employed, distributed power generation readily encompasses a broader range of power generation technologies, often operating at lower capacities of several mega watts or less. In particular, renewable technologies are well suited to distributed generation, as are stationary fuel cell systems (Ackermann *et al.,* 2001; Verda and Quaglia, 2008).

As well as offering the opportunity to incorporate novel, low carbon power generation technologies, distributed power generation is perceived to offer several additional benefits, especially with regard to sustainability issues. By its very nature, the positioning of a power plant in the immediate vicinity of the customer brings with it clear advantages. In the year 2000, it was estimated that losses associated with electricity transmission and distribution were in the order of 9.3% in the UK, with the average for the European Union being 7.3% and similar losses in the USA totalling 7.1% (Ofgem, 2003). From these statistics it is clear that a significant proportion of fuel used to generate electrical power is wasted, with the associated release of pollutants. Distributed power generation offers the opportunity for substantial reduction in these losses, simply by reducing the transmission distances required.

Given these facts, it is apparent that even small scale fossil fuel-based electricity generation technologies such as gas turbines and diesel engines, may offer benefits in distributed generation scenarios. The existing demand for such products offers some indication of the potential market for stationary SOFC systems of comparable electricity generating capacity. Figure 3.2 illustrates the historic market for reciprocating engines and gas turbines used for distributed stationary power generation. The statistics are based on orders placed each year for units with a generating capacity in the range of 1 MW to over 30 MW, from 1978 until 2005. From 2005, units with a generating capacity of 0.5 – 1 MW are also included. The general trend shown in Figure 3.2 is for an increase in demand for such energy generating products, and the breakdown shown for the years 2005 – 2009 indicates that the majority of demand is for the lower end of the market, in terms of generating capacity. At the peak of the market, prior to the recent economic downturn, over 35000 units with individual capacity between 0.5 MW and 2 MW were ordered globally. This size of generator is similar to that of the SOFC System products being developed for stationary power generation.

The generation of electrical power in close proximity to the customer allows additional

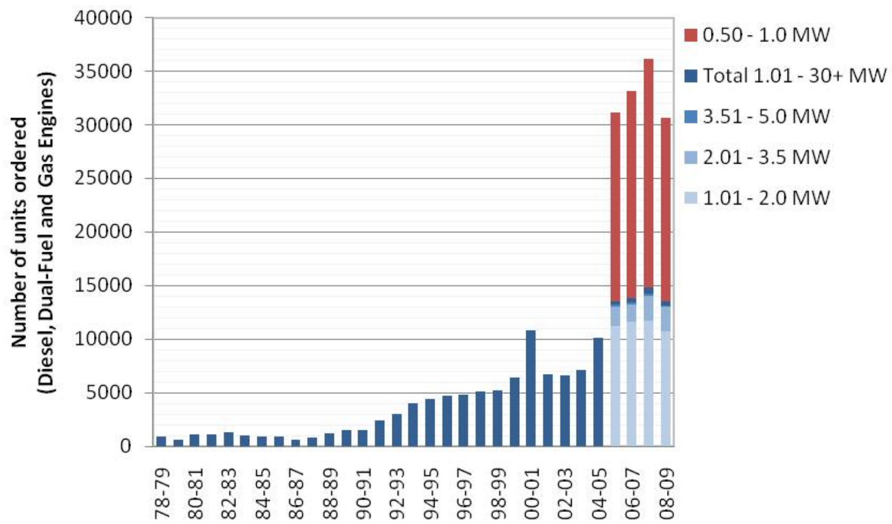


Figure 3.2: Annual worldwide orders for diesel, dual-fuel and gas engines for distributed generation between 1978 and 2009. Units with generating capacity of less than 1 MW were only included within the statistics since 2005. For these years a breakdown of the total 1.01 – 30+ MW range is also shown. (data collated from Diesel & Gas Turbine Worldwide, 2008, 2009 and 2010)

opportunities for effective use of waste heat generated from the process. Stationary fuel cells, especially those based on SOFC technology, are ideally suited for combined heat and power (CHP) applications, because of their high operating temperature (e.g. Pehnt, 2000; Lisbona *et al.*, 2007; Staffell *et al.*, 2008, Zhang, 2010).

Aside from these environmental benefits, distributed generation also increases the ease with which additional capacity can be introduced into a local electricity supply network. This may be relevant to regions of the developed world where the existing grid system can no longer cope with increased demand: distributed power generation may allow additional supply to be provided with much lower investment, compared with upgrading existing distribution networks or building new centralised power plants (Hoff *et al*., 1995; Pepermans *et al*., 2005). Distributed power generation also offers opportunities for the developing world, where the capital costs of introducing a centralised electricity network are prohibitive. Indeed, the literature indicates a growing interest in applying distributed power generation to isolated regions, often in developing countries (e.g. Lhendup, 2008; Ketlogetswe and Mothudi, 2009; Hallett, 2009; Contreras *et al.,* 2010).

These benefits of distributed power generation support forecasts indicating a growth in distributed generation capacity in the short to medium term. This growth offers important opportunities for the commercialisation of SOFC technology.

3.3 Solid oxide fuel cell technology

As demonstrated in the previous sections, SOFC technology offers the potential to contribute to meeting future electricity requirements, especially in a decentralised power generation scenario. The technical and commercial aspects of the technology are reviewed in the following sections.

3.3.1 Solid oxide fuel cell systems for stationary power generation

Various efforts are being made globally to develop SOFC technology suitable for stationary power generation applications. Development is being carried out often in collaboration between academia and industry, with the emergence of several leading product concepts in the past decade. The system under development by Rolls-Royce Fuel Cell Systems is illustrated in Figure 1.1. Alternative concepts are being developed by Siemens Power Generation and Mitsubishi Heavy Industries, as illustrated in Figures 3.3 and 3.4 respectively.

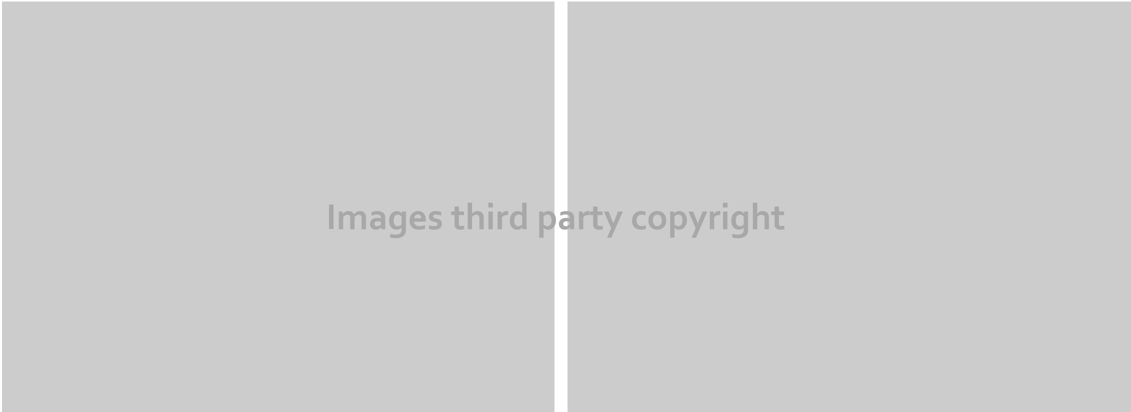


Figure 3.3: Schematic showing the 220 kW SOFC/gas turbine hybrid under development at Siemens Power Generation, and a schematic of the first demonstrator unit (Siemens AG, 2010a). The schematic illustrates the flow of fuel gas (yellow) and air (blue) through the system, with waste heat (red) recovered prior to exhaust. The principal sub-assemblies shown are the SOFC stack, a gas turbine, heat management system, fuel processor and power conditioning systems.

It is clear from these illustrations that a stationary power generation system based on SOFC technology is a complex product incorporating several different sub-assemblies. The fuel cells themselves are connected in a stack, in which the electrochemical conversion of fuel and air occurs. This process is discussed further in Section 3.3.3. However, in order for the stack to operate effectively, it must be incorporated into a larger system, commonly referred to as the balance of plant. The principal sub-assemblies within the balance of plant include a fuel processor, power conditioning equipment and a system for heat recovery or further power generation in a hybrid assembly (Hawkes *et al.*, 2006).

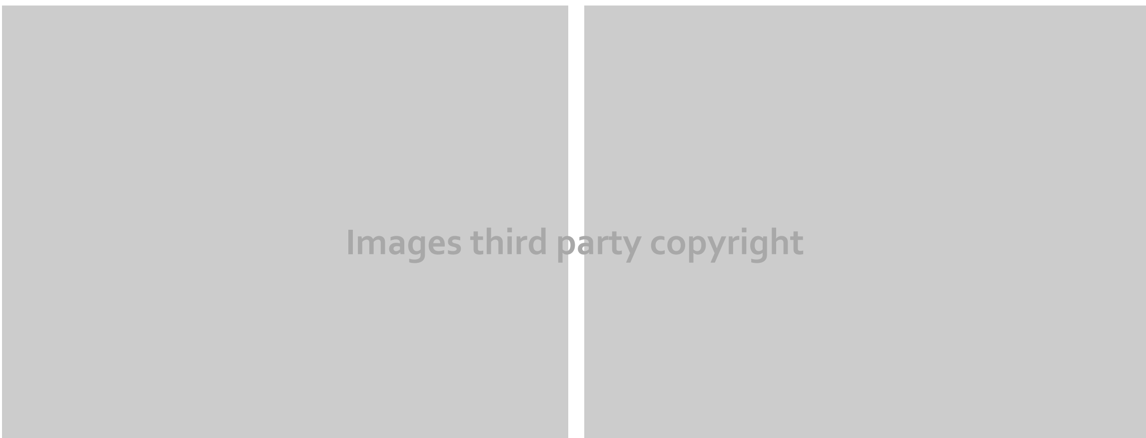


Figure 3.4: An artist's impression of the 200 kW SOFC system under development at Mitsubishi Heavy Industries, and a schematic showing the principal component within the system (Gengo *et al.*, 2007). Any fuel which remains unconverted after passing through the SOFC stack is combusted to power a micro gas turbine (pink flow). Excess heat is used to preheat the air inlet to the SOFC stack (blue flows). An inverter is required to transform DC electricity generated in the fuel cell into AC electricity.

The target life expectancy for large stationary systems is 20 – 25 years. However, the design target for the SOFC stack system is only in the order of five years, or 40,000 hours operation (Karakoussis *et al.*, 2001; Hawkes *et al.,* 2006; Thijssen *et al.,* 2010). Therefore, it is clear that the SOFC stack represents a consumable component, with replacement required four or five times throughout the lifetime of the stationary system.

3.3.2 Commercial status of solid oxide fuel cell technology

The current commercial status of SOFC technology is hard to ascertain. Publicly available information released by SOFC developers tends to present a rather optimistic view as to the timelines within which commercial products will be available. Industry reviews up to 2005 have been published by the Houston Advanced Research Centre (2006). In addition, surveys conducted by the organisation Fuel Cell Today are useful in identifying the principal players in SOFC commercialisation (Adamson, 2008; Crawley, 2007). Table 3.1 lists some important industrial SOFC developers, and identifies the most recent information available regarding the status of commercially available products.

Various collaborative programmes support the development of SOFC technology, incorporating industrial and academic partners from across the supply chain. In the United States, the Solid State Energy Conversion Alliance (SECA), under the auspices of the National Energy Technology Laboratory, is focused on cost reduction, fuel flexibility and scale-up, with the overall goal being the availability of SOFC technology for centralised power generation (> 100 MW plants) fuelled by coal (National Energy Technology Laboratory, 2011a). In working towards this goal, the development of materials, manufacturing methods and SOFC stack design will support commercialisation of SOFC technology across a range of applications. Partners in the SECA programme include Delphi Automotive Systems, involved in the development of auxiliary power units (APUs) based on SOFC technology. Other partners, including Rolls-Royce Fuel Cell Systems and UTC Power are more directly focused on the development of market entry products in the 500 kW to 1 MW scale (National Energy Technology Laboratory, 2011b). In Europe, recent collaborative projects have included LARGE-SOFC - Towards a Large SOFC Power Plant (European Commission, 2011a) and Real-SOFC (Realising Reliable, Durable Energy Efficient and Cost Effective SOFC Systems) (European Commission, 2011b).

While Table 3.1 does not provide a comprehensive list of SOFC developers, the data presented within it illustrates some trends with regard to commercialisation of the technology. In general, it is clear that the challenges associated with the development of large SOFC systems, often operating under pressurised conditions and in combination with gas turbine technology as hybrid power generation plants, have been greater than those associated with smaller-scale products operating at atmospheric pressure.

Smaller domestic-sized SOFC units appear to have achieved a degree of breakthrough in terms of market penetration. In the UK, Ceres Power has signed an agreement with British Gas regarding the development and installation of their residential combined heat and power products (Ceres Power, 2008). Field trials were commenced in February 2011, and British Gas

Table 3.1: Overview of some of the principal industrial developers of SOFC products

Company	Location	Product	Status	Reference
Acumentrics Corporation	Massachusetts, USA	250 W – 2 kW SOFC for CHP in military and residential applications.	Products commercially available and development ongoing	Acumentrics, 2011
Bloom Energy	California, USA	Atmospheric 100 kW units.	Commercially available.	Bloom Energy, 2010a
Ceramic Fuel Cells Limited	Australia	Atmospheric "BlueGEN" modular units, up to 2 kW for power generation or CHP.	Products available to commercial clients only for demonstration projects.	Ceramic Fuel Cells Limited, 2011
Ceres Power	UK	Atmospheric residential CHP units	Field trials underway, contract with British Gas in place.	Ceres Power, 2011
Cummins Power Generation	USA	General SOFC development, including auxiliary power unit for	Not commercially available.	Cummins Power Generation, 2011
General Electric Company	California, USA	Atmospheric 3 – 10 kW modular system for broad range of applications	Not commercially available.	General Electric Company, 2011
Kyocera	Japan	Atmospheric residential CHP units	Field trials underway in collaboration with Osaka Gas Co. Ltd.	Kyocera, 2011
Mitsubishi Heavy Industries	Japan	Pressurised hybrid 200 kW unit, tubular cells, demonstrated operation time of 3000 hours	Not commercially available.	Mitsubishi Heavy Industries Ltd, 2011
		Atmospheric 30 kW unit, planar cells.	Not commercially available.	
Rolls-Royce Group Plc.	UK and USA	Pressurised hybrid 1 MW unit, integrated planar cells	Not commercially available.	Rolls-Royce plc, 2011a
Siemens Westinghouse Power Corp.	USA	Variety of product concepts based on tubular cells, pressurised hybrid and atmospheric.	Not commercially available, various demonstration products installed.	Siemens AG, 2010a
Versa Power Systems	USA and Canada	2 – 10 kW units	Not commercially available	Versa Power Systems, 2011

has committed to purchase a minimum of 37500 of the units for installation in UK homes. In the USA, Bloom Energy (formerly Ion America) is offering SOFC power generators of 100 kW capacity for distributed generation. Commercial customers include Walmart, the Coca-Cola Company and Bank of America (Bloom Energy, 2010b).

Development of larger scale systems continues, and the continuation of programmes such as the SECA programme in the USA indicate an ongoing commitment to the technology based on a firm belief in the market potential for SOFC products. However, during the course of the research activity reported in this thesis a marked change has been observed in the claims made by industrial SOFC developers with regard to predicted product launches. The Fuel Cell Industry Review of 2005 identified the tendency of fuel cell developers to *"...overstate their readiness for product launch..."* (Houston Advanced Research Centre, 2006). Five years later, SOFC developers appear much more cautious about making such claims via websites or other media. While at a superficial level this might appear to mark a reduction in effort with regard to market penetration, the continued commitment of many major companies and government funding sources to pursue SOFC development indicates that the technology very much remains a contender for future power generation scenarios.

3.3.3 Operating principle of solid oxide fuel cells

SOFCs derive their name from the solid oxide, or ceramic, material used in the electrolyte layer. Although the general perception might be that fuel cells are a novel concept, ceramic fuel cells were first demonstrated in 1937 (Baur and Preis, 1937, cited in Minh, 2003). Baur and Priest used yttria-stablized zirconia (YSZ) in their early cell, and over seventy years later this remains the most common material for SOFC electrolytes.

The electrolyte material is conductive to the oxide ions (O^{2-}) formed from the reduction of oxygen gas at the cathode. At the anode the hydrogen-rich fuel gas (H_2) is oxidised, releasing electrons (e^-) and producing water (H_2O) as the by-product of the overall reaction. This is shown pictorially in Figure 3.5. An external electrical connection between the anode and the cathode provides a pathway for electron flow, resulting in the generation of electrical power.

These electrochemical processes occur quickly enough for efficient operation at temperatures around 800 – 1000 ^{o}C. Alternative oxide materials have been developed for use in the electrolyte layer which has allowed the introduction of low and intermediate temperature SOFCs (Huijsmans *et al.*, 1998; Steele, 2000; Fuentes and Baker, 2007; Bozza *et al.*, 2009).

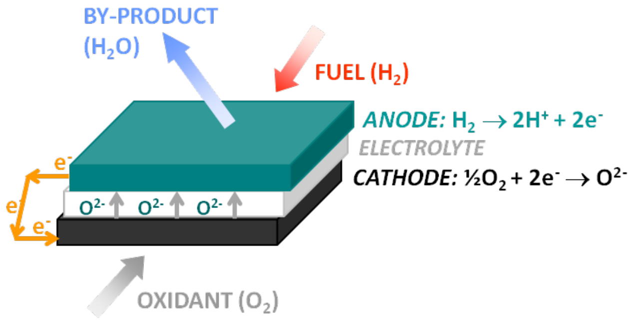


Figure 3.5: Schematic showing mechanism for electricity generation in SOFCs

3.3.4 The solid oxide fuel cell – design, materials and manufacture

Since the early days of SOFC development by the likes of Baur and Preis, several well developed SOFC cell and stack designs have emerged. Figure 3.5 illustrates the required arrangement of electrodes (anode and cathode) in relation to the ceramic electrolyte. In addition to these cell components, electrical interconnects are required to connect individual cells within the fuel cell stack, and inert sealing materials are also necessary, dependent on cell design, to prevent fuel and air gases from mixing directly and undergoing a combustion reaction. The high operating temperature of SOFCs and the exposure of components to reducing (anode side) and oxidising (cathode side) environments presents a substantial challenge to material scientists. Materials are required which will provide the correct electrochemical properties necessary for effective and efficient cell performance, and which will also remain chemically and physically stable throughout the target 5-year operating lifetime of the cell. Detailed reviews of material selection for SOFC components are provided in Singhal and Kendall (2003), Haile (2003) and Wincewicz and Cooper (2005). The material and design characteristics of three different cell and stack concepts are analysed in some detail in Chapter 7 of the thesis.

The two principal barriers to commercialisation, and hence the areas on which design, materials and manufacturing research and development activities are focused, are cell reliability/durability and cost (Williams *et al.*, 2006; Minh *et al.*, 2008). Minh *et al.* (2008) identify that these barriers require addressing at every level of the technology, from materials to cell and stack design and manufacture and, finally, systems integration. Technical improvements in each of these areas are required to achieve a product which is commercially viable.

3.3.5 Environmental performance during SOFC operation

There is no doubt that the security of future energy supply is a significant concern for politicians, businesses, engineers, scientists and the general public alike. The concern is largely based on society's dependence on fossil fuels of which reserves are finite and subject to the fragilities of international trade relations. In addition, global warming and its association with the combustion of fossil fuels has been the major environmental issue of the past decade.

Fuel cell technology has been presented as a means of electricity generation which is clean and efficient and which would be an attractive alternative to conventional technologies. This image arises primarily from the concept that fuel cells will be fuelled by hydrogen gas. In this scenario the overall chemistry occurring in the cell would result in the generation of electricity with only water as a by-product (Equation 3.1):

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(g) \qquad \textit{Equation } 3.1$$

The widespread use of hydrogen as a fuel is at present uneconomical, unsustainable and impractical, with major breakthroughs required in terms of its production, storage and cost (Steele, 1999; Lattin and Utgikar, 2007). The advantage of high temperature fuel cells, such as SOFC, over other fuel cell types is that the technology is equally well suited to operate on natural gas, or other hydrocarbons. In the presence of a suitable catalyst and water, steam reforming takes place (Equation 3.2) leading to the generation of a carbon monoxide and hydrogen gas mixture. Where excess steam is present the carbon monoxide is further oxidised in the shift reaction (Equation 3.3) releasing carbon dioxide and more hydrogen:

$$CH_4(g) + H_2O(g) \rightarrow CO(g) + 3H_2(g) \qquad \textit{Equation } 3.2$$

$$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g) \qquad \textit{Equation } 3.3$$

This process occurs readily at the SOFC anode under operating conditions. The carbon monoxide generated in the steam reforming process can also act as a fuel for the cell. Therefore the overall reaction in a SOFC supplied with natural gas (where the methane component acts as fuel) is shown in (Equation 3.4):

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g) \qquad \textit{Equation } 3.4$$

Equation 3.4 is identical to a combustion reaction typical of any conventional fossil-fuel based technology. The difference between conventional combustion and the electrochemical processes occurring in the fuel cell is the efficiency with which fuel is used. Unlike in a combustion engine, or gas turbine, where the chemical energy of the fuel is converted to heat

Table 3.2: Comparison of alternative power generation technologies (EG&G Technical Services Inc., 2004)

Technology type	Generating capacity	Estimated efficiency (%)
Reciprocating engine	50 kW – 6 MW	33 – 37
Micro turbine	10 kW – 300 kW	20 – 30
Phosphoric acid fuel cell	50 kW – 1 MW	40
Solid oxide fuel cell	5 kW – 3 MW	45 – 65
PEM fuel cell	< 1 kW – 1 MW	34 – 36
Photovoltaic	1 kW – 1 MW	NA
Wind turbine	150 kW – 500 kW	NA
Hybrid renewable	< 1 kW – 1 MW	40 – 50

energy to kinetic energy to electrical energy, the electrochemical conversion in a fuel cell occurs in a single step.

As a result of the direct electrochemical conversion of fuel to electrical energy the losses associated with conventional technologies are reduced. Carbon dioxide emissions are directly related to the efficiency of fuel consumption; therefore, according to the efficiencies quoted in Table 3.2, a SOFC plant operating on natural gas has the potential to reduce greenhouse gas emissions by up to 50% when compared to an equivalent reciprocating engine operating on the same fuel (EG&G Technical Services Inc., 2004).

In addition to the environmental benefits associated with improved fuel efficiencies, SOFCs in operation as stationary power generators have additional benefits. In their assessment of the benefits of fuel cells in the use phase, Bauen and Hart identify seven significant species present in emissions from conventional technologies (Bauen and Hart, 2000). These are listed as oxides of nitrogen and sulphur, carbon monoxide, non-methane hydrocarbons, particulate matter, carbon dioxide and methane. Using a quantitative model, a comparison was made of a CHP SOFC-gas turbine hybrid system with an equivalent conventional heat/power gas engine. The results from the model showed complete elimination of particulate matter emissions, and improvements of 98% and 95% for nitrogen oxides and carbon monoxide respectively. Emissions of sulphur oxides and non-methane hydrocarbons were reduced by around 37% and emissions of methane by 31%. Overall carbon dioxide emissions were improved by 28%. Other studies, including those by Pehnt and Ramesohl (2003), Baratto and Diwekar (2005) and Pehnt (2008) confirm the environmental benefits of power generation by SOFC technology across a range of applications.

Fuel cells therefore do not present a complete solution to the future of energy supply since they are still constrained by the requirement for fuel. They do, however, present a means of utilising fossil fuels more efficiently and cleanly than current technologies and could contribute to a renewable energy network based on alternative hydrogen-rich fuels.

3.3.6 Environmental performance across the SOFC product life cycle

A thorough investigation of the ecological aspects of fuel cells must extend beyond fuel utilisation efficiencies and emissions during the use (electricity generation) phase of the technology (Pehnt, 2001). For a technology in the very early stages of transition from laboratory to marketplace, the disillusionment of shareholders, funding bodies and potential customers poses a major risk to successful commercialisation. Figure 3.6 shows the life cycle of a SOFC system, broken down into seven individual phases, each of which has an associated environmental impact. Investigations into the wider environmental impacts of fuel cell technology have been previously conducted and are reviewed in the following section.

3.3.6.1 Life cycle studies of SOFC technology

Life cycle studies of SOFC technology, with a specific focus on the environmental impacts across the product life cycle, are wide ranging in their goal and scope. Some studies have focussed on particular aspects such as manufacturing processes (Hart *et al.*, 1999), while others have attempted to conduct complete life cycle assessments with the aim of comparing different fuel cell designs (Karakoussis *et al.,* 2001), or comparing fuel cells with conventional

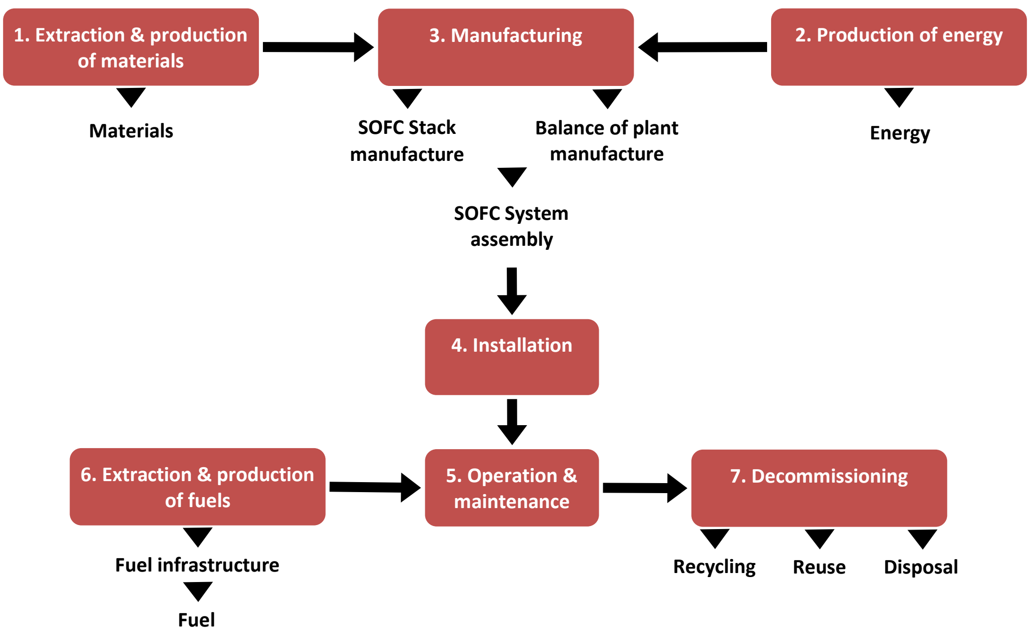


Figure 3.6: Life-cycle phases for a SOFC system (adapted from Karakoussis *et al.*, 2001)

power generation technologies (Seip *et al.,* 1991; Raugei *et al.,* 2005). Another area of interest has been concerned with the life cycle impacts associated with various alternative fuel supplies (Pehnt, 2000; Riva *et al.*, 2006). Table 3.3 provides an overview of this area of the literature.

Table 3.3: Summary of previous studies investigating the life cycle environmental impacts of SOFC technology

Reference	Goal	Scope
Siep *et al.*, 1991	Comparison of SOFC power plant with conventional coal and gas power plants.	Operation phase, including replacement of SOFC stacks.
Zapp, 1996	Comparison of SOFC power plant with 10 MW gas turbine.	Preliminary study.
Hart *et al.*, 1999	Comparison of alternative manufacturing processes for SOFC production.	Manufacturing of SOFC components.
Karakoussis *et al.*, 2000	Baseline study of SOFC manufacture, and associated emissions and environmental impacts.	Manufacture and end-of-life phases of the SOFC system.
Pehnt, 2000	Comparison of various stationary power generation technologies.	Manufacture and operation of SOFC system.
Karakoussis *et al.*, 2001	Comparison of tubular and planar SOFC stack designs.	Manufacturing of SOFC system.
Pehnt, 2003a and 2003b	Comparison of fuel cells with alternative power generation technology for transport and stationary applications.	Complete product life cycle, including manufacturing, operation and end-of-life.
Pehnt and Ramesohl, 2003	Extensive report on various barriers and opportunities regarding fuel cell utilisation, including LCA.	
Barrato and Diwekar, 2005	Comparison of SOFC-based APU with diesel engine in automotive application.	Manufacturing and operation SOFC-based APU.
Barrato *et al.*, 2005	Baseline LCA of SOFC-based AUP in automotive application.	Manufacturing and operation SOFC-based APU.
Wincewicz and Cooper, 2005	Taxonomy of material and manufacturing alternative for SOFC stack, for future LCA studies.	Materials and manufacturing of SOFC stack.
Osman and Reis, 2007	Comparison of SOFC with other CHP systems for commercial buildings.	Operation of SOFC CHP system.
Pehnt, 2008	Comparison of various micro-generation technologies, including SOFC.	Manufacture and operation of SOFC system.
Strazza *et al.*, 2010	Comparison of SOFC-based APU with diesel engine on board a ship.	Manufacture and operation of SOFC-based APU, including production of various fuel types.

By examining the studies presented in Table 3.3, it is clear that the majority of research in this area has been directed towards the manufacture and operation of various SOFC products. This would be expected, given the stage of the technology's development: the conclusions from these studies provide justification for the adoption of SOFC power generation products, in place of more conventional technologies.

Hart *et al.* (1999) assessed six fabrication routes with applications on SOFC manufacture. The routes were assessed by comparing the inputs of materials and energy required to fabricate a specified area of SOFC electrolyte. The work included four wet routes used in traditional ceramics processing and most commonly applied to planar SOFC stacks. Gas-phase processes are required for the fabrication of tubular stacks, where the substrate is a curved surface. These gas-phase routes were found to have the potential for higher environmental burden and one of them, electrochemical vapour deposition, was reported as having poor materials utilisation. However, the environmental impacts of manufacture were shown to be cancelled out within only three days of operation by the benefits in use when compared with conventional technologies.

In a more extensive study, Karakoussis *et al.* (2001) carried out life cycle inventory analysis to compare the environmental differences between the manufacture of tubular and planar SOFC stacks. This work took into account the energy inputs for materials production, as well as those required for the manufacturing processes themselves. The balance of plant was included in the assessment. Karakoussis *et al*. (2001) showed that the manufacturing phase gives rise to a significant proportion of particulate and carbon monoxide emissions when compared to the fuel cells in use. Emissions of sulphur oxides from the manufacture phase were also significant. A breakdown of the inventory analysis showed that the contribution from the production of materials was very large when compared with the energy and emissions required for the actual manufacturing process routes. This finding prompted the authors to comment that the recycling of materials, both in-house and post-consumer, would potentially play an important role in reducing these impacts.

Wincewicz and Cooper (2005) have published a detailed review of manufacturing processes and materials used in SOFC technology, as the initial part of a longer term project to carry out full environmental life -cycle assessment.

3.3.6.2 End-of-life considerations in previous life cycle studies of SOFC technology

As indicated in Chapter 2, previous researchers have reported a lack of data regarding the end-of-life management of SOFC products, and as such have in general excluded this phase of the product life cycle from the scope of the study.

In their research, Seip *et al.* (1991) include calculations for the replacement of the SOFC stack every three years. The use of this conservative estimate for the lifetime of the SOFC stack in commercial products predicts the generation of 16.6 tonnes of end-of-life SOFC stack per year, based on a total of 200 MW of generating capacity. However, the authors dismiss the significance of this waste stream with the assumption that, *"The cell material in the SOFC case is mostly ceramics, which is inert and should give no environmental problem".* This assessment of the material composition of the SOFC stack would appear to be over-simplified, ignoring the presence of materials with hazard ratings under EU waste legislation, such as nickel. In addition, the development of environmental legislation since the latter part of the twentieth century places increasing pressure on manufacturers to give more consideration to the end-of-life management of products.

Although Zapp's study (1996) provides only some preliminary thoughts on the environmental impacts of SOFCs across their life cycle, the attention given to the end-of-life phase is more insightful than in many more detailed life cycle studies. Zapp identifies particular challenges associated with the dismantling of end-of-life stack, with respect to waste prevention and reuse of components. These issues include the connection of individual cells in series, whereby the failure of one component results in the failure of the complete stack assembly. This, combined with the tendency of ceramic components to crack under stress, is identified as being detrimental with regard to opportunities for disassembly and repair of prematurely failed components. In addition, the highly integrated nature of the fuel cell components is identified as being problematic for the separation and recovery of individual materials.

Karakoussis *et al.* (2001) include a qualitative discussion on the environmental impacts of the end-of-life phase in their life cycle comparison of tubular and planar SOFC stack designs. The primary focus of their work is on the manufacturing processes required for the production of these different design concepts and in their study they assume that none of the production waste is recycled. While in the conclusions to the research the authors acknowledge that the recycling of production waste could reduce the materials burden of the manufacturing phase, they also identify the importance of managing the end-of-life SOFC stack in a responsible manner. Specifically, they envisage a scenario where design for disassembly is applied to SOFC stack development, in order to facilitate the recovery of some reusable components, with other materials being recycled using chemical or other metallurgical treatments. Interestingly, the authors identify the development of the Extended Producer Responsibility concept, and associated legislation (reviewed in Chapter 4 of the thesis) as an incentive for SOFC manufacturers to consider end-of-life options for the stack assemblies. A more extensive discussion on the end-of-life management of planar and tubular SOFC concepts is reported in Karakoussis *et al.* (2000) with this phase of the life cycle being identified as providing an opportunity for the reduction of environmental burdens associated with the SOFC material production. This publication emphasises the need for further research in this area.

Pehnt has published several articles concerned with the life cycle assessment of fuel cells, with his interest focused on PEMFCs and SOFCs for both stationary and transportation applications. In his studies on PEMFCs, which rely on the use of platinum group metals, Pehnt (2001) considers various recycling scenarios, based on closed-loop recovery of precious metals in a model similar to that proven in the autocatalyst industry. In this study recycling is shown to reduce the environmental impacts associated with these materials by a factor of up to 100 (in the case of SO_2 emissions). Although Pehnt cites the existence of adequate recycling processes, following development by major developers of PEMFC technology, there are many known problems associated with the reprocessing of end-of-life PEMFCs, arising from the other materials present in the fuel cell assemblies (Handley *et al.*, 2002; Grot *et al.*, 2005a; Grot *et al.*, 2005b). These issues are not considered in Pehnt's LCA work (Pehnt, 2001).

In his LCA studies concerning SOFC technology, Pehnt generally avoids any quantitative inclusion of the end-of-life phase (Pehnt, 2000, 2003a, 2003b, 2008; Pehnt and Rahmesol, 2003). In a more detailed account of his work in this area (Pehnt, 2003c) a simple recycling scenario is mentioned. This scenario is envisaged for a planar SOFC stack design where the cell components are supported on a chromium-rich steel bipolar plate. Pehnt assumes a 90% recycling rate for this heavy metallic component, which would most likely be recycled through the existing value chain for scrap metal. However, this simplistic assumption does not address the wider issues surrounding the end-of-life management of the SOFC stack, nor the recycling of the other stack components. In addition, many SOFC stack concepts do not contain these heavy (and easily recyclable) metallic components, and as such the recycling scenario presented by Pehnt (2003c) has limited validity.

Baratto and Diwekar (2005) do not consider the end-of-life phase of the SOFC life cycle, based on the absence of available data. Similarly Osman and Ries (2007) and Strazza *et al*. (2010) exclude the end-of-life phase from the scope of their research.

3.4 Summary

The review of SOFC technology presented in this chapter provides important background to the research. The potential significance of SOFCs in a future energy scenario has been identified, providing a view of the volume of market uptake and consequential volumes of end-of-life units. By examining some of the products being developed for commercial application, some of the challenges of successful implementation of the technology have been identified. Finally, by reviewing the literature reporting on life cycle assessment studies of the technology it is apparent that the methodology has been applied in various studies, but that in each case data relevant to the end-of-life management of the technology is missing and therefore warrants further investigation.

CHAPTER 4 A REVIEW OF END-OF-LIFE MANAGEMENT

4.1 Introduction

This chapter presents a review of the literature related to end-of-life management. It begins by identifying the legislative context in which end-of-life management must be approached with a specific focus on the development of concepts such as Extended Producer Responsibility and Integrated Product Policy. The review then extends to the academic literature, exploring theoretical and practical approaches to end-of-life management, including environmental and economic considerations. Finally, methods for evaluating end-of-life management scenarios are reviewed, and their benefits and shortcomings discussed.

4.2 End-of-life management

End-of-life management is concerned with the management of products, after they have fulfilled their designated task or function. Products may be classified as having reached the end-of-life phase when they are worn out or broken; no longer useful; obsolete; no longer cost-effective to use; no longer compliant with legislative requirements and standards; or simply no longer wanted (Ashby, 2009). The need for end-of-life management of products has become increasingly significant with the rise in consumerism observed throughout the twentieth century, as illustrated in Figure 4.1 (Sheehan and Spiegelman, 2005).

Although end-of-life management is closely related to waste management, and is subject to traditional legislation controlling the handling, processing and disposal of waste, it has, in

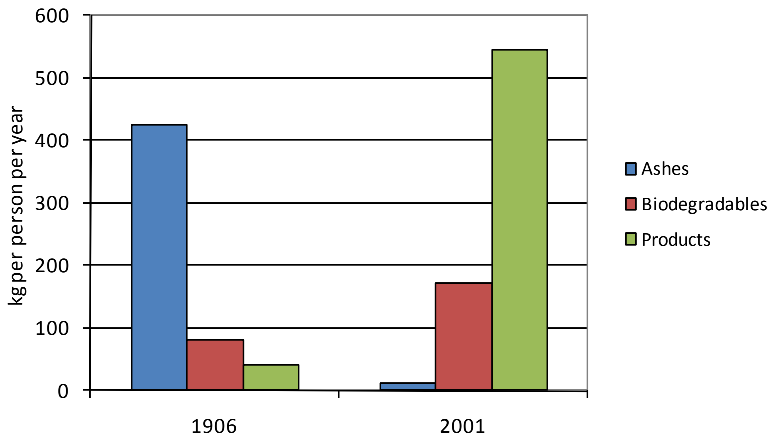


Figure 4.1: Comparison of the composition of US municipal waste in 1906 and 2001 (Sheehan and Spiegelman, 2005)

fullness, emerged from the development of concepts such as Industrial Ecology (Graedel and Allenby, 1995) and Sustainable Product Design (Maxwell and van der Vorst, 2003). As such, the concept of end-of-life management is strategically important within the context of the complete product life cycle: the material and energy resources consumed during the extraction of raw materials and manufacture of a product can eventually be recovered or lost, depending on end-of-life management decisions. However, the opportunities available for resource recovery at end-of-life are often limited by product design (Ishii *et al.,* 1999; Harper and Graedel, 2004; Wright *et al.*, 2005; Pigosso *et al.*, 2010). The benefits of incorporating end-of-life management considerations in the very early stages of the design process are captured in the following quote from Harper and Graedel (2004):

> *"If the designer does not consider what will happen at the end of life of his or her product, the product can be so complicated, labor-intensive, or dangerous to disassemble and reuse that it will automatically be discarded. Conversely, if it is designed for recycling and reuse, the linear approach to materials use in products will likely be circumvented."*

As awareness has grown regarding the potential of effective end-of-life management to contribute to goals such as resource efficiency and reduction in waste going to landfill, various policy principles and instruments have been developed to support end-of-life management considerations. These are reviewed in Section 4.3 below, with particular attention given to policies developed in Europe and the UK, North America and Japan. In order to support the implementation of end-of-life management practices, it is necessary to be able to justify them, based on environmental benefits and economic viability. The later sections of the chapter examine various evaluation methodologies, and review their application to the development of effective end-of-life management solutions.

4.3 Policy principles and instruments supporting end-of-life management

Current environmental policies, in which the concept of end-of-life management finds its place, are the result of several decades of progress in the understanding of human impact on the environment. The origins of modern environmental policy are generally considered to lie in the First International Conference on the Human Environment, held in Stockholm in 1972 (United Nations Environment Programme, 1972). This landmark event catalysed global efforts to address, in a unified manner, the increasingly apparent detrimental impact of human activities on the environment. Included in these efforts was the World Commission on Environment and Development which, in 1987, led to the introduction of the phrase "sustainable development". Although the interpretation of this phrase is diverse, and often strays from the original definition (Hicks, 2006), the concept of *"…development that meets the needs of the present without compromising the ability of future generations to meet their own…"* (Brundtland, 1987), has become a dominant term in current environmental policy.

Tukker (2006) describes a shift in the focus of environmental policy over recent decades (Table 4.1). Early policies in the 1960s and 1970s were reactionary, developed in an ad-hoc manner in response to high-profile environmental crises. The 1980s saw a focusing of policy aims to support a reduction in the frequency of the occurrence of such events by targeting point-sources in order to minimise emissions and waste generation from obvious polluters. The concept of "cleaner production" was introduced. The focus of environmental policy in the 1990s shifted again, introducing a product-centred approach as a means of achieving environmental sustainability in a consumer-based society.

Tukker identifies more recent movement towards a more radical approach to environmental sustainability, embodied in the re-thinking of conventional production-consumption scenarios and behaviours. However, for the time-being, the attention of policy makers and legislators appears to be directed towards the challenge of fully implementing a product-based approach to environmental sustainability.

Various policy principles have been adopted which support the reduction of the environmental impact of products by promoting specific consideration of end-of-life management. At the most basic level, the desire to redirect waste from disposal in landfill sites promotes consideration of alternative waste management solutions, including reuse and recycling of products. More strategically, transferring the responsibility for the end-of-life management of goods from the consumer or local government to the manufacturer has the aim of promoting proactive behaviours, such as "design for disassembly" (e.g. Jovane *et al.*, 1992; Harjula *et al.*, 1996; Ryan *et al.*, 2011), "design for remanufacture" (e.g. Mabee *et al.*, 1999; Kerr and Ryan, 2000; Ijomah *et al.*, 2007) and/or "design for recycling" (e.g. Krewit *et al.*, 1995; Knight and

Table 4.1: Historical trend in environmental policy, leading to the development of a proactive product-focused policy approach (Tukker, 2006)

Decade	**Focus of environmental policy**	**Approach**
1960s and 1970s	Responding to environmental crises	Reactive
1980s	Processes – cleaner production, minimisation of waste and emissions from point sources	↓
1990s	Products – environmental product policy	Proactive

Sodhi, 2000; Masanet and Horvath, 2006). Finally, the most holistic policy principles identify the benefits of life cycle thinking with regard to product design, such that materials selection, manufacturing, use and disposal are all considered at the very earliest stages of the design process.

4.3.1 Waste Reduction

The reduction of waste generation and disposal underlies all policy principles promoting end-of-life management of products, and is an important feature of many environmental strategies in the developed world.

In Europe, the Thematic Strategy on Waste, which forms part of the Sixth Environmental Action Programme, states that:

> *"The long-term goal is for the EU to become a recycling society that seeks to avoid waste and uses waste as a resource."* (European Commission, 2005)

In order to achieve this goal, the approach to waste management adopted by the European Union encompasses the following principles (European Commission, 2011c):

- Waste prevention, incorporating reduction in volume of waste produced and the level of hazard associated with that waste.
- Recycling and reuse, in order to recover material and energy resources and divert waste from disposal in landfill.
- Improving final disposal and monitoring, by designating landfill as a "last resort" in waste management, and by placing tight controls on both landfill and incineration in order to minimise pollution.

In 2008 a revised Waste Framework Directive was implemented (European Parliament and Council, 2008) which requires the adoption of the hierarchy for waste management (Figure 4.2) by Member States in their national waste management policies. The hierarchy identifies waste prevention, or reduction, as the priority action, with disposal being identified as the least favourable option, to be adopted only as a last resort.

Specifically, all Member States are required by the end of the year 2013 to have established national waste prevention programmes. Examples of non-legislative waste prevention initiatives suggested by the European Union for application in national programmes extend from the promotion of eco-design activities, to the promotion of environmental management systems and eco-labelling schemes (European Council and Parliament, 2008).

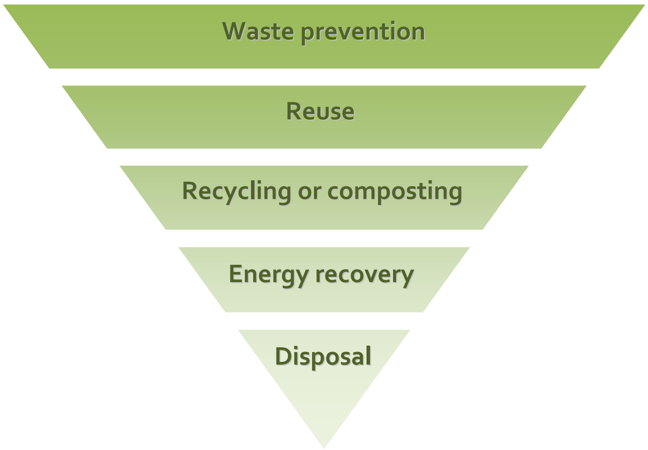


Figure 4.2: Waste management hierarchy

In Europe, the legislative framework supports the implementation of the waste management hierarchy through a number of additional Directives. Various Directives have been developed reflecting the policy principle of Extended Producer Responsibility (EPR), which are discussed further in Section 4.3.2. These promote reuse, recycling and recovery activities, with reference to specific product streams. Overall, the Waste Framework Directive sets targets for recycling of household and similar waste at 50% and recycling of construction waste at 70% for the year 2020 (European Commission, 2008).

As well as policy instruments supporting the adoption of reuse, recycling and recovery, other legislative and non-legislative measures act directly to divert waste from landfill. The Landfill Directive, while primarily concerned with the operation of landfill sites and the minimisation of pollution arising from them, also bans specific waste streams from being accepted for disposal. More generally, the Directive dictates that all wastes accepted by landfill sites must have been pre-treated in order to reduce their hazardous properties and/or volume. Separate licensing requirements are established for landfill sites accepting wastes categorised as inert, non-hazardous and hazardous (European Council, 1999).

Waste reduction appears to form a part of waste policy in most of the developed world, with concepts similar to the European waste management hierarchy used to support waste reduction efforts. In Europe, the role of legislation in the implementation of waste reduction policies is significant: a similar situation is observed in Japan, in contrast to a reliance on voluntary and market-based instruments employed in the United States of America.

Japan’s approach to environmental issues is significant, especially given the influence that it has over developing economies in Asia (Ito, 2011). In Japan, the waste management policy is based on the "3R" policy, where the three Rs stand for "Reduce, Reuse and Recycle". This order of preference, for the development of sustainable approaches to waste management, echoes the European hierarchy for waste management. In part, the drive to divert waste from landfill in Japan is prompted by a lack of land availability. In 2010 it was predicted that landfill capacity for general waste would be exhausted in less than 16 years, and for industrial waste in less than 8 years (Ministry of Economy Trade and Industry, 2010). However, the waste reduction policy in Japan is also closely linked with an awareness of material consumption and use patterns, illustrated by legislation such as the Basic Law for Establishing a Sound Material-Cycle Society, established in 2001. Together with the Basic Environment Law, which came into force in 1994, this legislative framework provides quantitative targets for improving resource productivity (a measure of material consumption); cyclical use rate (a measure of recycling); and final disposal (Terazono, 2009). This framework legislation is supported by a range of more focused laws, summarised by the Ministry of Economy, Trade and Industry (2010). Synergies between Japanese and European policies, supporting waste minimisation are identified in Figure 4.3.

The situation in the USA is somewhat different to that in Europe and Japan, in that the approach to waste management policy varies considerably between individual states. At a federal level, waste policy is established in the Resource Conservation and Recovery Act, which has as its principal goals (United States Environmental Protection Agency, 2008):

> " *To protect human health and the environment from the potential hazards of waste disposal; To conserve energy and natural resources; To reduce the amount of waste generated; To ensure that wastes are managed in an environmentally sound manner."*

While these aims follow similar principles to the waste policies identified in Europe and Japan, the USA appears to have focused more on the development of voluntary instruments (such as industrial partnerships, and voluntary schemes) to support these aims, rather than on the development of a targeted legislative framework (United States Environmental Protection Agency, 2010). Improvements in recycling rates for municipal waste were observed in the 1990s, but since then further improvements have been counterbalanced by increasing consumption and associated waste generation (Sheehan and Spiegelman, 2005).

In addition to reducing the volume of waste, policy in much of the developed world is also concerned with reduction of the hazards arising as a result of waste treatment operations. In Europe, the Hazardous Waste Directive (European Council, 1991), established rules for the

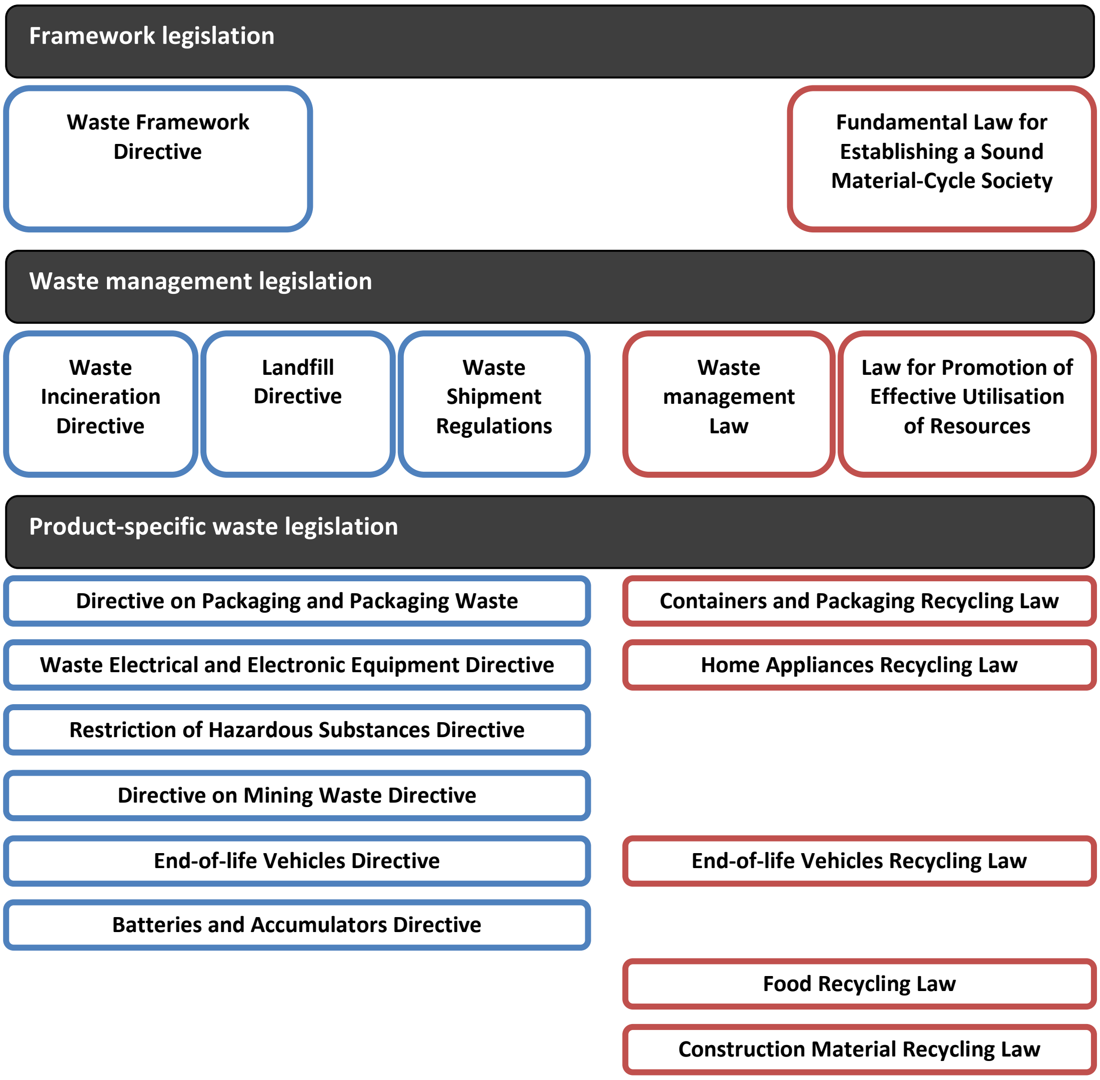


Figure 4.3: Illustration of synergies between the structure of EU and Japanese waste legislation (adapted from Ministry of Economy, Trade and Industry, 2010 and European Commission, 2003a).

identification and classification of hazardous waste streams, thereby supporting segregation and separate treatment of such wastes. In addition, and to prevent geographical displacement of environmental hazards associated with wastes, regulations regarding the international shipment of wastes (European Council, 1993) are in place. These regulations implement the conditions of the Basel Convention, which arose in response to developed countries seeking to avoid increasing domestic costs associated with the treatment of hazardous wastes by exporting wastes to developing countries and Eastern Europe (Secretariat of the Basel Convention, 2011). The Convention has the aims of:

- Establishing a framework for controlling the transboundary shipment of waste
- Developing the criteria for environmentally sound management of hazardous waste, thus promoting waste minimization

The basic principle established by the Convention is that hazardous waste should not be exported from developed countries (including members of the OECD, the European Union and Lichtenstein) to developing countries. Some concessions are in place for wastes destined for recycling and recovery operations, but only where justification of the shipment can be made based on processing availability in the countries of export and import (Secretariat of the Basel Convention, 2011). Under European regulations (European Council, 1993), all shipments of hazardous waste to non-OECD countries, are prohibited.

4.3.2 Extended Producer Responsibility

In Figure 4.1, the contribution of products to the overall composition of municipal waste in the USA is shown to have become dominant in the last century (Sheehan and Spiegelman, 2005). This increase in product-based waste is symptomatic of the increase in consumerism observed across the developed world. In Europe, it has been recognised that as well as seeking to achieve the aim of becoming a “recycling society” by discouraging disposal of waste in landfill sites (European Commission, 2005) it is also necessary to adopt a more proactive approach to reduce the generation and environmental impact of discarded products. One such approach is the implementation of policy measures and legislation incorporating the concept of Extended Producer Responsibility (EPR), defined by Lindqhvist (2000):

> *“Extended Producer Responsibility...is a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product.”*

In contrast, Thierry *et al.* (1995) sum up the conventional attitude of manufacturers towards end-of-life products:

> *“The traditional approach of many manufacturers towards used products has been to ignore them. Manufacturers typically did not feel responsible for what happened with their products after customer use. Most products were designed in such a way that while materials, assembly and distribution costs were minimized, the repair, reuse and disposal requirements were not taken into account. Manufacturers generally believed that the costs of incorporating these requirements would outweigh the benefits. Most of their customers were not prepared to pay an additional fee for a “green” product.”*

EPR therefore has been developed within environmental policy with the aim of incentivising product manufacturers to take proactive measures during the design process which will facilitate the end-of-life management of their products in such a way as to facilitate resource efficient practices, such as recycling and recovery. The concept has been embodied in a number of legislative and other instruments, in the EU and in other geographical regions.

The first legislation incorporating an EPR approach was adopted with respect to packaging waste (European Parliament and Council, 1994), and more recently is illustrated by the End of Life Vehicles (ELV) Directive (European Parliament and Council, 2000) and the Waste Electrical and Electronic Equipment Directive (European Parliament and Council, 2003a). An overview of the requirements of these Directives is provided in Table 4.2.

On its implementation in 2000, the ELV Directive established an initial reuse/recovery target of 85% by weight for all new vehicles manufactured from 1st January 2006, set to rise to 95% by weight by 2015. These recovery rates include the reuse of components, the recycling of materials, and the recovery of energy by incineration or similar waste treatment processes. Separate recycling rates are specified, to ensure that energy recovery can only account for a small proportion of the total recovery rate. In addition to these targets, the ELV Directive also incorporates requirements to reduce the use of hazardous materials in vehicle manufacture; to increase the use of recycled materials; and to improve documentation to facilitate identification of recyclable materials and components at end-of-life (European Parliament and Council, 2000). Given that the responsibility for compliance falls with vehicle manufacturers, it is assumed that the legislation will prompt innovative approaches to re-design and will encourage a reduction in the hazardous materials used, an increase in recyclable materials and more emphasis on design for disassembly (Crotty and Smith, 2006).

Similarly the implementation of the WEEE Directive has set challenging recycling and recovery targets for manufacturers of electrical and electronic equipment, and the anticipated results of the legislation are based on two underlying assumptions. The first assumption is that producers are provided with an economic incentive to revise designs in order to eliminate aspects which would prohibit reuse, recycling and recovery at the end-of-life phase. The second assumption is that an increase in reuse, recovery and recycling of materials from this waste stream will have a positive environmental effect (Mayer *et al*., 2005).

The case study conducted by Mayer *et al*. tests these assumptions, taking the recycling of printers in the UK as an example. The conclusions from the study, which uses life cycle assessment and life cycle costing methodologies to compare four different recycling scenarios, suggest that the outcomes of implementing the WEEE Directive may not be as positive as anticipated. The primary conclusion from the study is that the WEEE Directive does not necessarily provide an economic incentive to producers to redesign products to minimise environmental impact, since the recycling costs will not necessarily decrease as a result. This finding is in agreement with the conclusions of Gottberg *et al.* (2006) who report on an initial exploration of the link between eco-design activities and EPR legislation in the lighting industry.

The findings by Mayer *et al*. (2005) in conjunction with further criticism of the WEEE Directive as an effective means of implementing EPR concepts (Castell *et al.*, 2004; Clift and France, 2006) suggest that the although this new style of legislation might divert waste from landfill

Table 4.2: Summary of recovery and recycling rate targets for different end-of-life products in the European Union.

Waste types	Recovery rate	Recycling rate	Legislative measure
Large household appliances Automatic dispensers	80%	75%	Directive 2002/96/EC on waste electrical and electronic equipment (WEEE)
IT and telecommunications equipment Consumer equipment	75%	65%	
Small household appliances Lighting equipment Electrical and electronic tools Toys, leisure and sports equipment Monitoring and control instruments	70%	50%	
Gas discharge lamps	-	80%	
Vehicles	95%	85%	Directive 2000/53/EC on end-of life vehicles (2015 targets)
Glass, paper and board packaging	60%	60%	Directive 94/62/EC on packaging and packaging waste (2008 targets)
Metal packaging		50%	
Plastic packaging		22.5%	
Wood packaging		15%	

**including component, material and substance reuse and recycling and energy recovery*
*** including component, material and substance reuse and recycling*

sites, it will not in itself guarantee reduced environmental impact from end-of-life waste streams. Similarly, Gerrard and Kandlikar (2007) report mixed evidence regarding the effectiveness of the ELV Directive. While some positive trends among vehicle manufacturers have been observed, such as a reduction in the use of toxic materials and an increase in the use of recyclable materials, their study concludes that end-of-life issues have not become a priority in design.

Outside of Europe, the ELV Directive has been mirrored by similar legislation in Japan, Taiwan and South Korea (Gerrard and Kandlikar, 2007). Similarly EPR legislation regarding electrical appliances has been established in the form of the Home Appliances Recycling Law in Japan (Ministry of Economy, Trade and Industry, 2010), with Taiwan, South Korea and, most recently, China following suit (Chong *et al.*, 2009).

The USA has been slow to follow the trend of EPR-based legislation, with the term EPR itself being changed to stand for Extended *Product* Responsibility (Davis *et al.*, 1997) and then superseded with the term Product Stewardship (Sheehan and Spiegelman, 2005). These terms move emphasis from the producer towards a shared responsibility across all stakeholders involved in the product life cycle (Davis *et al.*, 1997; Chong *et al.*, 2009). Implementation of these policy concepts in the USA has not, in general, been by legislative means. Rather, voluntary efforts involving a list of stakeholders (including federal and State environment agencies, producers, recyclers, retailers, research institutes and non-governmental organisations) have been the predominant approach to implementing EPR principles (Renckens, 2008). An exception to this is in the State of California, where legislation governing the treatment of electrical and electronic waste was introduced in 2003. Renckens (2008) suggests that while voluntary efforts have had some positive effects in terms of raising awareness and prompting some increase in product take-back schemes and recycling efforts, participation by leading manufacturers of electrical and electronic products has been very varied. As a result, the environmental benefits of such efforts are questionable, and Renckens (2008) is of the opinion that in time federal legislation will be passed to harmonise practice.

4.3.3 Integrated Product Policy

Whereas the concept of EPR has become synonymous in Europe and Asia with the end-of-life management of products, Integrated Product Policy (IPP) promotes a more holistic approach to managing the environmental impacts of products. A Green Paper on IPP was first adopted by the European Commission in 2001 (European Commission, 2001), and further developed in a Communication in 2003 (European Commission, 2003b). This Communication summarises the intention of the policy, to *"…ensure that environmental impacts throughout the life-cycle are addressed in an integrated way – and so are not just shifted from one part of the life-cycle to another…".* Thus, IPP has at its heart the concept of "life-cycle thinking".

Since the introduction of IPP in Europe in 2001, various implementing measures have been put in place. EPR legislation could be considered to fall under the wider IPP policy principle. Complementary to the Directives described in Section 4.3.2 are legislative measures concerned with the selection of materials, and the restriction of the use of hazardous materials. Of particular significance is the Restriction of Hazardous Substances (RoHS) Directive (European Parliament and Council, 2003b) which entered into force alongside the WEEE Directive (European Parliament and Council, 2003a). This Directive has specifically restricted the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and polybrominated biphenyl ethers in products placed on the market since 2006. Similar requirements have been adopted in other legislatures, most notably China (Design Chain Associates, 2010). Whereas the RoHS Directive in Europe targets hazardous material commonly used in electrical and electronic equipment, the ELV Directive incorporates similar restrictions on the use of certain hazardous materials in vehicles (European Parliament and Council, 2000). The removal of hazardous materials from products not only reduces exposure to substances during the manufacturing process, but also results in a decrease in hazardous waste arising from end-of-life products. In their review of the effectiveness of legislation in prompting eco-design activities, Yu *et al.* (2007) note that the RoHS Directive appears to have had a much greater influence on product design than the WEEE Directive. Whereas the adoption of eco-design activities to support compliance with recycling targets established by the WEEE and ELV Directives requires the correct economic climate to be in place, the requirements of the RoHS Directive fall directly and inescapably on product designers (Yu *et al.*, 2007).

The first European Directive to fully encompass the fundamental principles of IPP is the Directive establishing a framework for setting requirements for the Ecodesign of Energy using Products (European Parliament and Council, 2005). This really is simply a framework Directive which targets high volume consumer goods; however, a life cycle approach to reducing the environmental impact is captured. Within the Directive the end-of-life management of products plays a significant role in the overall life cycle management. Annex I lists a number of measures by which the environmental impact of products might be assessed. Many of these are of particular relevance to the end-of-life phase, including:

- Consumption of energy and other resources across the product life cycle

- Use of hazardous materials
- Ease of reuse/recycling, including the feasibility of separating hazardous substances and/or materials of high recyclable value
- Product life expectancy, including the ease of maintenance and repair
- Levels of waste and hazardous waste generated
- Emissions to air, water and soil

The Directive has been updated (European Parliament and Council, 2009) since its initial adoption and regulations targeting specific product groups have been developed (European Commission, 2011d).

The intention of IPP was that it would be implemented by a broad range of voluntary and compulsory measures. Therefore in addition to the legislative measures described above, the adoption of eco-labelling schemes; environmental purchasing policies for public bodies; taxes and subsidies and environmental management systems, all support the implementation of IPP (European Commission, 2010a).

The real impact of IPP on the improvement of the environmental impact of products is yet to be seen, and the effectiveness of the policy is a matter of some debate (Rubik, 2001; Nuij, 2001). It is apparent that policy and legislation are not in themselves the solution to reducing the environmental impact of products, and therefore it is reassuring that other stimuli prompt eco-design activities. Table 4.3 presents an overview of the results obtained by van Hemel and Cramer (2002) from a survey of 77 SMEs in the Netherlands.

The survey showed that although government regulation played an important role in prompting eco-design activities, other factors – both external and internal – were found to be equally influential.

Table 4.3: Stimuli to eco-design practices – overview of results from a survey of 77 SMEs in the Netherlands (van Hemel and Cramer, 2002)

		External stimuli	Internal stimuli	Barriers
Most frequently mentioned	1	Customer demands	Environmental benefit	Conflict with functional requirements
	2	Government regulation	Cost reduction	No clear environmental benefit
	3	Supplier developments	Image improvement	Commercial disadvantage

4.3.4 Legislative requirements for the end-of-life management of SOFC stacks

Regardless of the effectiveness of environmental legislation on reducing the impact of products across their life cycle, compliance with legislation is a fundamental requirement for any reputable business. From the review of policy and legislation reported in Sections 4.3.1 – 4.3.3 the legislative aspects identified as being directly relevant to the end-of-life management of SOFC stacks are:

- Classification of waste streams as hazardous or non-hazardous
- Restrictions on trans-boundary shipments of waste
- Disincentives to dispose of waste to landfill
- The recent legislative trend promoting EPR through mandatory recycling targets
- The IPP approach, and associated implementing measures

Environmental legislation can be viewed as a constraint on an end-of-life scenario, with the legislative requirements providing boundaries within which the scenario must operate. At the same time, legislation can be viewed as a motivating force for the development of new and improved end-of-life solutions.

One substance of particular interest with respect to end-of-life management of the SOFC stack is nickel oxide, which is commonly used to fabricate the anode component and is classified by European legislation as a category 1 carcinogen. Waste containing nickel oxide in quantities equal to or greater than 0.1 wt% is categorised as hazardous (Environment Agency, 2008). This has the potential to influence the end-of-life model by, for example, determining that early separation of nickel oxide from the bulk material might result in simplified transport and treatment scenarios in subsequent process steps. It is also interesting that nickel metal has a lower hazard classification than nickel oxide, and can be present in waste up to 1 wt% before the waste stream is classified as hazardous (Environment Agency, 2008). During the start-up cycle of the SOFC stack, nickel oxide undergoes a reduction reaction to form nickel metal. This reaction is only reversible if the SOFC stack is shut down under oxidising conditions: therefore the service history of the SOFC stack may have a significant impact on the legislative requirements at end-of-life (Wright *et al.*, 2009).

Another constraint introduced by waste legislation pertains to the geographical aspect of the end-of-life management of SOFC stacks. It is likely that for a company selling to a global market the generation of end-of-life wastes will be widely distributed. If specialised treatment is required the waste may need to be shipped to a dedicated plant. These movements of waste may be restricted under the Basel Convention (Secretariat of the Basel Convention, 2011) or other implementing regulations (European Council, 1993).

Although existing EPR Directives do not apply explicitly to SOFC stacks within stationary systems it is necessary to understand this area of legislation for two principle reasons. Firstly, it is highly plausible that this type of legislation will evolve and that at some point the stationary SOFC systems will have to meet specified end-of-life targets. Secondly, it is likely that SOFC technology will evolve and become incorporated in a wider range of applications which themselves fall within the scope of existing or future legislation. Already SOFC stacks are being considered for applications in auxiliary power units in automobiles (e.g. Baratto *et al*., 2005). In their study of the impact of the ELV Directive on the end-of-life management of PEMFC technology, Handley *et al*. (2002) state that the Directive "...*re-enforces the need to recycle and re-use components of the fuel cell stack"*. Failure to anticipate indirect legislative requirements could preclude or hamper the utilisation of fuel cell technology as a power generation source in other product types.

4.4 Environmental considerations in end-of-life management

As with all industrial processes, end-of-life management of products has an associated impact on the environment. The end-of-life process is likely to incorporate an element of collection and transportation of products; some type of processing, which may require energy and/or material inputs; and potentially disposal of some residual materials. All of these stages will consume resources and release emissions. Some environmental benefits may also be obtained at end-of-life, through the production of recycled materials and the consequent avoidance of impacts arising from virgin material production.

While compliance with environmental legislation should achieve an acceptable level of environmental performance, it is likely that two compliant end-of-life management processes will differ in their overall environmental impact. Therefore, in order to select the most appropriate end-of-life management solution, it is useful to be able to quantitatively evaluate the total environmental impact associated with the end-of-life phase of the product life cycle. Life cycle assessment (LCA) is an appropriate tool for conducting such an evaluation.

4.4.1 Life cycle assessment as a tool for the evaluation of the environmental impacts of products and processes

LCA is an established methodology for evaluating the environmental impacts of products and processes across the complete life cycle (Baumann and Tillman, 2004). One of the earliest examples of an LCA study was commissioned by Coca-Cola to investigate the environmental impacts associated with alternative beverage containers (Darney and Nuss, 1971). Early studies were concerned primarily with solid waste production and were most commonly applied to packaging. Following the energy crisis of the 1970s, more focus was given to life cycle energy consumption. Finally, by the 1990s a broader range of environmental impacts were being considered routinely (Hunt *et al.*, 1996). Since the earliest LCA-types studies, the methodology has been developed and standardised, culminating with the publication of the first series of International Standards between 1997 and 2000 (Marsmann, 2000). In 2006 a revised set of International Standards was released, including ISO14040:2006 on the general principles and framework behind LCA (ISO, 2006a) and ISO14044:2006 on more specific requirements and guidelines for LCA completion (ISO, 2006b).

LCA methodology is highly dependent on data being available to allow quantification of input and output flows for each life cycle stage. This requirement is one of the principal problems facing LCA practitioners. As such, the framework methodology defined by the International Standards Organisation (ISO) provides a degree of flexibility, allowing for individual studies to be tailored in order to accommodate shortcomings in data availability and/or to support specific research goals (Kluppel, 1998). Definition of the goal of the LCA is the initial stage in the ISO methodology (Figure 4.4), and must be defined in combination with the scope of the study and the identification of a functional unit (Guinée *et al.*, 1992).

The goal of an LCA study might be to compare alternative products (e.g. Nicoletti *et al.,* 2003; Kozac, 2003; Nilsson *et al.*, 2010), design concepts (e.g. Franklin Associates, 2008) or processes (e.g. Azapagic, 1999; Ruhland *et al.*, 2000; Burgess and Brennan, 2001), or to develop a baseline understanding of the environmental impacts of a product or process. More recently,

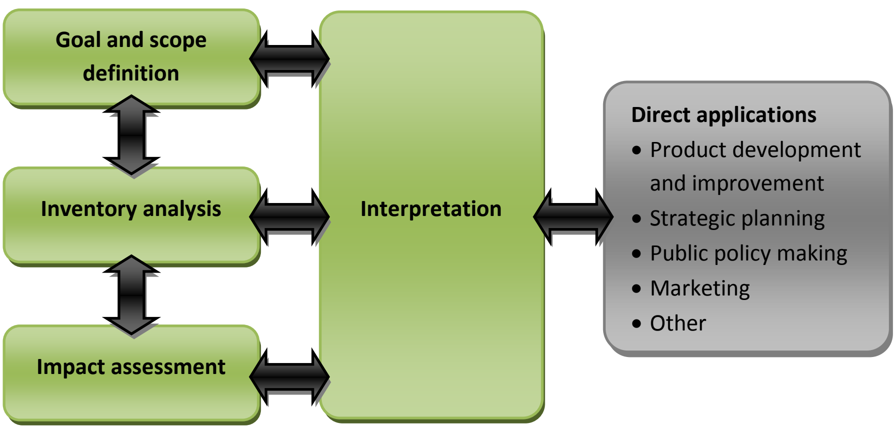


Figure 4.4: LCA methodology, as defined by ISO14040:2006 (ISO, 2006a)

LCA has been used to support declarations regarding the environmental impacts associated with products on the market (Doublet and Jungbluth, 2010; Volkswagen AG, 2010; ABB, 2011). In terms of the scope of a study, a full LCA examines all life cycle stages from “cradle” (extraction of raw materials) to “grave” (final disposal of materials), however, many LCA studies are “cradle to gate”, examining the environmental impacts of a product up to the point of sale. Other LCA studies may focus on a specific stage in the life cycle, such as raw material production; energy production; manufacture; use; or end-of-life.

Based on the defined goal and scope, the next stage in the LCA methodology is the completion of the inventory analysis (Rebitzer *et al.*, 2004). This, in simple terms, requires the quantification and collation of all input and output flows which cross the system boundary. Flows of materials, energy, emissions and wastes are all considered. The development of a comprehensive inventory may be supported by the collection of site-specific data, based on measured processes or design parameters. Alternatively more generic data may be taken from a database or other literature source. Several commercial and open access databases have been developed which provide inventories for individual processes such as transportation, material production, energy generation, waste disposal), with the specific purpose of supporting the completion of LCA studies. The Ecoinvent database (Ecoinvent Centre, 2007) is perhaps one of the most comprehensive commercially available. Regional development of open access databases has been conducted in Europe, resulting in the ELCD database (European Commission, 2010), and in individual European countries, as well as in the USA (National Renewable Energy Laboratory, 2010) and Japan (Narita *et al*., 2005). Various sector-specific life cycle inventories have also been developed by industry associations and other private and public bodies (e.g. LCA Food, 2007; Mortimer *et al.*, 2010 (National Non-food Crops Centre); World Steel Association, 2010; PlasticsEurope, 2011). A comprehensive summary of global life cycle inventory data sources has been compiled by Curran and Notten (2006).

The third step in the LCA methodology requires the input and output flows defined in the inventory to be related to specific environmental impacts. This is achieved through the following steps:

- Classification of inventory data, in terms of identifying the impact categories to which they contribute. Some species may contribute to more than one environmental impact, whereas others may be essentially environmentally benign.

- Application of characterisation coefficients, in order to calculate individual impact category indicators. Characterisation coefficients relate to the extent to which an individual substance contributes to a specific impact category.

These are the two compulsory steps in life cycle impact assessment, as defined by the ISO methodology. Examples of impact categories commonly considered in LCA studies are shown in Table 4.3. Additional optional steps include the normalisation of impact category indicators, to allow the application of weighting factors and grouping to obtain a single figure result (Pennington *et al.*, 2004). The process of life cycle impact assessment is shown in Figure 4.5.

Table 4.3: Examples of environmental impact categories included in the impact assessment stage of LCA (developed primarily from information in Ecobalance, 2000)

Impact category		**Units**	**Cause**	**Effect**	**Examples of relevant inventory species**
ADP	Abiotic Depletion Potential	kg Sb-Equiv.	Consumption of non-renewable resources	Depletion of non-renewable resources.	All non-renewable resources
AP	Acidification Potential	kg SO_2-Equiv.	Release of species which form acidic solutions.	Detrimental impacts on eco-systems and materials, including destruction of fresh-water fish populations and forests, and corrosion of buildings.	SO_2, NO_x
EP	Eutrophication Potential	kg Phosphate-Equiv.	Release of excess quantities of nutrient species (containing nitrogen and/or phosphorous) into the environment.	Detrimental changes in flora and fauna populations.	PO_4, NO_x, NH_3
GWP	Global Warming Potential (100 years)	kg CO_2-Equiv.	Release of species which absorb thermal radiation from the sun.	Increase in the earth's temperature, which has been linked to changes in weather patterns and eco-systems. Melting of the polar ice caps is a specific result of this impact.	CO_2, CH_4, CFCs, SF_6
ODP	Ozone Layer Depletion Potential (Steady state)	kg R11-Equiv.	Release of gaseous species which may rise into the stratosphere and acts as catalysts for the depletion of ozone.	Increased exposure to harmful radiation from the sun, normally blocked by the ozone layer.	Halogenated hydrocarbons, N_2O
POCP	Photochemical Ozone Creation Potential	kg Ethene-Equiv.	Release of species which form photochemical oxidants when exposed to sunlight.	Formation of photochemical oxidants which are detrimental to the health of humans and plants. Summer smog is an effect of this impact.	Hydrocarbons, VOC, CO, NO_x

Different methodologies for conducting environmental impact assessment as part of LCA have emerged. The differences in these methodologies lie principally in the scientific assumptions underlying the development of characterisation coefficients, as well as in the approach taken to the optional additional steps. Some impact assessment methods are concerned with a single issue, such as global warming potential (Intergovernmental Panel on Climate Change, 2007), or cumulative energy demand (Hischier *et al.*, 2010), while others cover a broad range of impact categories.

Examples of impact assessment methods include the CML (Centre of Environmental Science, Leiden University) method (Guinée *et al.*, 2002), EDIP (Environmental Design of Industrial Products) (Hauschild and Wenzel, 1998; Hauschild and Potting, 2004) and TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) (Bare *et al.*, 2003). Other methods, such as Eco-indicator 99 (Goedkoop and Spriensma, 2000) and ReCiPe (Goedkoop *et al.*, 2009) have been specifically developed to produce a single figure result. More detailed discussion of selected impact assessment methods in LCA, and the benefits and drawbacks of different approaches can be found in Dreyer *et al.* (2003).

The final step in the LCA methodology is the interpretation of results. This step is important for ensuring that justifiable conclusions are drawn from an LCA study: the results generated by the application of an impact assessment methodology must be considered in line with

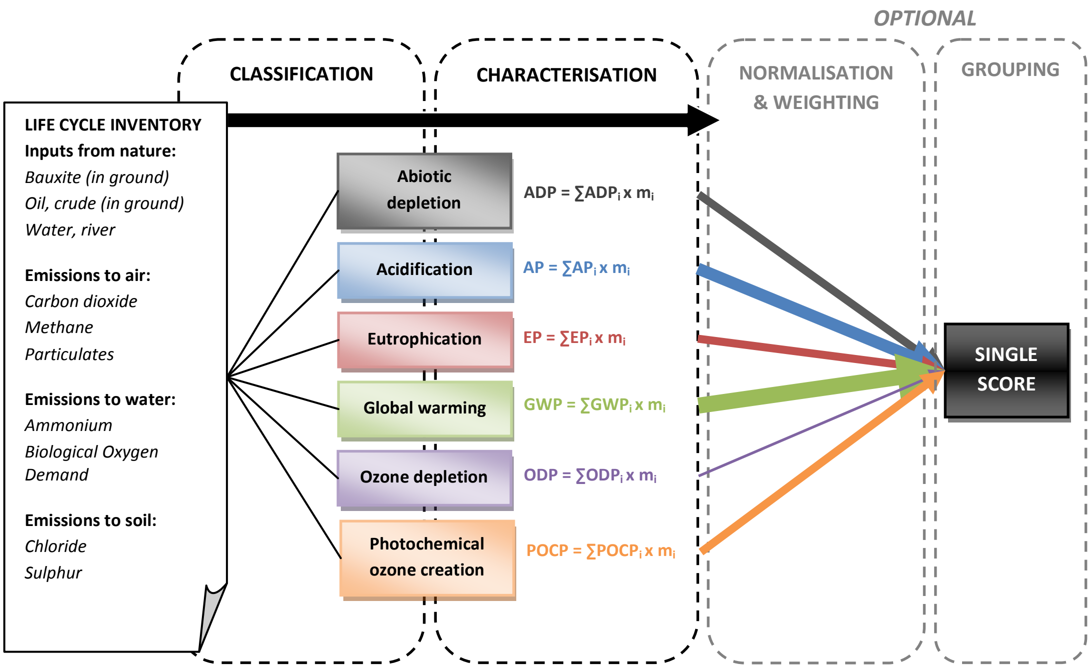


Figure 4.5: Overview of the steps in life cycle impact assessment

assumptions and/or simplifications made during the life cycle inventory analysis.

Various software tools have been developed to support the completion of LCA studies, facilitating the collation of inventory data, the application of impact assessment methods and the analysis of results. The most advanced software packages currently in use globally are GaBi4 (PE International GmbH, 2007) and SimaPro7 (Pré Consultants, 2006).

4.4.2 Life cycle assessment as a tool to support end-of-life decision making

Section 3.3.7 in the previous chapter reviewed published studies reporting the application of LCA as a tool to evaluate the environmental impacts of SOFC technology. It was shown that the end-of-life phase of the SOFC product was in most cases excluded from the scope of the study (Baratto and Diwekar, 2005; Osman and Reis, 2007; Strazza *et al.*, 2010); considered qualitatively (Zapp, 1996; Karakoussis *et al.*, 2000 and 2001); or at best modelled based on very simplistic assumptions (Pehnt, 2003c). As such, the literature does not offer much specific guidance regarding the application of LCA as a tool to evaluate the end-of-life management of SOFC stacks.

The absence of data regarding the end-of-life management of SOFC stacks is not unique to this product. Many LCA studies investigating the environmental impacts of products identify this phase of the life cycle as being poorly understood. Of particular interest are several LCA studies of photovoltaic cells in which an absence of reliable end-of-life data is reported (Battisti and Corrado, 2005; Raugei *et al.*, 2007; Kannan *et al.*, 2006; Azzopardi and Mutale, 2010). Statements such as:

> *"So far, no proven technology has been developed for large-scale disposal of solar PV* (photovoltaic) *modules*." (Kannan *et al.*, 2006)

and:

> *"... the need for the development of specific recycling strategies for the decommissioning of CdTe and CIS PV modules is recognised..."* (Raugei *et al.,* 2007)

are reminiscent of the language used by authors of LCA studies of SOFC technology, quoted in Chapter 1. As well as reporting a lack of data, the authors of such LCA studies often emphasise the importance of obtaining such data, in order to fully understand the life cycle impacts of the technologies and products under review (e.g. Kannan *et al.*, 2006; Zhong *et al.*, 2011). The recognition that the end-of-life phase has potential significance in terms of the life cycle impacts of products which fulfil the same function as SOFC stacks (i.e. the generation of electrical power) further supports the research aims and objectives addressed in the thesis.

It is encouraging to note that knowledge regarding end-of-life management of photovoltaic cells has grown in recent years and has been included with some detail in some more recent LCA studies of the technology (García-Valverde *et al.*, 2009; Berger *et al.*, 2010; Nishimura *et al.,* 2010; Zhong *et al.*, 2011).

With regard to more mature product types, LCA has been applied more directly to support the comparison of alternative end-of-life management routes. Examples from the literature are diverse and include: comparison of nine alternative recovery methods for end-of-life tyres (Clauzade *et al.*, 2010); comparison of recycling, incineration and landfill following pre-treatment, as alternative end-of-life solutions for a car bumper skin (Le Borgne and Feillard, 2001); identification of the lowest environmental impact recycling process for mobile phone networks (Scharnhorst *et al.*, 2005); development of a modified LCA approach to evaluate alternative reuse, recycling and remanufacturing options for a domestic fridge (Gehin *et al.*, 2009).

4.5 Economic considerations in end-of-life management

Although the identification and implementation of an end-of-life management solution with low environmental impact is important, a truly sustainable end-of-life solution will also be economically viable. Macauley *et al.* (2003) provide a breakdown of costs associated with the end-of-life management of electronic waste. Costs of collection, transportation, recycling processes, storage, incineration and disposal all contribute to the overall cost of the end-of-life phase of the product life cycle. In addition to these inherent costs, the use of financial measures to implement environmental policy can also contribute to the overall costs of waste management.

This is exemplified most clearly by Landfill Tax. Further to the legislation governing landfill of wastes, various countries, including the UK, have established landfill tax as an additional measure to divert waste to alternative treatments. The Landfill Tax system was introduced in the UK in 1996. Two years after its introduction a study was carried out to assess its contribution to sustainable waste management (Morris *et al.*, 1998). The tax was described as being purposefully designed to achieve the joint aims of increasing the cost of landfill as a waste disposal option, to ensure the price would *"reflect its environmental cost"* and to encourage a reduction in waste generation and an increase in reuse and recycling. Morris *et* *al.* summarise the results from a review of the legislation by the Customs and Excise Department, which include reports that the tax had prompted one third of companies to review their waste management strategies, and survey results indicating two thirds of businesses, councils and contractors had implemented waste reduction measures. The survey also reveals that a substantial proportion of respondents had observed an increase of around 10% in waste disposal costs. Little impact was observed on domestic waste generation (Morris *et al.*, 1998).

In the years since the study by Morris *et al.* (1998), landfill tax has been incrementally increased and currently stands at £56 per tonne for general waste. A lower rate is charged for inert waste. In the 2004 Budget, the standard rate was forecast to increase by £3 per year up to a limit of £35 per tonne. In the pre-budget report of November 2008, this annual increase was confirmed as rising to £8 per tonne, as illustrated in Figure 4.6 (H.M. Revenue and Customs, 2010). When compared with other waste treatment options, the addition of landfill tax to the standard gate fee results in landfill being generally more expensive, as shown in Figure 4.7. (WRAP, 2010).

A similar situation is reported in the Netherlands, where costs of disposal to landfill have increased significantly since the 1980s. The legislation controlling landfill sites introduces permit requirements and operational standards which have associated costs and add to the basic charge per unit of waste. It is reported that the differentiation of rate for the disposal of hazardous and recyclable wastes to landfill has made separation for recycling economically

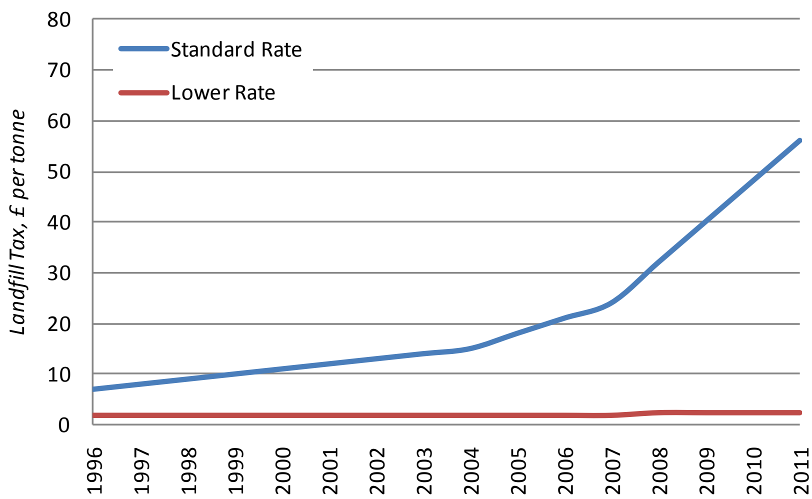


Figure 4.6: Landfill tax was charged at £7 per tonne on its introduction in 1996. The standard rate currently stands at £56 per tonne, with an annual increase of £8 in place since 2008. (Data from H.M. Revenue and Customs, 2010).

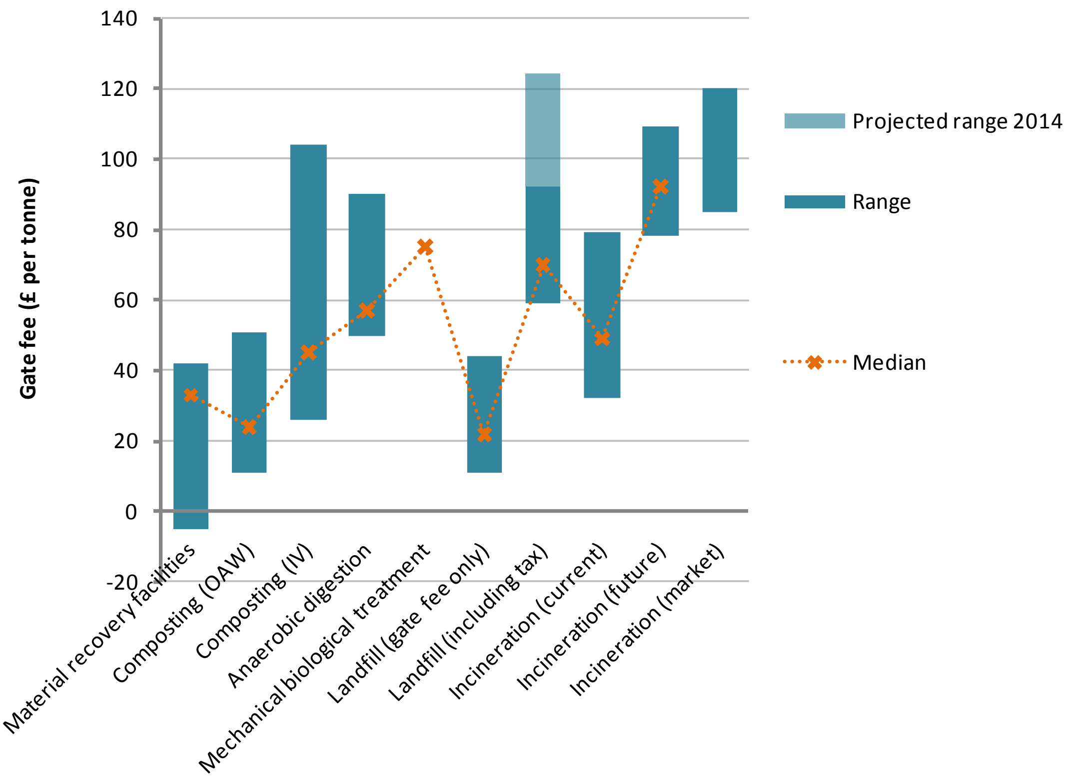


Figure 4.7: Costs of alternative waste treatment processes in the UK (data from WRAP, 2010).

viable in some cases. Batteries are cited as an example, where the costs of disposal to landfill increased eightfold since the 1980s, to around €2,200 per tonne in the 1990s (Krozer and Doelman, 2003).

As well as the costs associated with end-of-life management, it is possible that revenue can be generated through the recovery of valuable materials. Indeed, for valuable metals such as platinum and palladium, recycling rates are high (Materials KTN, 2011). While high market values for recycled materials can provide an attractive incentive for good end-of-life management of products, fluctuations in the market are a risk for those investing in the development of recycling infrastructure and product take-back schemes (Rahimifard *et al.*, 2009).

4.6 Multi-criteria decision making in end-of-life management

Zeleny (1982) captures the tautological nature of the phrase “multi-criteria decision making” in his introduction to the decision making process:

> *“...whenever we face a single attribute...there is no decision making involved. The decision is implicit in the measurement...It is only when facing multiple attributes, objectives, criteria, functions, etc., that we can talk about decision making and its*

> *theory. As alternatives of choice become more complex and are characterised by multiple attributes as well as multiple objectives, the problem of combining these various aspects into a single measure of utility becomes more difficult and less practical."*

However, by formalising the decision making process, it is possible to collate, organise and evaluate all available information using a structured approach, such that decision makers can feel that all factors have been considered properly and can therefore have confidence in the outcome from the decision making process (Belton and Stewart, 2002). Belton and Stewart (2002) dispel some common myths regarding multi-criteria decision making, indicating that the approach will not guarantee a "correct" answer, nor will it ensure an objective analysis of the situation. Rather, they argue, a formal multi-criteria decision process allows subjectivity to be dealt with in a fully transparent manner. They emphasise the importance of understanding multi-criteria decision making as being as much about developing an understanding of the controversies surrounding the decision process, as being about the decision outcome. As such, multi-criteria decision methods should be considered to support decision making rather than provide definitive answers to problems.

Seppala *et al.* (2002) define the distinction between multi-attribute decisions, where a finite number of choices are available to the decision maker, and multi-objective decisions, where an infinite number of options are available. The selection of a preferred end-of-life solution from a defined number of alternatives would therefore require a multi-attribute decision making process to be adopted. Defined methods for multi-attribute decision making range from very simple approaches, classified by Seppala *et al.* (2002) as "Elementary", to more complex methods such as the Analytical Hierarchy Process. Wang *et al.* (2009) provide a more detailed review of alternative methodologies, including comments on the merits and drawbacks of each. Belton and Stewart (2002) indicate that even the most simple of multi-criteria decision making methods can be effective.

The life cycle impact assessment step of the LCA methodology described in Section 4.4 itself incorporates a multi-criteria decision approach (Seppala *et al.,* 2002) in the optional normalisation, weighting and grouping steps. Common features are normalisation (a process which allows dissimilar metrics to be considered together) and weighting (whereby different performance criteria are assigned relative importance) which allows the development of single-figure impact scores.

4.7 Summary

The review documented in this chapter has explored the principal challenges associated with end-of-life management. It is clear that end-of-life management has close links with broader concepts such as Sustainable Design and Industrial Ecology. Increasingly, environmental policy and legislation place emphasis on the end-of-life management of products, such that manufacturers are under pressure to meet stipulated recycling and recovery targets. However, as well as working towards legislative compliance, it is also important to quantify the environmental and economic impacts of the end-of-life phase of the product life cycle in order that end-of-life management is not only compliant, but also sustainable. The complexity of the issues identified with relation to end-of-life management justifies the requirement for a framework to support further exploration of alternative end-of-life scenarios for SOFC products. This framework is developed in Chapter 6, following an overview in Chapter 5 of the methodology adopted in carrying out the research reported in the thesis.

CHAPTER 5 RESEARCH METHODOLOGY

5.1 Introduction

This chapter describes the methodology adopted in carrying out the research reported in the thesis. The chapter begins with an overview of common research methodologies, identifying the principal characteristics of each. This provides the context against which the methodology used in the current research is developed and rationalised.

5.2 Overview of research types

Many different types of research exist and are useful for addressing a broad range of questions and problems. Kumar (2005) suggests that any specific research activity may be defined in terms of three principal attributes, namely its application, its objectives and its inquiry mode. These attributes are represented in Figure 5.1.

With regard to application, two possibilities are identified – research may either be pure or applied. In the case of pure research, the focus of the research may be an intellectual concept or hypothesis which may or may not have practical application at the time at which the research is conducted, or in the future. Pure research may also be concerned with the development and refinement of research techniques, procedures and tools, where the

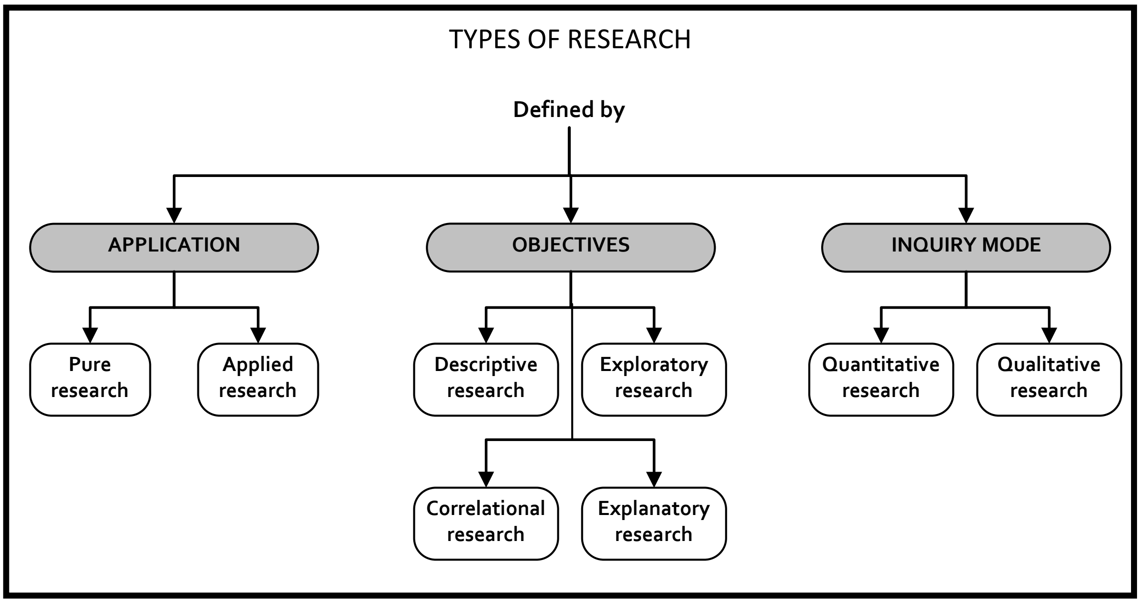


Figure 5.1: Overview of different research types (adapted from Kumar, 2005).

knowledge gained from the research adds to the existing body of knowledge of research methods. In applied research, research methods are applied in order to collate information about a specific situation, problem or issue, such that some further purpose may be achieved. Following the definition of the research aim and objectives in Chapter 2, it has been identified that the thesis will incorporate primarily applied research, since it is concerned with the investigation of a specific problem (namely the end-of-life management of the SOFC stack), with an element of pure research, since it is concerned also with the development and validation of an evaluation methodology which incorporates both existing and novel evaluation tools.

Kumar further classifies research types based on the objectives of the research. Where the objective is to systematically collate information in order to “describe what is prevalent”, the research is classified as descriptive (Kumar, 2005). Correlational research aims to prove or disprove the existence of an association between two or more aspects of the situation being studied, while explanatory research aims to provide an explanation of how or why such an association exists. Finally, exploratory research describes the early stages of research into a field about which little is known, in which case a small scale study may be carried out prior to the development of more detailed objectives. In addition, exploratory research describes that which has the principal objective of testing and refining evaluation procedures and tools.

Within the thesis, it is necessary to employ a research methodology encompassing a range of approaches, in order to address the objectives defined in Chapter 2. Descriptive research is required in order to develop a thorough understanding of the nature of end-of-life waste arising from SOFC stacks, relevant legislative requirements and possible scenarios for end-of-life management. The evaluation of alternative end-of-life scenarios and analysis of the findings from case studies is considered to incorporate both correlational and explanatory research. The use of exploratory research is required in defining the initial research aims and scope, following the completion of a literature review, and is also required in assessing the suitability of various evaluation tools employed in the later stages of the thesis.

Finally, Kumar (2005) suggests that research type may also be defined in terms of the inquiry mode employed, with research being classified as either quantitative or qualitative. Within the thesis, the emphasis is primarily on quantitative methods, such as life cycle assessment and cost-benefit analysis, which are data driven. Qualitative methods will be employed to evaluate legislative compliance, and are useful in supporting the development of the research in areas where data are unavailable and/or unreliable.

Effective integration of these different types of research into a coherent methodology will provide a systematic approach to addressing the research aim and objectives defined in Chapter 2. This research methodology is described in Section 5.3.

5.3 Research methodology

The research methodology adopted in the research is based on a conventional four-stage approach (Greenfield, 1996), which begins with the definition of the research hypothesis and the refinement of this hypothesis into specific aims and objectives. The following stages are: theoretical research in which frameworks and models are developed; the testing and validation of the theoretical research using case studies; and finally the analysis of research results. These stages of the research methodology as applied in the thesis are illustrated in Figure 5.2.

The research assertion and hypothesis are originally defined based on the author’s prior knowledge and experience of SOFC technology and end-of-life management requirements. This knowledge is then further developed by conducting an extensive review of the literature, regarding both the technology and various aspects of end-of-life management. Legislative requirements are explored, to determine current and future requirements of relevance to the end-of-life management of the technology. Evaluation methods previously used to support decision making in end-of-life management of other technologies and products are also reviewed, to provide knowledge on which a new evaluation methodology can be based.

During the period in which the early part of the research was conducted, the author was closely involved with the industrial partner, Rolls-Royce Fuel Cell Systems Limited in Loughborough and Derby, gaining practical experience of the challenges of end-of-life management of the SOFC stack. This involvement included the co-ordination of a complementary research project between the industrial partner and the Singapore Institute of Manufacturing Technology, in which novel processes for recovering materials from end-of-life SOFC components were explored at a laboratory level. In addition to this, a programme of visits was conducted, with representatives from the industrial partner, to potential commercial partners in a future end-of-life supply chain.

The additional knowledge gained from continuing literature review activities and practical experience informs the development of the research assertion and hypothesis, and the refinement of a specific research aim, supported by clear objectives and scope.

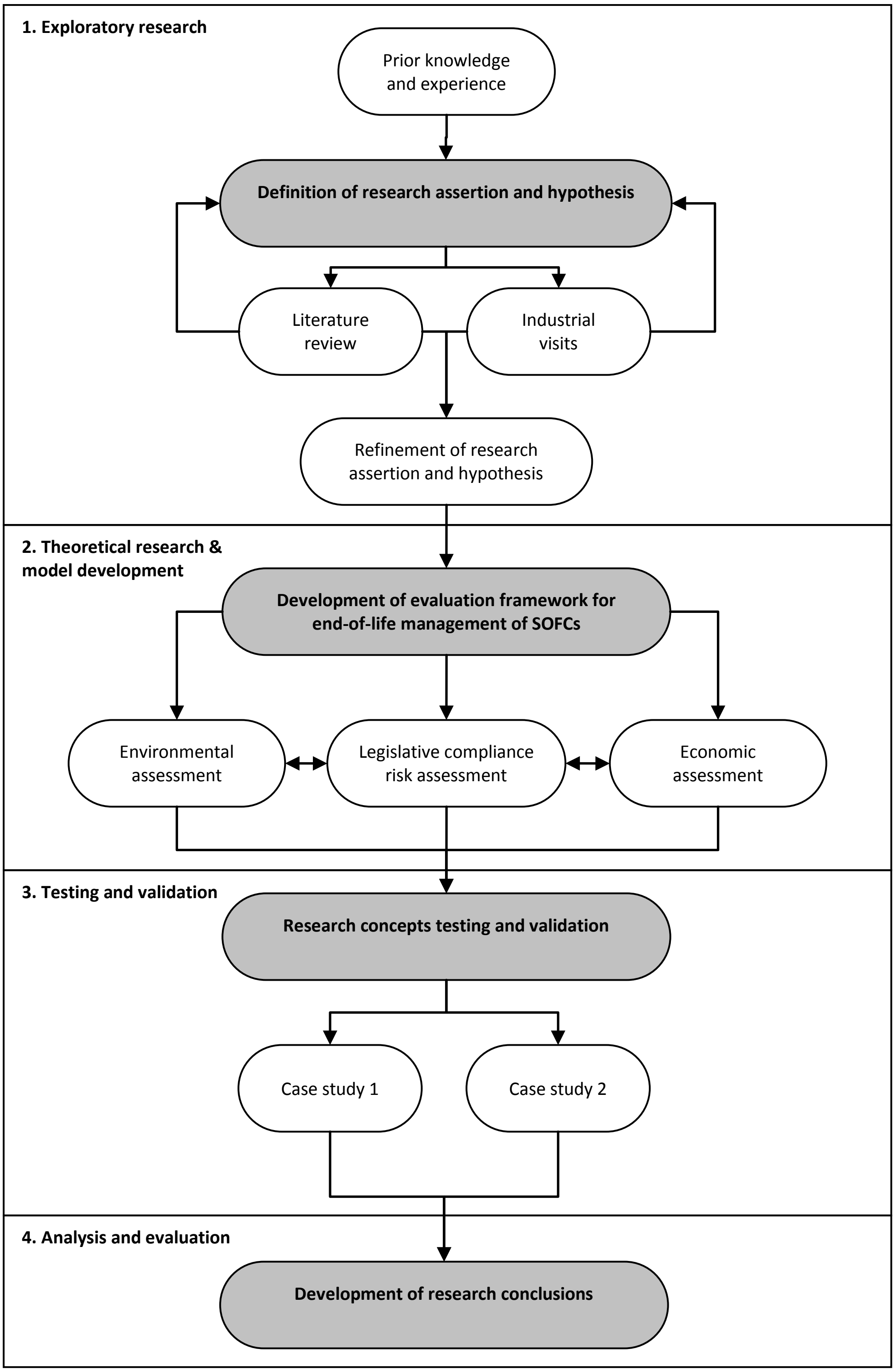


Figure 5.2: Research methodology applied within the thesis.

The theoretical research and model development is focused on the development of framework by which alternative end-of-life scenarios for the SOFC stack can be defined, assessed and compared. Based on the research objectives, the evaluation methodology adopted in the framework is required to evaluate legislative compliance, environmental performance and economic performance. With respect to environmental and economic performance, existing evaluation methods are available, namely life cycle assessment and cost-benefit analysis respectively. This phase of the research requires the development of an integrated multi-criteria decision support tool which employs these existing evaluation methods, in combination with a novel method for evaluating legislative compliance.

The third phase of the research involves the validation of the research concepts, namely the framework for end-of-life management of SOFC stacks, through two case studies. The case studies will be selected to test two different applications of the framework; the first dealing with straightforward scenario comparison (i.e. reactive application) and the second exploring the impact of design on end-of-life management (i.e. proactive application). A systematic approach will be developed to conduct both of the case studies, with data collated from a variety of primary and secondary sources.

The final phase of the research methodology is to analyse the findings from the case studies, and, in the context of all research results documented in the thesis to draw some overall conclusions. These conclusions, and a discussion of their value and limitations, are provided in Chapters 11 and 12 of the thesis.

Although the methodology presented in Figure 5.2 suggests a linear progression through the four stages defined in this section, it is acknowledged that research has an iterative nature, such that specific aspects may require revisiting and refinement in light of new findings, as the research progresses.

5.4 Summary

This chapter has identified the different types of research utilised in the thesis, based on the requirement to address the research aim and objectives identified in Chapter 2. Following this general overview, the research methodology adopted in the thesis has been presented. The four phases of the research methodology have been illustrated schematically, showing the chronological development of the thesis. The research supported by the first phase of the methodology is reported in the earlier part of the thesis, in Chapters 1 – 4. The rest of the thesis documents the research findings supported by phases two, three and four of the research methodology.

CHAPTER 6 A FRAMEWORK FOR END-OF-LIFE MANAGEMENT OF SOLID OXIDE FUEL CELLS

6.1 Introduction

In this chapter a framework for end-of-life management of SOFC stacks is developed. The philosophy behind the framework and its relationship to the waste management hierarchy is presented in the initial section. The framework is constructed in four stages as outlined in the later sections of the chapter. Finally, the opportunities for applying the framework, and its limitations, are discussed.

6.2 End-of-life management of solid oxide fuel cells

The fundamental principles of the waste management hierarchy provide the most obvious foundation for the development of an end-of-life management solution for SOFC stacks. These principles have been adopted at an international level and identify the reduction of waste at source as the preferred approach to waste management, followed by reuse, recycling and, only as a last resort, disposal to landfill.

Figure 6.1 shows a schematic of the waste management hierarchy, developed within the research, which outlines the means by which compliance with the principle can be approached within end-of-life management. Reduction of waste volume and toxicity by addressing the primary source (namely the product design) can be considered to be a proactive approach to end-of-life management. This requires early consideration of how design and materials selection define the waste streams arising from end-of-life products. Similarly, the opportunities for reuse of components will be significantly improved if disassembly considerations are incorporated at the design stage.

Reducing waste by recycling the materials contained within end-of-life products requires segregation and purification of different material-types in order to produce useful inputs to downstream processes, whether in a closed-loop scenario (where the recycled material is re-supplied for use in the original application) or in an open-loop scenario (where the recycled material is supplied for use in a new application). While incorporating recyclability into design by careful materials selection is a proactive approach to end-of-life management, recycling can also be applied in a reactive approach as most end-of-life products offer some opportunity for

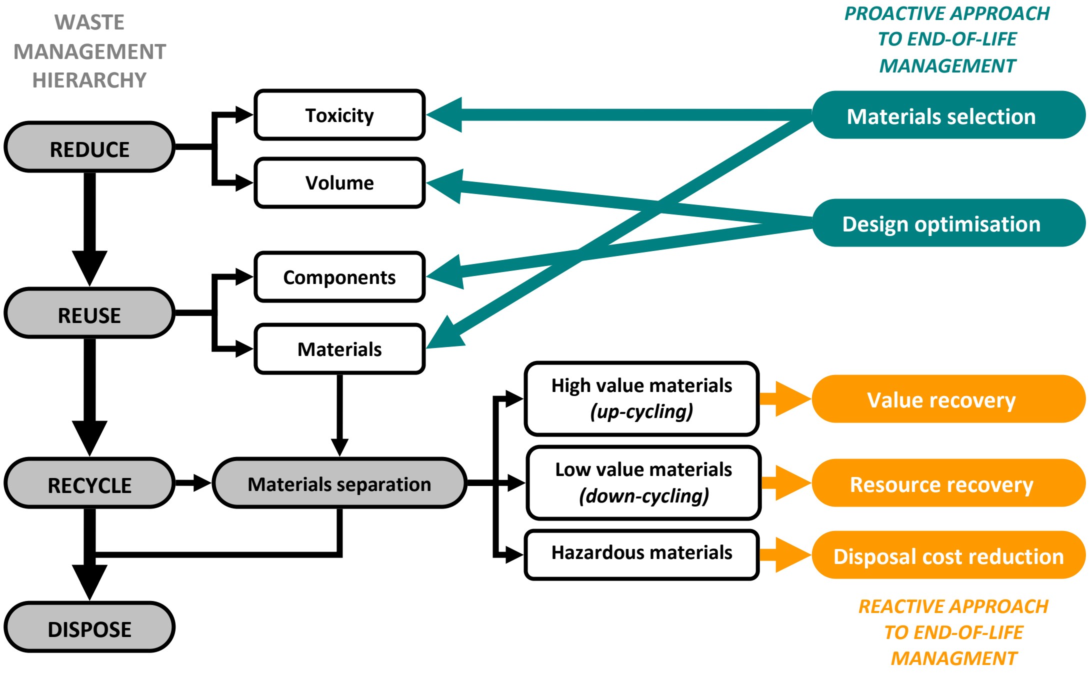


Figure 6.1: A representation of the waste management hierarchy applied to end-of-life management.

the recovery of useful materials. As a last resort, disposal may be considered for any non-recyclable fraction. The separation of hazardous materials from a non-hazardous bulk waste stream prior to disposal may have benefits from both environmental and economic perspectives.

A proactive approach to end-of-life management clearly supports the preferred routes of reducing waste at source and reusing components; however, there may be barriers to applying this approach to novel products, such as SOFC stacks, which are based on immature technologies. During early product or technology development, the focus of the design process is likely to be heavily dominated by technical, reliability and cost requirements. Therefore, it is proposed that an initial solution to end-of-life management must be developed in reaction to an initial product (or prototype) design. During the development of this solution, a body-of-knowledge will be generated. This body-of-knowledge should determine the limitations of existing waste management capability in coping with the requirements posed by the novel product. Where limitations exist these may be eliminated either by modification of the design in future product development, or, if this is not possible, by the development of new waste management processes. It is anticipated that most product manufacturers will be more inclined to invest in design improvement than in the development of a bespoke waste treatment capability. This evolution from a reactive to proactive approach to end-of-life management is illustrated in Figure 6.2.

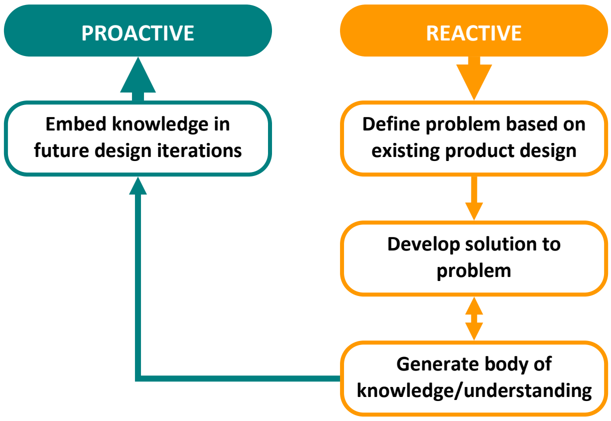


Figure 6.2: Illustration of how a reactive approach to end-of-life management can evolve into a proactive approach.

The end-of-life framework presented in the remainder of this chapter therefore supports a reactive approach to end-of-life management, based on the challenges posed by existing SOFC stack concepts. The framework supports the selection of a practically feasible solution for end-of-life management of this novel product, based on defined performance criteria. During the selection process supported by the framework, a body of knowledge is generated which can support the future implementation of a more proactive approach to end-of-life management of SOFC technology.

6.3 The SOFC-EOL framework

Figure 6.3 provides an overview of the framework developed to support end-of-life management of SOFC stacks, referred to hereafter as the SOFC-EOL framework. The SOFC-EOL framework has been developed with a modular structure and comprises four distinct stages.

The initial stage in the framework is concerned with the development of a detailed definition of the end-of-life management problem. This requires characterisation of the end-of-life product stream and analysis of the legislative constraints within which any end-of-life solution must operate.

In the second phase of the framework, alternative end-of-life scenarios are defined based on initial studies of existing waste management capability and laboratory studies of alternative processes. Within the research, three different end-of-life process routes are identified as being practically feasible for application to existing SOFC stack concepts, incorporating a range of different material separation and recycling processes.

Evaluation of the defined end-of-life scenarios is performed in the third and fourth stages of the framework. In the third stage, three individual aspects of the end-of-life management

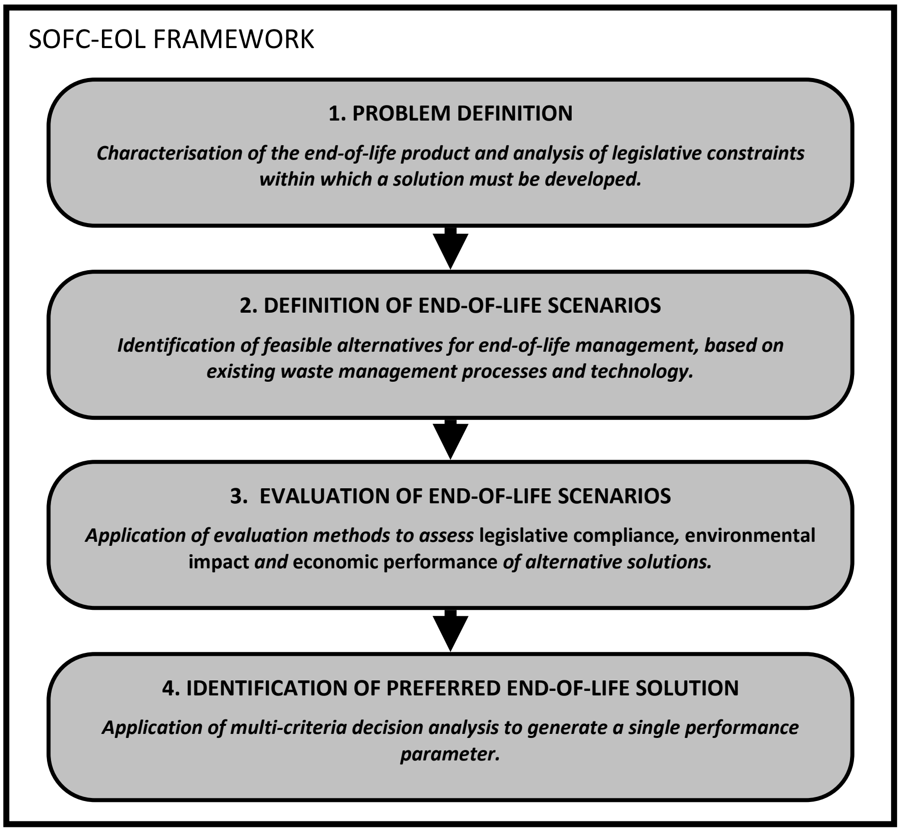


Figure 6.3: The four stages in the SOFC-EOL framework

scenario are assessed separately. The three performance criteria identified as being critical to the feasibility of any end-of-life solution are legislative compliance, environmental impact and economic performance. In the final stage of the framework, a multi-criteria decision support tool is applied to combine the output from stage three into a single factor, which may be used to direct the selection of a preferred end-of-life solution.

With reference to the approach discussed in Section 6.2, the output from stage four determines a short to medium-term solution for end-of-life management of SOFC stacks, while the additional knowledge generated in stage three provides a foundation which may be used to direct the development of a proactive, long-term solution, by influencing future product design iterations. The individual stages of the framework are described in more detail in the following sections.

6.3.1 Stage 1 - Problem definition

The first stage of the SOFC-EOL framework involves the definition and collation of all parameters which may constrain or dictate the nature of the end-of-life solution, as illustrated in Figure 6.4.

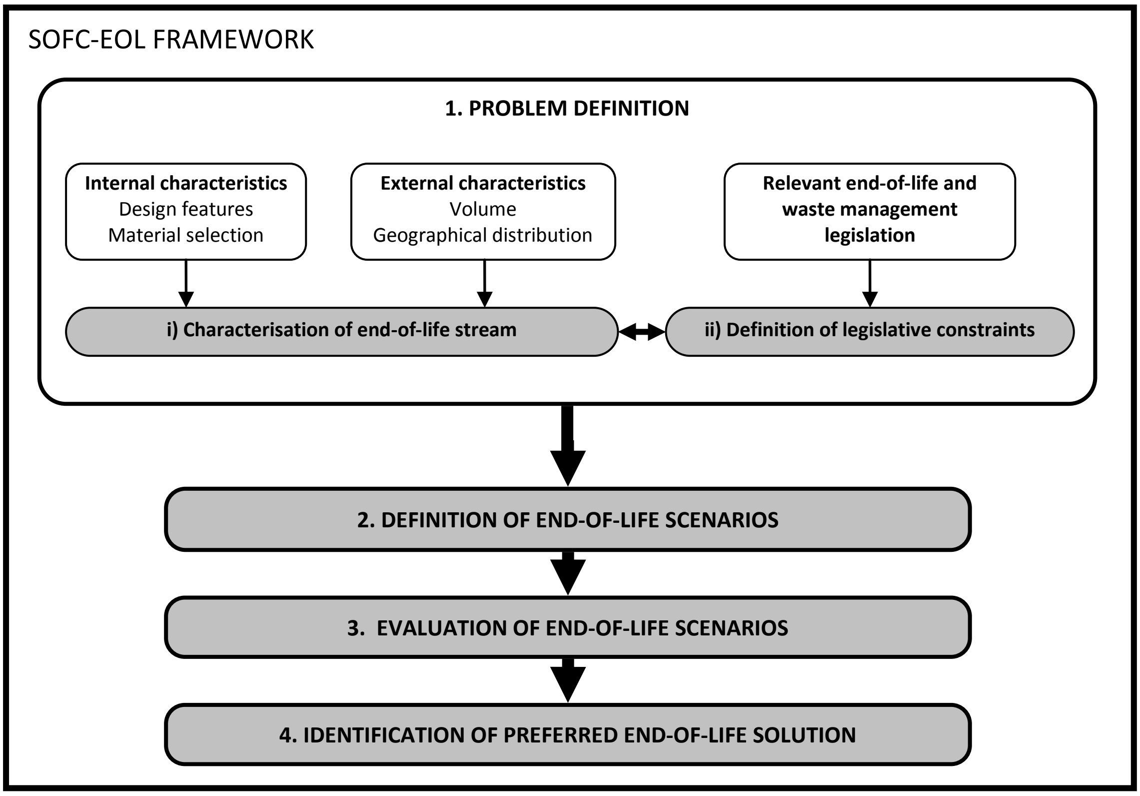


Figure 6.4: Stage 1 of the SOFC-EOL framework showing definition of the problem by characterisation of the end-of-life stream and identification of legislative constraints.

Within the Problem Definition stage these constraining factors are identified as arising from:

i) the characteristics of the end-of-life product stream

ii) end-of-life and waste management legislation

6.3.1.1 Characterisation of the end-of-life product stream

The end-of-life stream can be defined in terms of its internal and external characteristics. Internal characteristics are those defined principally by the product design, while external characteristics are defined by external influences, such as market performance. Table 6.1 summarises the characteristics of the end-of-life stream which are considered relevant to the development and evaluation of an end-of-life solution and as such are considered within Stage 1 of the SOFC-EOL framework.

The internal characteristics of the end-of-life stream can be identified by analysis of existing SOFC stack concepts in order to establish principal design features and the materials selected for fabrication.

Table 6.1: Defining characteristics of the end-of-life stream and their classification as internal or external

Characteristic	Relevance to EOL management solution	Defining influence	Classification
Physical properties	• Weight, strength, toughness of materials influence suitability of mechanical separation techniques • Weight influences transport requirements	Product design	Internal
Chemical properties	• Presence of hazardous/toxic substances influence handling/transport/disposal requirements • Chemical composition Influences suitability of chemical recycling processes	Product design	Internal
Value	• Influences economic feasibility of material recovery and recycling processes	Product design	Internal
Volume of end-of-life waste	• Influences economics of end-of-life processing and decision for localised or centralised end-of-life treatment	Product lifetime/ Market behaviour	Internal/ External
Geographical distribution	• Influences whether central treatment plant or localised end-of-life management is required • Determines transport requirements and local legislative constraints	Market behaviour	External

Within the first stage of the SOFC-EOL framework, the following specific aspects are considered:

i) Material composition

- Identification and quantification of materials present in the SOFC stack product
- Identification of hazardous and valuable materials which may be of particular interest at the end-of-life stage.

ii) Manufacturing processes

- Identification of principal processes utilised in the fabrication of the SOFC stack
- Characterisation of material/component interfaces

iii) Effects of service

- Identification of any likely changes in the SOFC stack after use, arising from exposure to contaminants, loss of material and degradation processes.

For the SOFC stack, which has not yet been adopted into a commercial market, the external characteristics of the end-of-life stream are harder to define. Volumes of end-of-life waste may be predicted based on commercial targets and business scenarios; however, these are subject to change, depending on the success of the new technology in breaking into the energy market-place. Similarly, some idea of the likely geographical distribution of end-of-life products may be generated from business plans and knowledge of the geographical distribution of energy demand; however there is likely to be much uncertainty in predicting real future scenarios. Therefore, within the current research, these external attributes are considered primarily in a qualitative manner.

6.3.1.2 Specification of legislative constraints and requirements

After the product system has been fully characterised, the legislative constraints and requirements for the end-of-life management solution are defined. Whereas general requirements can be defined from knowledge of environmental legislation in isolation, the specific requirements are determined in relation to the characterised end-of-life stream. Factors such as the content of hazardous materials and transportation requirements impact the relevance of some individual pieces of legislation. Any specific requirements arising from the geographical location of end-of-life SOFC stack assemblies and/or waste treatment facilities are also determined in this stage of the framework. In some cases, legislation may prohibit certain actions to be included in the end-of-life management process (constraints); in other cases legislation may introduce administrative requirements with associated economic burden (requirements). Both constraints and requirements are defined in this initial stage of the SOFC-EOL framework.

6.3.2 Stage 2 - Definition of end-of-life scenarios

Whereas the initial stage of the framework defines the problem posed by end-of-life SOFC stack assemblies, the second stage defines potential solutions to the problem, as shown in Figure 6.5. The end-of-life management of the SOFC stack is a largely unknown field, and therefore the second stage of the framework incorporates a significant portion of the research novelty of the thesis.

The first step in this stage of the SOFC-EOL framework is the identification of feasible end-of-life scenarios. These scenarios are developed based on existing end-of-life processes and technologies, evaluated for their applicability to the SOFC stack end-of-life stream. In addition some laboratory scale trials are required to evaluate the feasibility of customising processes to meet the specific requirements of the SOFC stack.

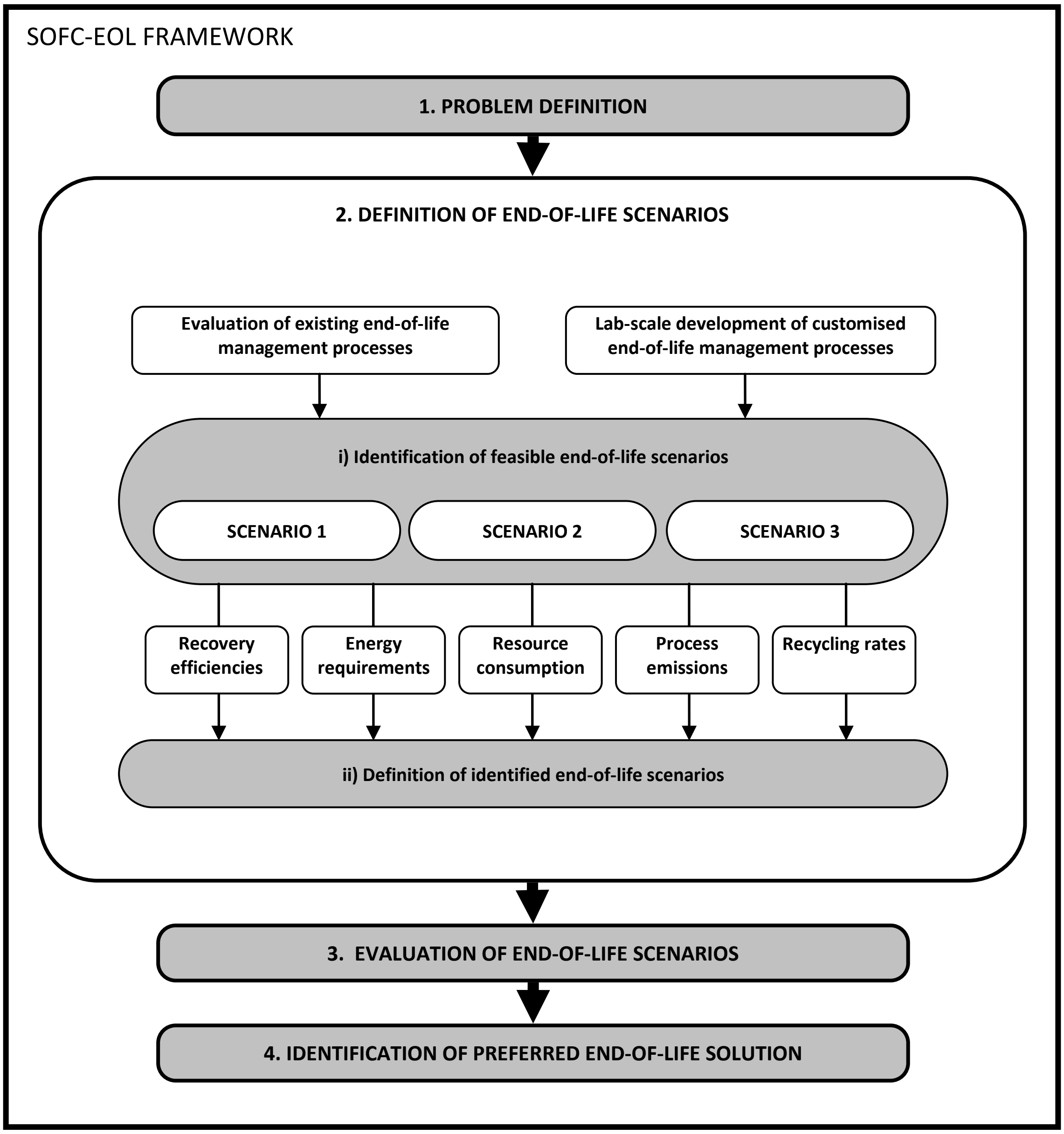


Figure 6.5: Stage 2 of the SOFC-EOL framework showing identification and definition of alternative end-of-life scenarios.

Based on the data available in the current research, three feasible alternative end-of-life solutions were developed, although the framework supports comparison of any number of alternative process routes. In the first scenario a mechanical process was used to separate materials within the end-of-life SOFC stack assemblies, allowing selective recycling to be implemented. The second scenario followed a similar process, using a chemical process in the first material separation step. Finally, the third scenario employed a non-specific recycling route. The development of these three scenarios is described in Chapter 8.

Following the identification of feasible end-of-life scenarios, the framework requires these processes to be defined in sufficient detail for evaluation using the methods applied in stage three. Important parameters requiring definition are those which are most likely to affect the legislative compliance, environmental impact and economic performance of the end-of-life phase. Examples of these are shown in Figure 6.5. The definition of alternative end-of-life scenarios are based on a range of documented assumptions which can be updated as knowledge of end-of-life management of SOFC stack assemblies develops prior to commercialisation. As described in Section 6.2 the approaches defined in the current work are reactive, based on recovery and recycling of materials from end-of-life assemblies. Although three end-of-life scenarios are defined within the current research, the SOFC-EOL framework has sufficient flexibility to allow for the definition and comparison of any number of alternative end-of-life options.

6.3.3 Stage 3 - Evaluation of end-of-life options

The requirements of the end-of-life management solution are based on environmental and economic performance, as well as compliance with relevant legislation. In the third stage of the framework these three aspects are evaluated individually before being integrated in the final stage of the framework (Figure 6.6).

6.3.3.1 Evaluating legislative compliance

In the SOFC-EOL framework, compliance is evaluated based on the specific legislative requirements and constraints determined in stage one. It is essential that any end-of-life management solution is compliant with the relevant legislative requirements: non-compliant operations can be immediately discarded. However, the compliance evaluation provides a more detailed assessment of the proposed end-of-life solution within the defined legislative climate. Risk of future non-compliance and the introduction of tighter controls are assessed and contribute to the decision support tool. This aspect of the SOFC-EOL framework reflects the fact that legislation is constantly changing and it is good business practice to anticipate rather than react to change. In addition, legislative requirements change with growth of business; for example a research and development facility with minimal throughput is exempt from many of the requirements which apply to large-volume production facilities. This is an important aspect for the SOFC industry, which is currently at the very beginning of commercial activity.

6.3.3.2 Evaluating environmental impact

The environmental performance of the end-of-life management solution is the aspect of greatest interest to the current research. As described in Chapter 1, SOFC technology is

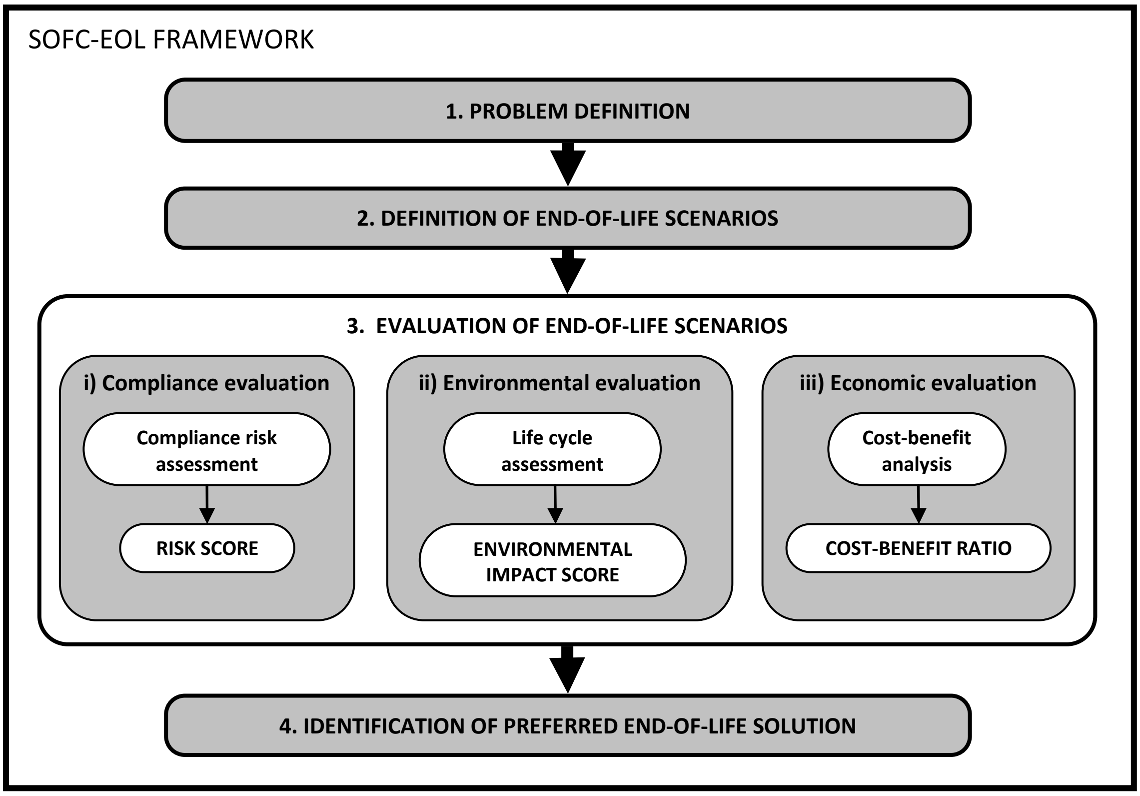


Figure 6.6: Stage 3 of the SOFC-EOL framework showing the generation of three performance parameters for each end-of-life scenario.

believed to offer power generation with a lower environmental burden when compared with traditional power generation technologies. Environmentally responsible management of end-of-life waste is a high-profile issue across all industry sectors, and failure to demonstrate responsibility is detrimental to the image of businesses and products. The assumption underlying the current research is that the environmental nature of SOFC technology only acts to increase the sensitivity of stakeholders to this issue.

Environmental evaluation within the SOFC-EOL framework is based on the use of life cycle assessment (LCA). LCA is a well established methodological approach used to obtain a quantitative evaluation of selected environmental impacts, and its application has been reviewed in some detail in Chapter 4. LCA requires as an input a complete inventory (including all energy and resource consumption and outputs in the form of wastes, emissions and recovered materials) for the end-of-life scenario. The outputs from LCA are presented as numerical values relating to selected environmental impacts. Methodologies for evaluating a wide range of environmental impact factors are reported in the literature and are available for use; however, within the SOFC-EOL framework only the impact factors identified as being of significant interest to SOFC developers are included. Detailed information on LCA methodology and its application in the SOFC-EOL framework are discussed in Chapter 9.

6.3.3.3 Evaluating economic performance

In order for the end-of-life solution to be adopted by businesses, the economic implications need to be understood and must not be prohibitive to the profitability of the SOFC product. A cost-benefit model is developed to quantify the costs of implementing a proposed end-of-life process and the revenues generated from recovery of valuable materials from the recycling steps. The overall economic performance is presented as the benefit-cost ratio arising from each end-of-life management scenario. The methodology for performing economic evaluation of alternative end-of-life management scenarios is described in more detail in Chapter 9.

Within the current research, environmental performance is considered to be the dominant factor, and therefore its assessment is carried out in detail using LCA. Economic performance is considered to be a less critical factor in the selection of an end-of-life solution; however, this parameter is still important in supporting or disregarding a proposed end-of-life solution. This weighting is determined in the final stage of the SOFC-EOL framework, and reflects the purpose of the framework in delivering an environmentally responsible end-of-life solution while acknowledging the practical requirement for that solution to be economically viable.

6.3.4 Stage 4 - Identification of preferred end-of-life solution

In the final stage of the SOFC-EOL framework, a multi-criteria decision support tool is developed to combine the output from the legislative compliance risk assessment, environmental, economic and evaluations. Multi-criteria decision making is a recognised approach to dealing with decisions involving several non-comparable requirements and its general application, benefits and limitations are discussed in Chapter 4. The SOFC-EOL framework utilises a bespoke multi-criteria decision support tool, the development of which is reported in Chapter 9 of the thesis. Using this tool, priorities are defined for each of the three individual evaluation criteria and an overall performance score is generated for each proposed end-of-life scenario. This EOL performance score is calculated to support the selection of an end-of-life solution which most effectively meets the legislative, environmental and economic requirements, as illustrated in Figure 6.7.

6.3.5 Application of the SOFC-EOL framework

Considering the immaturity of SOFC technology, the SOFC-EOL framework described in this chapter is intended to be applied primarily in a reactive approach to end-of-life management.

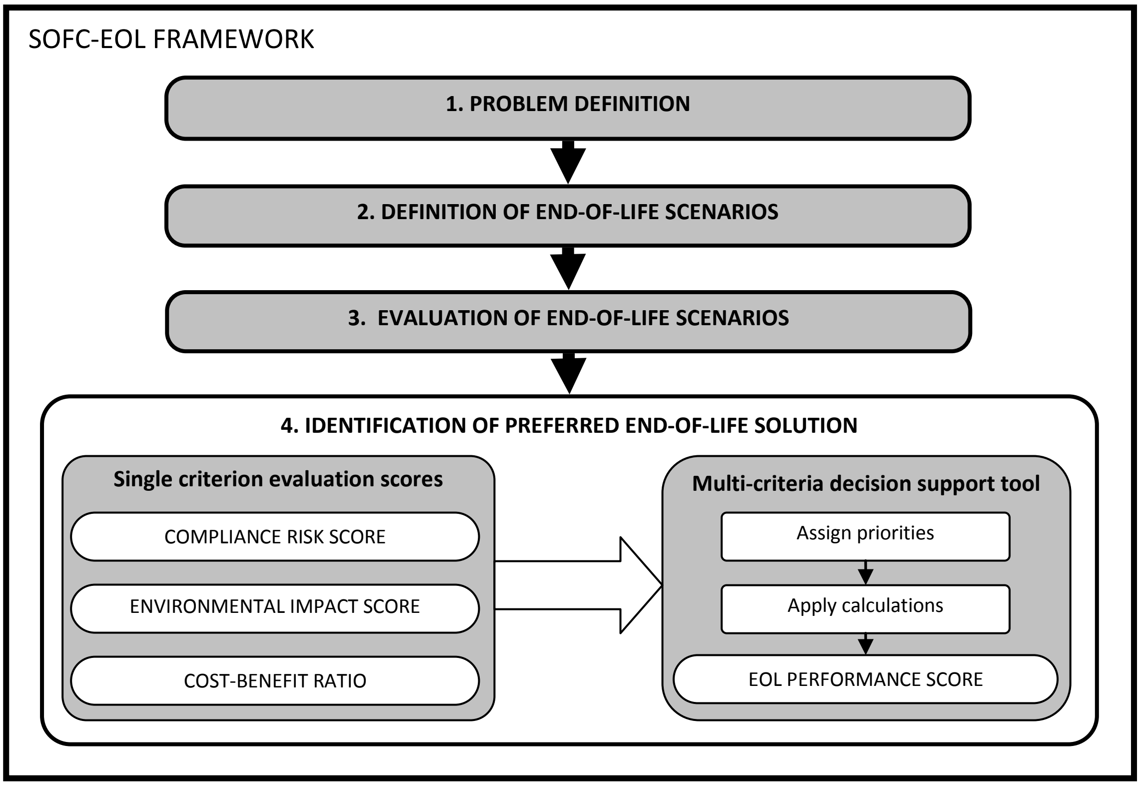


Figure 6.7: Stage 4 of the SOFC-EOL framework in which a multi-criteria decision support tool is used to combine the output from the evaluation stage into a single score.

As a reactive tool, the framework supports the evaluation of alternative end-of-life management scenarios, and identification of the preferred solution, based on the three evaluation criteria: legislative compliance, environmental impact and economic impact. While beneficial in terms of helping to understand and, where possible, reduce the impacts associated with the end-of-life stage of the product life cycle, the impacts arising at end-of-life are likely to be determined to a significant degree by the design of the SOFC stacks.

The second case study explores the application of the framework as a proactive tool. In this mode of application the framework is used to evaluate the effects of changes to the SOFC stack design on the impacts arising during the end-of-life phase. In this mode of application the alternative end-of-life scenarios are differentiated not by process route, but by the material and design characteristics of alternative SOFC stack concepts. The flexibility of the framework in supporting either a reactive or proactive approach to end-of-life management is anticipated to be of particular benefit as SOFC technology matures and product developers become better placed to optimise the design of SOFC stacks based on a product life cycle approach.

6.4 Summary

In this chapter the SOFC-EOL framework has been presented, and each of the four stages in the framework described in detail. The first stage of the framework, in which the end-of-life stream is characterised in terms of design and materials, is explored in detail in the following chapter. Chapter 8 continues by reporting the research supporting the second stage of the framework, namely the definition of alternative end-of-life scenarios. In Chapter 9 the final evaluation stages of the framework are developed. Finally, the application of the complete SOFC-EOL framework is demonstrated through case studies documented in Chapter 10.

CHAPTER 7 DESIGN AND MATERIAL CHARACTERISTICS OF SOLID OXIDE FUEL CELLS

7.1 Introduction

Before beginning to develop and evaluate alternative end-of-life management solutions for the SOFC stack, it is necessary to understand the design and material characteristics of existing SOFC stack concepts. In this chapter some common design and material characteristics are identified that will influence the selection of end-of-life options. This general understanding is developed further by more detailed analysis of three existing SOFC stack concepts. The identified design and material characteristics are then evaluated in order to understand their potential influence on legislative compliance, environmental impact and economic performance at the end-of-life phase.

7.2 Design and material characteristics of solid oxide fuel cells

The design of a product has direct influence over the opportunities and challenges faced during end-of-life management. One particularly significant aspect of design is the selection of materials. Material selection may be based on a number of factors, including functionality, aesthetics and cost. However, when the product reaches end-of-life, the presence of hazardous, valuable and/or recyclable materials will have an impact on the legislative compliance, environmental impact and economic feasibility of alternative end-of-life processing routes.

Material selection is not the only aspect of design which affects end-of-life management. At a fundamental level the design dictates the size and mass of the product and its individual components, thus defining the quantity of waste arising from each end-of-life unit. The accessibility of hazardous substances within the design may allow de-pollution to be carried out easily, or may result in the entire material stream being classified as hazardous, with the introduction of risk to handlers and/or the environment throughout the entire re-processing cycle. The ease with which components containing valuable materials can be removed may allow a high value material fraction to be separated and recycled, or alternatively opportunities for separation may be limited, resulting in loss of value. Joining methods for dissimilar recyclable materials may facilitate disassembly prior to recycling, or may lead to a non-selective re-processing route. In each case, compliance with legislation, environmental performance and economic aspects of end-of-life management are likely to be influenced.

It is therefore essential that the development of an end-of-life management strategy for any product is founded upon a clear understanding of relevant design and material characteristics. In a reactive approach to end-of-life management this allows a feasible re-processing route to be developed within the constraints dictated by the existing product design. Opportunities for minimising environmental impact and maximising economic benefits in a compliant manner can be explored. In a proactive approach to end-of-life management, these considerations are taken into account during the very earliest phases of product design.

In the framework presented in Chapter 6, a reactive approach to end-of-life management is presented and justified. The first stage in the framework requires the characterisation of the waste stream arising from end-of-life SOFC stacks. In the following sections, three existing SOFC stack concepts are analysed in order to determine their principal design and material characteristics. The results from this analysis are then used to identify the key parameters required as input to Stage 1 of the framework to support development of an effective end-of-life management solution.

7.2.1 General design and material characteristics of existing SOFC stack concepts

The SOFC stack is an assembly of individual fuel cells. Each cell contains four fundamental components: the electrodes (anode and cathode) to which fuel and oxidant are provided respectively; the electrolyte, a solid ceramic layer which separates the electrodes and must be impermeable to gases while demonstrating good ionic conductivity; and the interconnect, which allows electrical connectivity between individual cells. For optimised performance, these individual layers within the cell typically have thicknesses in the range of 10 – 100 µm, depending on individual design concepts. Structural support can be provided by increasing the thickness of any one of these functional components, or by introducing an additional inactive substrate. Figure 7.1 summarises the principal cell and stack configurations which determine the design characteristics of different SOFC stack concepts (Minh, 2004).

The requirements for SOFC stack materials are complex. In general, the functional requirements of the materials dominate material selection since the material selected for each component must facilitate the electrochemical processes by which the fuel cell functions and must demonstrate chemical and mechanical durability under the extreme conditions experienced during operation. A common set of materials has emerged for application in high temperature SOFCs, as summarised in Table 7.1.

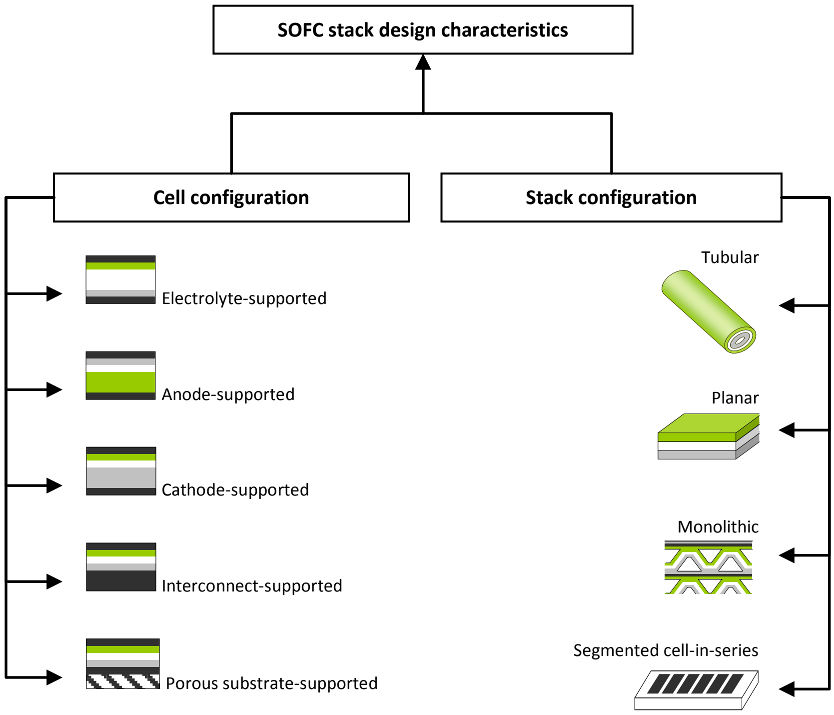


Figure 7.1: SOFC stack design characteristics are determined by the combination of cell and stack configuration selected.

In order to understand how these general design and material characteristics are applied in specific SOFC stack concepts, three existing concepts have been analysed in more detail. Findings from the analysis of an existing tubular, planar and integrated-planar concept are reported in Sections 7.2.2 – 7.2.4 respectively.

Table 7.1: Summary of typical SOFC materials

SOFC stack component	Typical materials	Typical chemical composition	Abbreviation
Electrolyte	Yttria-stabilised zirconia (YSZ)	$(ZrO_2)_{0.92}(Y_2O_3)_{0.08}$	YSZ
Anode	Nickel oxide (NiO)	NiO	NiO
Cathode	Strontium-doped lanthanum manganese oxide (LSM)	$La_{0.85}Sr_{0.15}MnO_3$	LSM
Interconnect	Doped lanthanum chromate	$La_{0.85}Sr_{0.15}CrO_3$	LSC
	Metallic nickel	Ni	Nickel
	Chromium steel	Cr-Steel	Cr-Steel
	Precious metal*	Au, Pt, Pd or similar	PM

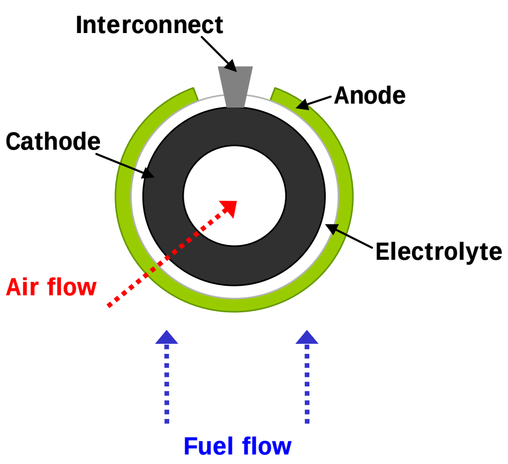
**Precious metal interconnects are often used for development purposes but are not considered to be economically viable in a commercial product*

7.2.2 Analysis of design and material characteristics of tubular SOFCs

The tubular SOFC stack concept has been developed principally by Westinghouse, and later by Siemens-Westinghouse. A schematic of the concept is shown in Figure 7.2, illustrating the cross-section of the individual fuel cell, and the geometry of the stack assembly. Based on the classifications presented in Figure 7.1, the concept can be described as having a cathode-supported cell configuration.

The cell design is based on an extruded tubular component, fabricated from cathode material. This tube is then coated with a thin-layer electrolyte, and a further later of anode material. During operation, air is channelled through the centre of the tube, where it has access to permeate the porous cathode material. Fuel gas is passed over the surface of the tube and permeates the anode material. The interconnect runs the complete length of the tubular cell, and allows a pathway for electron-flow. Electrons released during the oxidation of the fuel gas at the anode are conducted to the cathode of the adjacent cell, where they are used in the reduction of the oxygen gas. Thus the voltage produced in the stack assembly can be harnessed externally to provide electrical power.

The round geometry of the tubular substrate reduces manufacturing options for the electrolyte and anode layers. Electrochemical vapour deposition (EVD) is used to achieve a dense, gas-tight electrolyte. The anode layer can also be applied by EVD, although slurry dipping may have lower cost. It is clear from the schematic of the cell cross-section that the majority of weight in the tubular stack assembly arises from the cathode substrate.



a) Cell configuration (cross-section)

b) Stack configuration

Figure 7.2: Design characteristics of a tubular SOFC concept
(adapted from Siemens AG, 2010b)

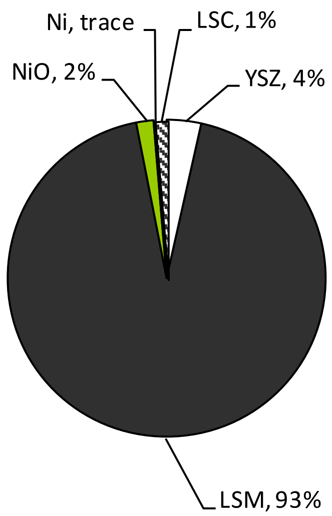


Figure 7.3: Illustrative material composition (by weight) of the tubular SOFC stack (values estimated from Karakoussis *et al.,* 2001)

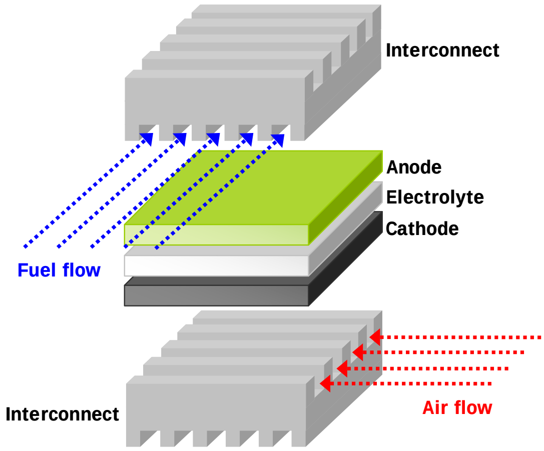
An estimated breakdown of the material content of the tubular stack concept is provided in Figure 7.3. This is based on the life cycle assessment work reported by Karakoussis *et al.* (2001), which reports total quantities of materials used in the production of a quantity of tubular stack capable of producing 1 kW of electrical power under design-point operating conditions. The material breakdown presented in Figure 7.3 accounts for documented assumptions regarding material losses during the manufacturing process. It can be seen that the material composition is heavily dominated by the cathode material (LSM).

7.2.3 Analysis of design and material characteristics of planar SOFCs

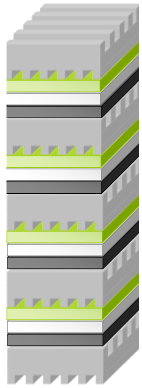
The planar SOFC stack concept has been developed in a number of variations. Figure 7.4 shows one variation of the planar SOFC stack concept. Here the planar cells have a square geometry and the concept adopts an interconnect-supported cell configuration. Alternative variations include circular cell geometry.

The cell is built upon an electrical interconnecting plate, fabricated from chromium-rich steel. The high chromium content is required to prevent degradation at high temperature operating conditions. The flat geometry of the cell allows the anode, electrolyte and cathode layers to be fabricated by a number of alternative routes, including screen printing, tape casting or other conventional thick-film fabrication processes.

The interconnect substrate is engineered with two sets of channels running perpendicular to each other. This allows fuel gas to be passed through the channels adjoining the anode layer of the cell, and air to be passed through the channels adjoining the cathode layer of the adjacent cell. The fuel undergoes oxidation at the anode with the release of electrons. These



a) Cell configuration



b) Stack configuration

Figure 7.4: Design characteristics of a planar SOFC concept
(adapted from Singhal, 2002)

electrons can pass through the interconnect, and are used in the reduction of oxygen at the cathode. As a result of this electron flow through the fuel cell stack, electrical power can be harnessed in an external circuit.

Based on the results reported by Karakoussis *et al.* (2001), an estimated material breakdown has been developed for one variation of the planar SOFC stack concept, as shown in Figure 7.5. The stack assembly is principally made up from the steel interconnect plates, with the additional SOFC materials contributing less than a quarter of the total material mass.

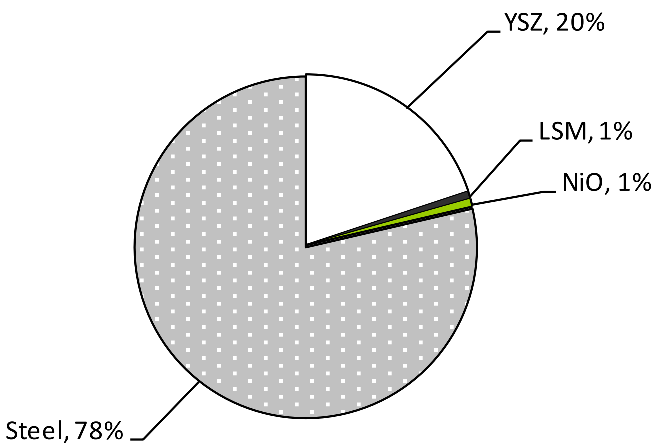
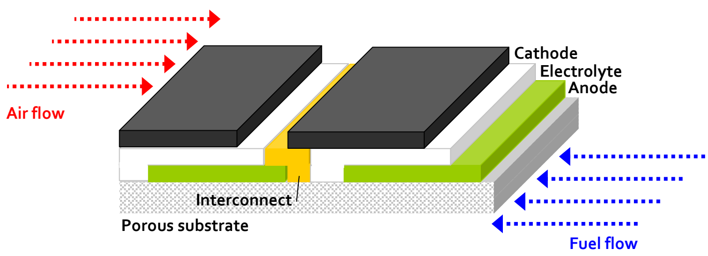


Figure 7.5: Illustrative material composition (by weight) of the planar SOFC stack
(values estimated from Karakoussis *et al.*, 2001)

7.2.4 Analysis of design and material characteristics of integrated-planar SOFCs

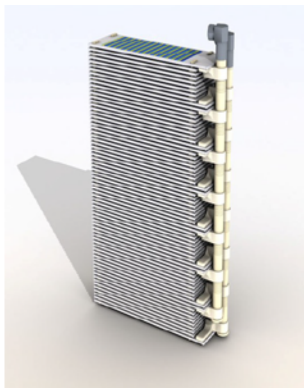
The Integrated Planar SOFC stack design (IP-SOFC) under development by Rolls-Royce Fuel Cell Systems Limited combines a porous substrate supported cell configuration with a segmented-cell-in-series stack configuration, and is described in Gardner *et al.* (2000), Agnew *et al.* (2003) and Agnew *et al.* (2007). The design is such that fuel gas is supplied through channels in a porous substrate "tube" and the porosity allows diffusion of fuel gas to the anode. Air is passed over the surface of the tube where it permeates the cathode. Individual active tubes represent small stacks, since they comprise a number of cell assemblies, connected in electrical series. These active tubes are assembled into larger units, with manifolds providing a pathway for fuel. The principle of operation is illustrated in Figure 7.6. One of the perceived benefits of this design is the lack of requirement for one of the active layers to provide structural support to the cell and stack. This allows the anode, cathode, electrolyte and interconnect components to be designed for optimum performance, with no secondary functional requirements. It also results in the majority of the mass of the stack assembly residing in the substrate. This allows the selection of a substrate material which is not a specialised fuel cell material, providing opportunities for cost reduction.

Figure 7.7 shows an estimated material composition for the integrated-planar SOFC stack concept. The majority of the composition is made up from the inert ceramic substrate material. Alternative materials are available for application in the cell-to-cell interconnects. Low-cost ceramic interconnects show some suitability for this application, although historically, during the technology development phase, precious metals have been shown to provide the required stability and performance.



Cells are configured on both sides of a porous substrate. Fuel is supplied through channels in the substrate and permeates to the anode. Air is supplied over the surface of the substrate to reach the cathode. Individual cells on the substrate surface are connected in series (adapted from Gardner *et al.,* 2000).

(a) Cell configuration



(b) Stack configuration

Figure 7.6: Design characteristics of an integrated-planar SOFC concept.

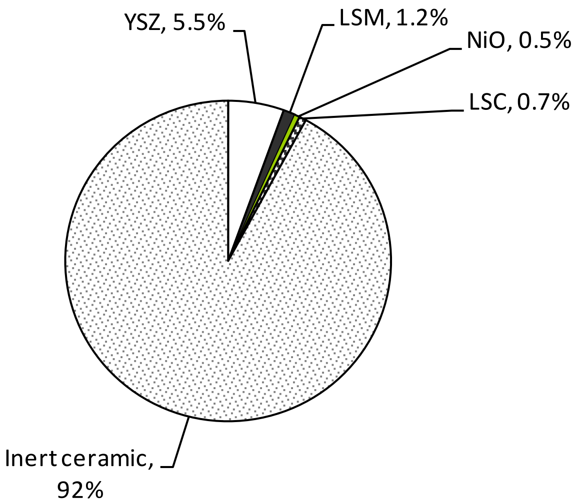


Figure 7.7: Illustrative material composition (by weight) of the integrated-planar SOFC stack (values estimated from Rolls-Royce Fuel Cell Systems, 2008)

7.3 Influence of design and material characteristics at end-of-life

From the analysis of general and specific design and material characteristics of SOFC stacks, some conclusions can be drawn regarding the impact of these characteristics on the end-of-life phase of the life cycle. In the framework for end-of-life management of SOFC stacks developed in Chapter 6, three performance metrics were identified as contributing to the overall feasibility of an end-of-life solution, namely compliance with legislation, environmental impact and economic impact. The influence of the design and material characteristics on each of these performance criteria is explored in the following sections.

7.3.1 Influence of design and material characteristics on legislative compliance

Following the review of end-of-life legislation in Chapter 4, three broad categories of relevant legislation were identified, each with the following aims:

- To designate the waste streams arising from end-of-life products as hazardous or non-hazardous
- To impose appropriate controls on the collection, storage, processing, transportation and disposal of end-of-life products, based on the hazards associated with a specific waste stream
- To divert end-of-life products from landfill

The designation of waste as hazardous or non-hazardous is based on the hazard classification of component materials, and the contribution of those materials to the overall composition of the waste stream. Hazard classification for each of the common SOFC stack materials were

Table 7.2: Threshold concentrations for SOFC materials and substances, above which European hazardous waste legislation applies

SOFC material	Constituent substance	EU hazard classification	Threshold concentration (Environment Agency, 2008)
YSZ	ZrO_2	Non-hazardous	N/A
	Y_2O_3	Non-hazardous	N/A
NiO	NiO	Category 1 carcinogen (R43, R49)	0.1 wt%
LSM, LSC	La_2O_3 (in LSM and LSC)	Irritant (X_i, R36/37/38)	20 wt%
	SrO (in LSM) and LSC)	Corrosive (C, R14, R34)	5 wt%
LSM	Mn_3O_4	Irritant (X_i, R36/37/38)	20 wt%
LSC	Cr_2O_3	Harmful (X_n, R20, R22, R36/37/38)	20 wt%
Cr-Steel	Cr-Steel	Non-hazardous	N/A
Nickel	Nickel	Category 3 carcinogen	1 wt%
Precious metals	Au	Non-hazardous	N/A
	Pt	Non-hazardous	N/A
	Pd	Non-hazardous	N/A

identified from manufacturer's material safety data sheets, and are summarised in Table 7.2. Based on the hazard classification the threshold composition was identified for each substance, above which the waste stream would be considered to be hazardous (Environment Agency, 2008). The data presented in Table 7.2 is based on legislative requirements within the European Union.

It is clear from the information presented in Table 7.2 that the classification of waste arising from end-of-life SOFC stack assemblies has the possibility to be classified as hazardous. This classification is most likely to arise from the presence of nickel oxide, since this is the common SOFC material with the highest hazard classification. However, the cathode and interconnect materials also contain hazardous substances. The classification as hazardous is dependent on design, since this dictates the respective quantities of each material present in the SOFC stack.

This relationship between SOFC stack design and the classification of waste streams arising from end-of-life products is clearly illustrated by examining the estimated material compositions of the three different design concepts presented in Figures 7.3, 7.5 and 7.7. In each case, the content of nickel oxide is above the threshold concentration of 0.1 wt% and thus would result in the end-of-life stack being classified as hazardous. However, it is known that during operation of the stack, the nickel oxide undergoes reduction to nickel metal. In the case of the fuel cell stack being shut down under reducing conditions, in which re-oxidation of the nickel does not occur, the presence of nickel oxide in the end-of-life waste stream may be eliminated. Nickel metal has a lower hazard classification compared to the oxide, and may be present in concentrations up to 1 wt% before a waste stream is classified as hazardous. Therefore, from the values presented in Figures 7.5 and 7.7 it is possible that waste from the planar or integrated-planar stacks may avoid classification as hazardous based on the nickel content. The tubular stack design dictates that lanthanum oxide compounds contribute substantially to the overall material composition, and as such would result in waste from end-of-life stacks being classified as hazardous, based on the 20% threshold concentration shown in Table 7.2.

As identified in the review of legislation in Chapter 4, classification of waste streams as hazardous has implications for the following aspects of the end-of-life management process:

- Transportation of wastes, including domestic and international transport
- Storage of wastes
- Disposal of wastes
- Health and safety issues for waste processing operations

The design and material characteristics of the SOFC stack may therefore define restrictions and impose additional administrative requirements, based on the legislation relevant to each of these issues.

7.3.2 Influence of design and material characteristics on environmental issues

Environmental concerns at the end-of-life stage are likely to arise primarily from the incorporation of hazardous materials in the SOFC stack design. These materials have been identified in Table 7.2 and require effective management at end-of-life to reduce the risk of their release into the environment. While reactive measures to manage these materials in an appropriate way at end-of-life may prove effective in reducing the environmental impacts of end-of-life processing, a proactive approach would explore opportunities for minimising the content of hazardous substances in future design iterations, or eliminating them completely by substitution with more benign alternatives.

Regardless of the hazardous nature of materials based on legislative definitions such as those presented in Table 7.2, all materials have a detrimental environmental impact associated with their production. Disposal of material at end-of-life means that the resources invested in their production are essentially lost. If materials can be recycled from end-of-life waste streams by a process which has a lower impact than that of the original material production route then it is beneficial to pursue recycling as part of the end-of-life management solution. In general, materials which have a particularly high environmental impact associated with their virgin production are most likely to offer benefits from recycling.

The environmental impacts of the production processes for the principal SOFC stack materials were therefore explored as part of the research. Life cycle assessment methodology was applied to evaluate the impacts of material production from initial extraction of resources to delivery of a useable material (cradle-to-gate). Data from the Ecoinvent database (Ecoinvent Centre, 2007) were used for each of the materials investigated, except in the case of nickel oxide for which data were obtained from the Nickel Institute (Ecobalance Inc, 2000). The CML (Centre of Environmental Science, Leiden University) impact assessment method (Guinée *et al.*, 2002) was applied in order to evaluate Global Warming Potential, Acidification Potential, Abiotic Depletion Potential and Energy, in terms of Net Calorific Value. Application of life cycle assessment and the CML impact assessment method are discussed in more detail in Chapter 9 of the thesis. Specialist life cycle assessment software, GaBi4 (PE International GmbH, 2007) was used to support manipulation of the data.

Results from the impact assessment analysis are shown in Figures 7.8, 7.9 and 7.10, for the tubular, planar and integrated-planar stack concepts respectively. For each of the stack designs the materials considered as contributing to the total material composition are all shown on the results charts. It is recognised that additional materials (for example joining and sealing materials) are likely to be present in each case, and that these additional materials will have additional environmental impacts associated with them. However, it was assumed that these materials would comprise a small proportion of the total material weight, and that their contribution to the total environmental impact would be minimal. It was therefore decided in the interests of simplicity and based on data availability to restrict the analysis to include only the principal SOFC materials as shown, similar to the approach adopted by Karakoussis *et al*., 2001.

For each impact category, results are presented in order to demonstrate the relative contribution of each material to the total value for that impact. Results are based on the estimated material compositions shown in Figures 7.3, 7.5 and 7.7. Since the intention of the analysis reported in this chapter is to support the identification of *priorities* for end-of-life management, in this case based on the environmental impacts associated with different SOFC materials, it was identified that the presentation of results as relative, rather than absolute, values would satisfy this objective. This decision also eliminates the risk of disclosing commercially sensitive data regarding detailed breakdowns of the material composition of alternative SOFC stack concepts. The same approach has been adopted in the presentation of the results of the economic evaluation (Figure 7.12).

For the tubular stack concept (see Figure 7.8), it can be seen that the lanthanum oxide materials are the most significant contributors to Global Warming Potential, Abiotic Depletion Potential and Energy impacts. Nickel oxide is the most significant contributor to the total Acidification Potential, being responsible for approximately half of the total impact in this category. Manganese, present in the cathode material, represents a contribution in the order of 10% in each impact category, while the zirconium dioxide present in the tubular stack has only a minor impact for each of the categories evaluated. These results are perhaps unsurprising, since the design characteristics of the tubular SOFC stack require the cathode material to be used as the structural support for each cell, reflected in high concentration of LSM in the overall material mix.

Figure 7.9 shows the results for the planar SOFC stack. In this case the chromium steel used to fabricate the interconnecting plates contributes most significantly to each of the impact categories evaluated. Nickel oxide contributes around 35% of the total acidification potential, while zirconium dioxide provides between 10 and 20% of the total impact for each of Global Warming Potential, Acidification Potential, Abiotic Depletion Potential and Energy. The lanthanum oxide and manganese constituents contribute a negligible proportion of each of the impacts.

The impact assessment results for the integrated planar SOFC stack are shown in Figure 7.10. Here the inert ceramic material contributes most significantly to Global Warming Potential, Abiotic Depletion Potential and Energy impacts, although it does not dominate as much as the material composition for this stack concept (see Figure 7.7) might have suggested. Interestingly, the very small fraction of the SOFC stack composed of nickel oxide provides a relatively large contribution to each impact category, and dominates the total Acidification Potential. These results reflect the inherent high impact associated with nickel oxide in comparison to the inert ceramic material used as the substrate for the integrated-planar SOFC stack.

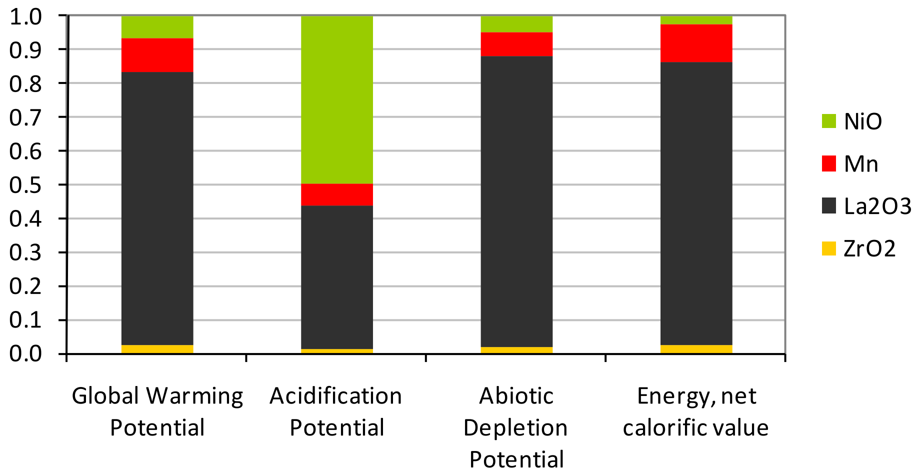


Figure 7.8: Relative contribution of different materials to selected environmental impacts arising from material production for a tubular SOFC concept.

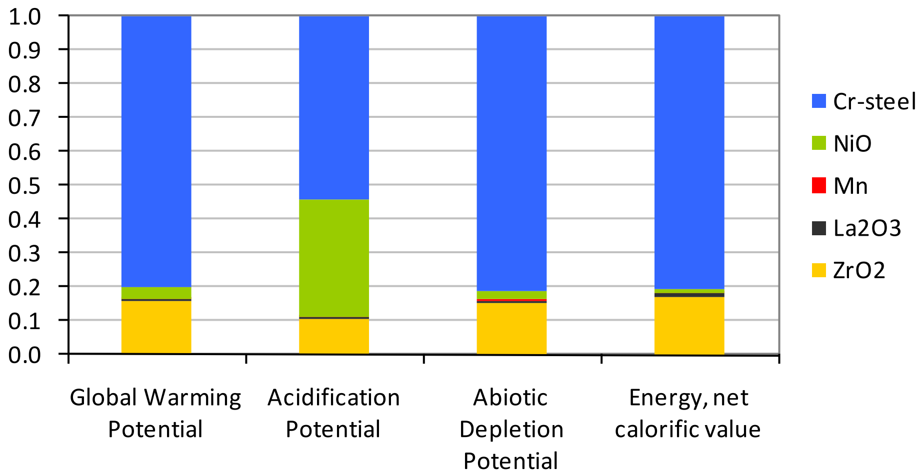


Figure 7.9: Relative contribution of different materials to selected environmental impacts arising from material production for a planar SOFC concept.

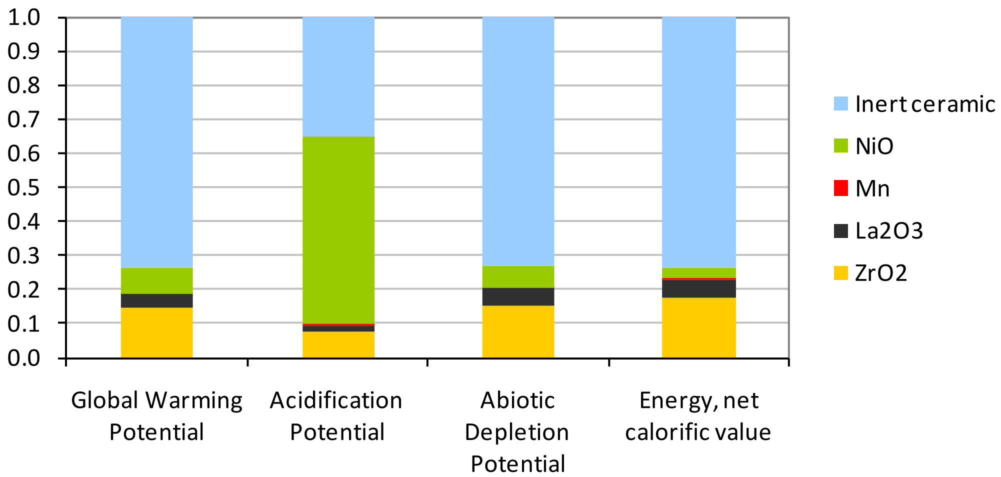


Figure 7.10: Relative contribution of different materials to selected environmental impacts arising from material production for an integrated-planar SOFC concept with an LSC interconnect.

As identified in Section 7.2.4, while the final integrated-planar SOFC stack concept, adopted in commercial products, is likely to use a low-cost interconnect material, such as doped lanthanum chromate, alternative materials have been used throughout the concept development. In particular, platinum group metals offering good conductivity and stability under operating conditions, although their high cost prohibit extensive use in an economically viable product. The environmental impacts associated with platinum group metal production are also considerable, when compared to the other materials used in the integrated-planar SOFC stack. In order to evaluate an alternative scenario, the impact assessment analysis for the integrated-planar SOFC stack was repeated, this time substituting palladium for doped lanthanum chromate in the interconnect component. These repeat results are shown in Figure 7.11. As can be seen, the impacts arising from the other SOFC materials become insignificant in comparison to the impacts associated with the production of palladium.

These results presented in Figures 7.8 – 7.11 illustrate how the design and material characteristics of the SOFC stack influence priorities at end-of-life, in particular where environmental impact is concerned. Depending on process availability and technical feasibility, it is likely to prove most beneficial to target material separation and recycling at those component materials which have the greatest impact in their virgin production. Differences in the design characteristics of the tubular, planar and integrated planar SOFC stacks result in different priorities being observed. In the case of the tubular concept, the impacts arising from the high content of lanthanum-based cathode material suggest that efforts in material recovery and recycling might best be directed towards this material. In the

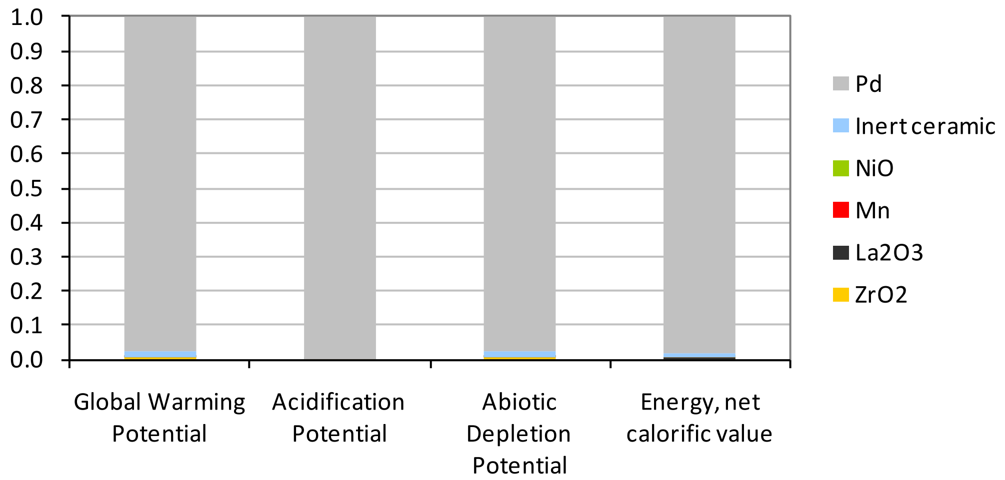


Figure 7.11: Relative contribution of different materials to selected environmental impacts arising from material production for an integrated-planar SOFC concept with a palladium interconnect.

case of the planar concept, the chromium-steel represents the priority for recycling while similarly for the integrated-planar SOFC stack it is again the substrate material, this time the inert ceramic, which may provide greatest opportunities for reducing impact through recycling. In all cases the production of nickel oxide contributes substantially to the total Acidification Potential, despite the use of relatively low quantities of the material in production and thus it is also a good candidate for recycling. The contrast between Figures 7.10 and 7.11 indicates how priorities at end-of-life may be substantially altered by substituting a low impact material with a higher impact material. In this case the introduction of platinum to the interconnect in the integrated-planar SOFC design results in a scenario where all attention should be directed to the recovery and recycling of this very high impact material.

Of course, these observations based on the impact assessment results for materials production only hold true if processes exist or can be developed which allow recovery and recycling of these materials with lower impact than that associated with their initial production. Identification of recycling priorities in this way can help in the development of an end-of-life solution which aims to reduce the total life cycle impacts of the product.

7.3.3 Influence of design and material characteristics on economic issues

As demonstrated in Section 7.3.2, the design and material characteristics of the SOFC stack may determine priorities at end-of-life, based on environmental aspect of the materials present. In a similar, and perhaps more obvious way, economic considerations are also significant in defining end-of-life priorities. Recovery and recycling of valuable materials in general makes good economic sense since where the cost of virgin material is high, the opportunities for recycling through a lower-cost process are greater. Low value materials may not be attractive for recycling from an economic perspective, even if recycling would provide clear environmental benefits.

In order to explore the influence of the design and material characteristics of the three SOFC stack concepts defined in Sections 7.2.2 – 7.2.4 on the economic priorities at end-of-life, a simple cost analysis of the tubular, planar and integrated-planar designs was conducted. The purpose of this analysis was to identify the economic priorities for material recycling, based on the intrinsic value of materials present within end-of-life SOFC stacks, and the approach taken is described below.

Initially, indicative market prices were obtained for the principal SOFC materials identified in Section 7.2. Table 7.3 provides an overview of the data collated, showing current commercial prices (April 2011) for bulk materials. The production of SOFC stacks requires the use of high purity ceramic powders, often with a very fine particle size. The processing requirements to obtain a suitable grade of material can result in prices up to seven times the price of bulk materials (Thijssen, 2010). However, it is unlikely that a recycling process would directly yield a material of such specialist quality. It is therefore envisaged that priorities in recycling are more likely to be driven by the value of materials of bulk commodity quality, rather than by the value of materials of a quality suitable for SOFC manufacture. Closed loop recycling would require an additional material refinement stage, between the recovery of materials from recycling of end-of-life SOFC stacks, and the manufacture of new SOFC stacks. While presenting the data in Table 7.3, the sensitivity of pricing to global markets and the rapid fluctuation of prices over time are acknowledged. These indicative prices are intended to provide an estimate of the relative value of materials present in end-of-life SOFC stacks, and are subject to change.

The prices shown in Table 7.3 were multiplied by the material compositions shown in Figures 7.3, 7.5 and 7.7 to identify an estimated breakdown in value for each of the different design concepts. In addition, the calculation was also applied to the integrated-planar stack with palladium replacing the lanthanum-based interconnect material. The results from this analysis are shown in Figure 7.12. Similar to the environmental results presented in Section 7.3.2, it is clear that for each of the different stack concepts different priorities must exist for material recovery and recycling activities at end-of-life.

Table 7.3: Indicative market prices for common SOFC materials in April 2011

Material	Price per kg ($)	Price per kg* (£)	Source
NiO	15-22	12	alibaba.com, 2011a
YSZ	35-45	25	alibaba.com, 2011b
LSM		25	Assumed to be similar to YSZ, based on individual prices for La_2O_3, SrO and MnO_2, and allowing for process costs.
La_2O_3	18-25	14	alibaba.com, 2011c
SrO	2-3	1.6	alibaba.com, 2011d
MnO_2	0.4-0.8	0.4	alibaba.com, 2011e
Inert ceramic	<1	<1	alibaba.com, 2011f
Cr-steel	-	15	Estimated
Pd	24000	15000	Johnson Matthey, 2011

*Assumes conversion £1 = $1.6

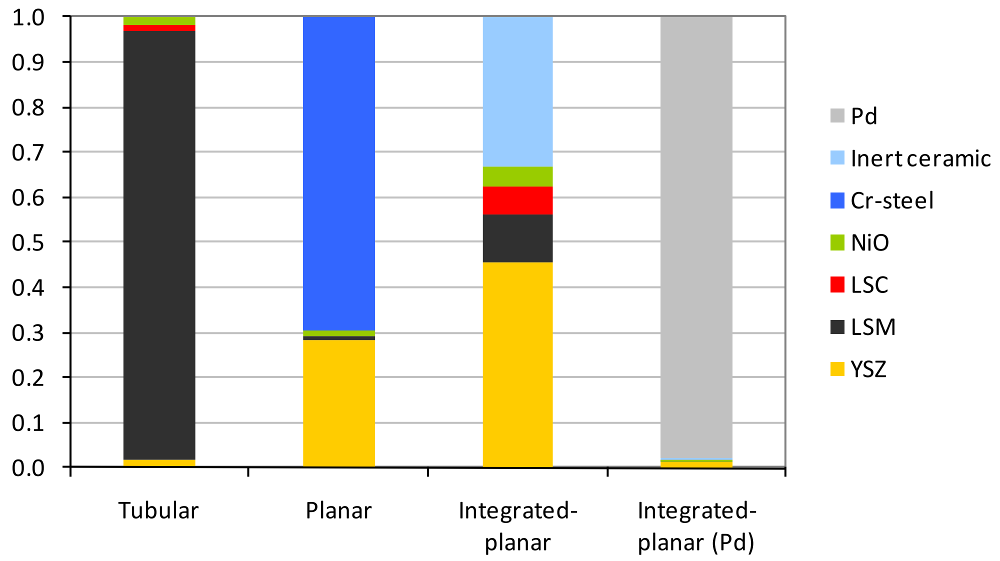


Figure 7.12: Estimated breakdown of material value for tubular, planar and integrated-planar SOFC stacks.

For the tubular SOFC stack, where the cathode material is used to create the substrate for the fuel cell, the majority of the inherent material value within the end-of-life stack is contained within the strontium-doped lanthanum manganese oxide material (LSM).

For the planar concept, the massive chromium steel interconnecting plates contain around 60% of the total materials value. Pursuing recovery and recycling of this material portion is likely to provide benefits, especially given that recycling processes for steel are mature and widely practiced. Although the content by weight of YSZ in the planar stack is considerably lower than steel (below 20% of the total weight, compared to around 80% for steel), the relatively high value of YSZ means that this fraction of the total material composition potentially holds interesting economic prospects for recovery and recycling, depending on the availability of a suitable process.

For the integrated-planar SOFC stack, the breakdown in material value is much more evenly distributed between the five principal materials present, although the dominance of the inert ceramic substrate material to the overall material composition results in 40% of the value being contained in this fraction, despite the low cost. When it is considered that the lanthanum-based cathode (LSM) and interconnect (LSC) materials have very similar chemical and physical properties, it is envisaged that recovery of these two fractions together could be economically beneficial. The final set of results presented in Figure 7.12 are for the integrated-planar SOFC stack, with palladium used in the interconnect in place of the lanthanum-based material. In this scenario it can be seen that the high value of palladium dominates the total value of the stack. In this case, economic priorities determine that efforts for material recovery and recycling should be focused on this high revenue material fraction, despite it representing less than 1% of the total material weight.

7.4 Summary

Design and material characteristics of three different SOFC stack concepts have been analysed. Despite commonalities in material selection for individual SOFC components, difference in design characteristics result in wide variations in overall material composition for tubular, planar and integrated-planar stacks. These variations in material composition for future end-of-life streams have an impact on the classification of waste under existing legislation, and hence may influence the actions necessary to ensure compliant processing at end-of-life. When life cycle impact assessment is applied to evaluate the inherent environmental impacts of the SOFC stacks, arising directly from the raw material production processes, these variations in material composition identify different priorities for recycling for tubular, planar and integrated-planar stacks. Similarly, economic priorities for recycling differ between the three different concepts, based on the breakdown in inherent value for each stack design. These findings demonstrate the relationship between product design and priorities for end-of-life management. The integrated-planar SOFC stack is used as the focus of the research in Chapters 8, 9 and 10 of the thesis, where alternative end-of-life scenarios are defined and evaluated.

CHAPTER 8 END-OF-LIFE MANAGEMENT SCENARIOS FOR SOLID OXIDE FUEL CELLS

8.1 Introduction

This chapter describes the development of alternative end-of-life scenarios for SOFC stacks. After an introduction to the principal issues involved in end-of-life management, the three main steps of the end-of-life process are described in detail. These include collection and sorting, reprocessing and redistribution. Specific examples are provided to support development of feasible end-of-life scenarios. Three scenarios are described, which form the basis of the case studies documented in Chapter 10. Data collection methods used to define each scenario in order to perform environmental and economic evaluation and comparison are described.

8.2 End-of-life management of the SOFC stack

The life cycle of the SOFC stack, as illustrated in Figure 8.1, is integrated with the life cycle of the complete SOFC product. For the purposes of this research the components of the SOFC Product, excluding the SOFC stack, are categorised together as the "SOFC system". This SOFC System incorporates systems for the processing and supply of fuel and air; exhaust and heat

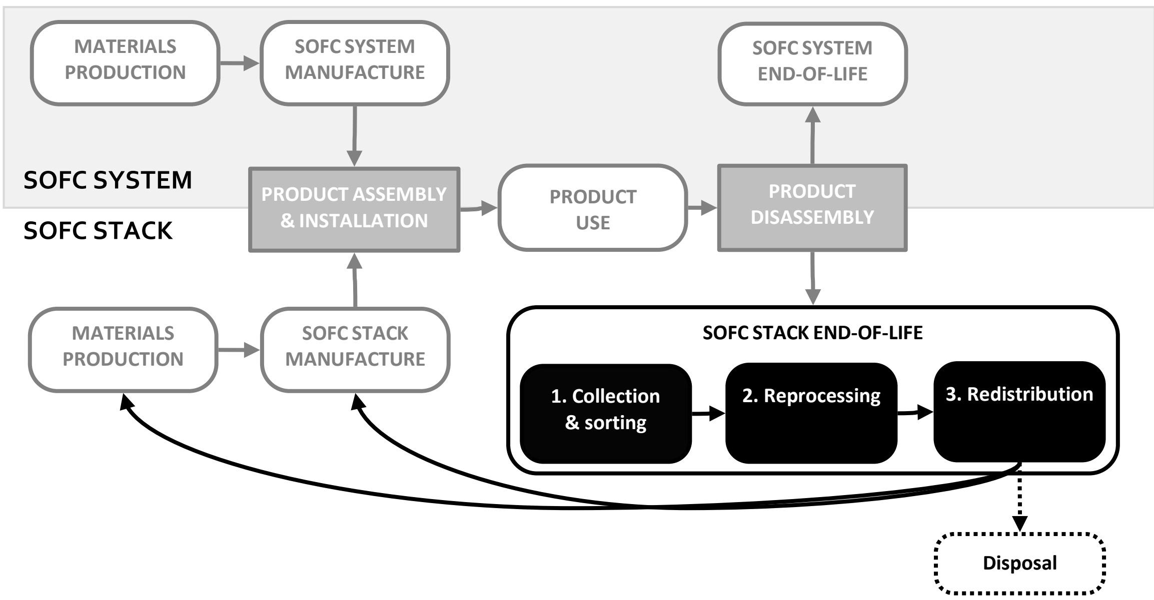


Figure 8.1: Product life cycle for the SOFC stack in the context of the complete SOFC product, illustrating the three principal steps within the end-of-life phase.

exchange systems; casing and insulation for the SOFC stack; all infrastructure associated with power conditioning and electrical connection to the customer; all external packaging and site infrastructure. The SOFC system element of the SOFC product is not considered in the development of end-of-life scenarios within the thesis. It is assumed that for the majority of components within the SOFC system, existing end-of-life management routes exist, since many of the components are common to other commercially mature technologies and utilise materials, such as steel, for which mature recycling infrastructure is readily accessible. This is in contrast to the SOFC stack, which comprises the fuel cells themselves and as such incorporates novel components and some uncommon, valuable and/or potentially hazardous materials for which end-of-life management processes have not been developed. In addition, the SOFC system is predicted to have a lifetime of around 20 years, during which period the complete SOFC stack will require replacement 3 or 4 times. The generation of end-of-life SOFC stack will therefore occur frequently within the SOFC product life cycle, and the first end-of-life SOFC stack components will need to be dealt with within 4 or 5 years of the product's installation. Thus the development of an environmentally and economically viable end-of-life management solution for the SOFC stack, in compliance with the relevant legislative requirements, has been identified as a priority, based on the gap in existing knowledge, opportunities for value recovery, possible toxicity issues and the sheer quantity of end-of-life waste generated during the SOFC product life cycle.

The disassembly of the SOFC stack from the SOFC product is a prerequisite for the subsequent end-of-life management steps. This ease with which this operation can be completed is highly dependent on the design of the SOFC system, and the nature of the interface between the SOFC system and the SOFC stack. As such, this process falls outside of the scope of the research. For the purposes of the end-of-life scenarios developed in this chapter, it is assumed that the removal of end-of-life SOFC stack during maintenance and/or when the SOFC product reaches the end-of-life phase is readily achieved.

Following disassembly of the SOFC stack from the SOFC product, three principal steps are defined within the end-of-life management phase. These are illustrated within the life cycle diagram shown in Figure 8.1. End-of-life management begins with the collection of the end-of-life SOFC stacks from the customer, and finishes with the redistribution of all outputs from end-of-life processing operations within appropriate supply chains. In the definition of alternative end-of-life scenarios for the SOFC stack, these three steps are considered.

8.2.1 Collection and sorting

The overall efficiency of the end-of-life scenario will be significantly influenced by this first step in the end-of-life management process. Failure to transfer end-of-life SOFC stack components from the customer into the appropriate reprocessing route has the potential to result in uncontrolled disposal, which in turn is likely to result in non-compliance, high environmental impact and/or high economic impact. Following collection of end-of-life SOFC stack, some level of inspection is required to assess the suitability of the components as input to alternative reprocessing steps. The factors influencing the collection and sorting of the end-of-life SOFC stack are explored in detail in Section 8.3. Transportation of end-of-life components between their site of origin and the reprocessing site is likely to be the most significant factor in determining the environmental and economic impacts of this step. Compliance with legislation governing the domestic and international transportation of waste is a requirement of this step.

8.2.2 Reprocessing

Following collection and sorting, the end-of-life SOFC stacks will progress through the appropriate reprocessing route. Sorting of components will define whether they are suitable for reuse, recycling or disposal. Recycled components and materials may be reprocessed into useful inputs for the manufacture of further SOFC stacks, or as inputs for the manufacture of other products. Reprocessing may result directly in the production of useable materials and components, or may produce crude materials requiring further processing. The options for reprocessing end-of-life SOFC stacks are discussed in greater depth in Section 8.4. In this step of end-of-life management the environmental and economic impacts are likely to be complex, and will depend on the material and energy inputs and outputs associated with the selected reprocessing route. Definition of these inputs and outputs is the primary objective in the second stage of the end-of-life management framework, and the approach developed in the research is described in Section 8.4. Various compliance requirements, associated with legislation controlling waste processing activities, are relevant to this step in the end-of-life management process.

8.2.3 Redistribution

The reprocessing of end-of-life SOFC stack results in the production of new material or component flows, which require distribution to a new user. In a closed-loop scenario, redistribution may be back to the fuel cell manufacturing facility, or to the original material supplier. In an open-loop scenario, recycled materials may be sold for the manufacture of other products. In order to conserve resources it is intended that the majority of the material arising from the reprocessing of end-of-life SOFC stacks can be redistributed, with only minimal quantities of material requiring disposal. The economic benefit achieved during the redistribution step is likely to play a significant role in influencing the overall economic viability of the end-of-life management process.

8.3 Collection and sorting of end-of-life SOFC stack

Generation of end-of-life SOFC stack will primarily arise during planned maintenance of the SOFC product, when the complete SOFC stack is replaced at regular intervals defined by the manufacturer. According to current estimates the service life of a SOFC stack assembly will be in the region of five years. Additional end-of-life SOFC stack assemblies will be generated at final decommissioning of SOFC products as well as during unplanned maintenance, in the case of premature failure of components.

The commercial model adopted by the manufacturer of the SOFC product has the potential to significantly impact upon the efficiency of this first stage of the end-of-life management process. Figure 8.2 illustrates alternative options for initial sales agreements and aftermarket care. Where the manufacturer retains ownership of the SOFC product through a leasing agreement, the end-of-life SOFC stack will remain the property of the manufacturer. In this situation the maximum level of control is maintained by the manufacturer, regarding the collection of end-of-life SOFC stack for reprocessing. Alternatively, the manufacturer may maintain a close relationship with the customer and product through provision of after-market services, such as a "TotalCare"-type agreement (Rolls-Royce plc, 2011b). At the other extreme, ownership will transfer to the customer at point-of-sale, and, unless a contract for aftermarket

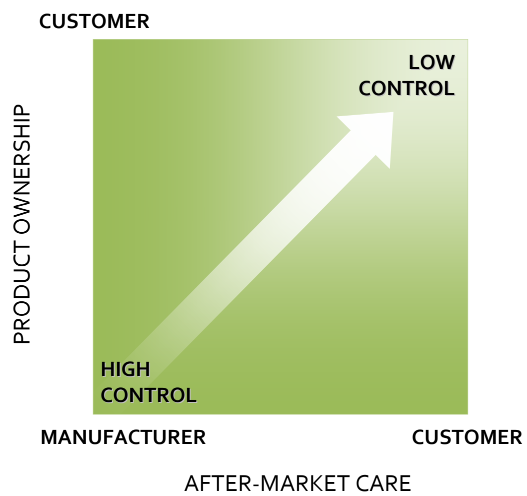


Figure 8.2: Impact of the commercial model for SOFC products on the level of control retained by the manufacturer over end-of-life SOFC stack components.

care is arranged and maintained between manufacturer and customer, the manufacturer potentially loses all direct control over the fate of end-of-life SOFC stack.

Despite these various commercial options, and the consequent variability in control over end-of-life SOFC stack, in all situations the nature of the SOFC product is such that a high proportion of SOFC stack assemblies released into operation should be available for reprocessing when they reach end-of-life. Evidence from the literature suggests that the larger and less portable the product, the higher the recovery rate for recycling. In addition, the fact that end-of-life SOFC stack will always require replacement with a new SOFC stack assembly (other than at final decommissioning of the SOFC product) a relationship with the manufacturer will need to be maintained in all cases.

This research therefore assumes that the environmental and economic impacts arising during the end-of-life phase of the SOFC stack life cycle can be predicted based on the development and implementation of an appropriate end-of-life management process. In contrast to highly dispersed products with uncertain end-of-life fates, these environmental and economic impacts may be considered with confidence to contribute to the total life cycle impacts of the SOFC product. Environmental and economic impacts arising during this initial step of the end-of-life management process are most likely to arise from transportation requirements between the SOFC product operating site, where the end-of-life SOFC stacks are generated, and the site at which initial reprocessing steps will be carried out. Given the potential for global marketing of SOFC products, these transportation requirements could be significant, and will depend substantially upon the location and number of reprocessing sites available. Compliance with legislation governing domestic and international transportation of waste, as well as waste storage, is relevant to this initial step in the end-of-life management process.

8.4 Reprocessing of end-of-life SOFC stack

Within the waste management hierarchy, the reuse of end-of-life products is preferential to the recycling of the materials contained within them. It is envisaged that, as the SOFC product gains maturity, exploration of opportunities for the repair/remanufacture and reuse of SOFC stack components will be required. This will be especially important for SOFC stack assemblies which fail prematurely, and where considerable life is left in the majority of the components. However, various characteristics of the SOFC stack and its function determine that any repair/remanufacturing operations will be technically challenging. The electrochemical mechanisms by which the fuel cell operates require high material purity, and even low levels of contamination could severely impact reliability, durability and performance. Based on the premise that the majority of end-of-life SOFC stack components will be removed from the SOFC product after completion of the planned service period, the reprocessing step in the end-of-life process, for the purposes of this thesis, concentrates on material recycling, rather than the repair of components for reuse.

Figure 8.3 illustrates the range of options for end-of-life processing which can be applied to the end-of-life SOFC stack. Following the collection of the end-of-life assemblies an initial sorting process is applied in order to segregate components for which reuse opportunities exist, from those which have lost their value as components and can be considered to represent mixed materials. Further disassembly operations may be applied to SOFC Stack components, as preparation for subsequent material separation and recycling steps. Following the segregation of useful components, the remaining material is available for reprocessing. Depending on the process technologies available it may be feasible to separate the mixed material into a number

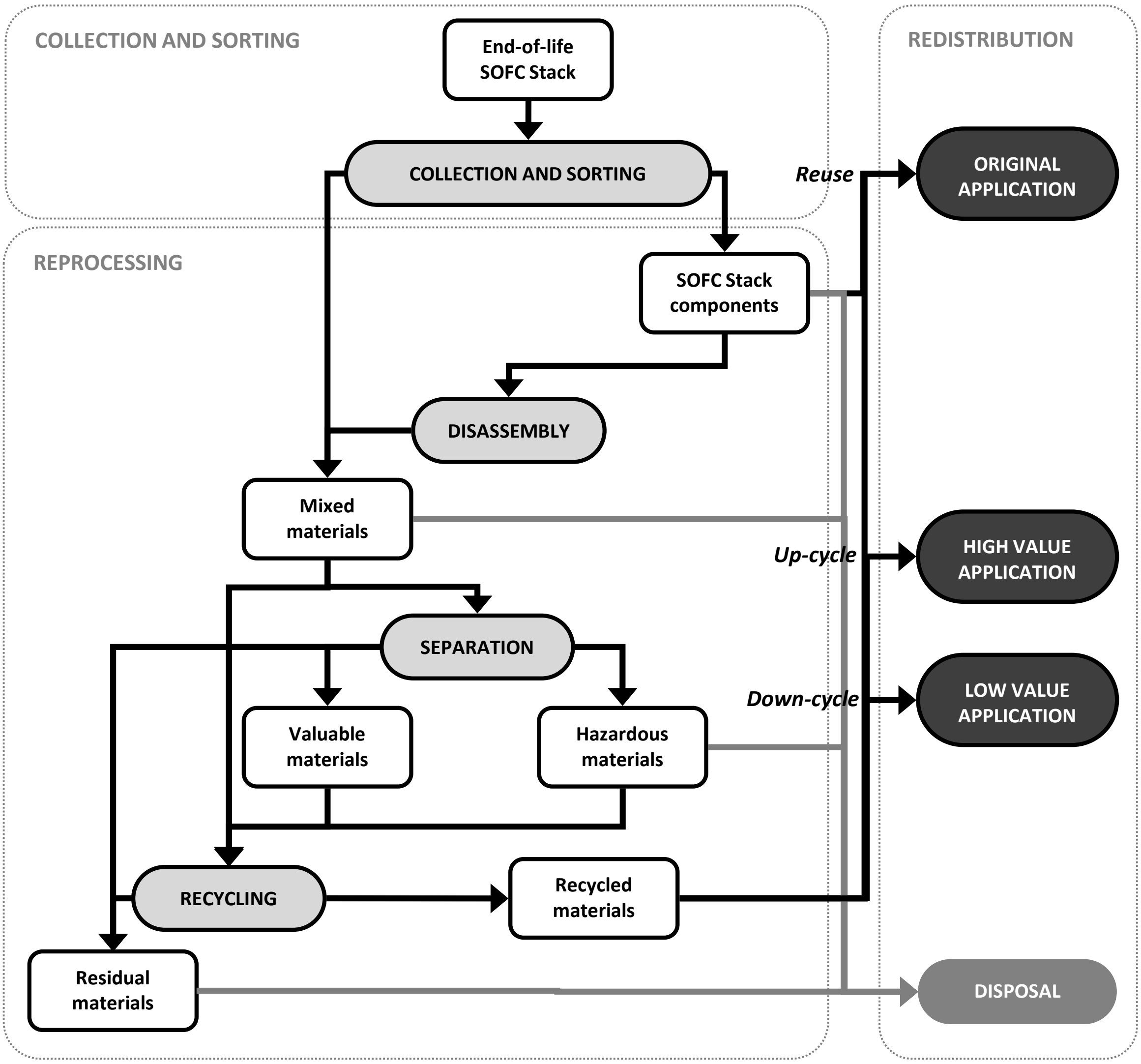


Figure 8.3: Overview of alternative processing routes for end-of-life solid oxide fuel cells

of different material-flows, prior to recycling. In particular, the isolation of valuable materials from the bulk material portion may support the obtainment of high recovery yields. Similarly, segregation of hazardous materials may reduce the risks associated with reprocessing the non-hazardous bulk material stream, ensuring that the tightest controls are applied to the management of the hazardous portion. In a less sophisticated recycling route, the mixed material arising from the end-of-life SOFC stacks may directly form the input to the recycling process.

Following recycling, materials may be produced with application in the manufacture of new SOFC stacks (reuse). Alternatively, recycled materials may be suited to other high value applications (up-cycling) or may only be suitable for low value applications (down-cycling). Residual materials from the recycling process are those which have no direct application or value, and thus are suitable only for disposal. Figure 8.3 also shows the possibility that components and/or mixed materials from the end-of-life SOFC stacks may be directly disposed of, with no material recycling. Options for each of the process stages highlighted in Figure 8.3 are discussed in the following sections.

8.4.1 Disassembly options for end-of-life SOFC stack components

Disassembly options for end-of-life SOFC stacks are considered in the context of subsequent material separation and recycling processes. Figure 8.4 illustrates some disassembly options

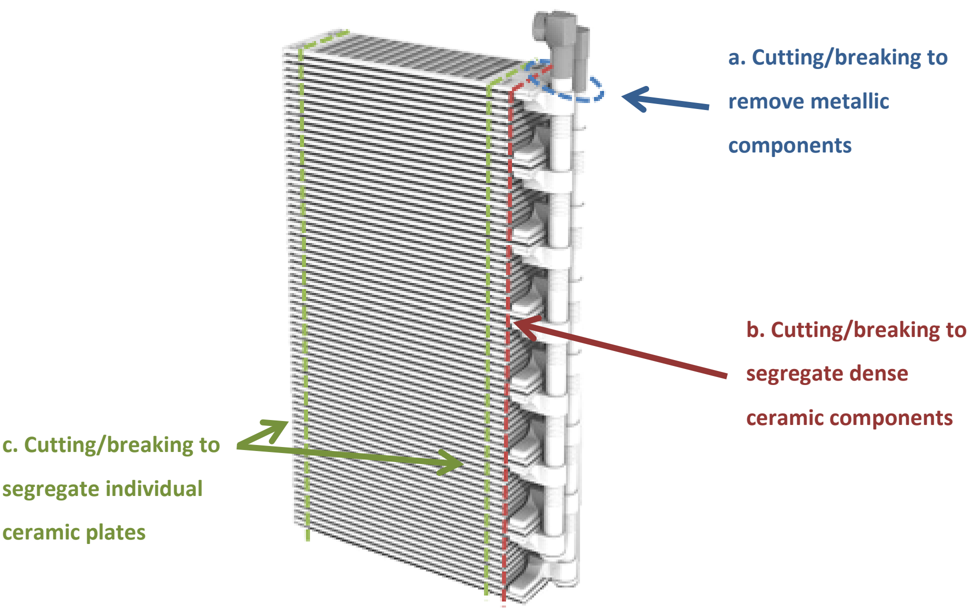


Figure 8.4: Disassembly options for end-of-life SOFC stack assemblies, prior to material separation and recycling operations.

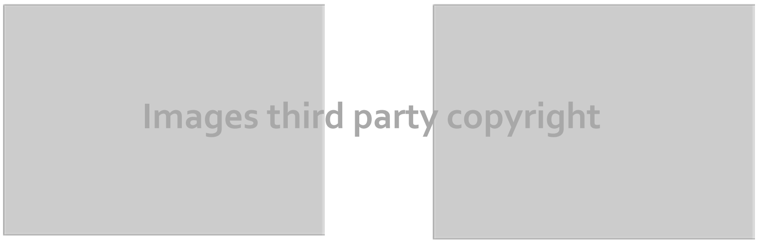
considered in the research. The strip assembly shown in Figure 8.4 is the lowest level assembly which can be removed from the SOFC stack without the need for any mechanical intervention. This strip assembly is constructed from porous ceramic plates, each with a layer of cells printed on both flat faces. Dense ceramic components form manifolds on one end of the assembly, through which fuel is distributed during operation. Metallic components allow the connection of fuel pipes for the delivery of the fuel gas. Ceramic and glass-based materials are used to join components and ensure gas-tight seals.

Disassembly options a and b (Figure 8.4) allow for the segregation of different material types. The metallic components are likely to act as contaminants for any recycling steps developed for the ceramic fuel cells. These can simply be removed from the strip assembly by means of cutting or, more crudely, breaking the joint with the dense ceramic manifolds. In a more complex operation, the dense ceramic components can be segregated from the porous ceramic plates by cutting or breaking the joints between these two material types. This level of segregation allows the separation of a heavy, uniform material fraction from a relatively light fraction which incorporates a mix of hazardous and potentially valuable materials.

Within the stack assembly, access to the surfaces of the flat ceramic plates on which the active layers of the fuel cell are printed is restricted by adjacent plates. Therefore disassembly of the stack into individual plates, illustrated as disassembly option c in Figure 8.4, introduces additional opportunities for material separation. Surface treatment of individual plates, by either mechanical or chemical processing, has the potential to segregate the materials present in the fuel cell anode, electrolyte, cathode and current collectors, from the bulk ceramic substrate.

8.4.2 Material separation options for end-of-life SOFC stacks

Various material separation methods were explored within the research, with the specific aim of separating the inert ceramic material, used in the substrate, from the materials present in the active fuel cell layers. These materials, characterised in Chapter 7, include hazardous materials and, potentially, valuable materials. Efficient processes require good separation to be achieved, in combination with high recovery rates. The processes were classified into mechanical separation methods, chemical separation methods and combined separation methods. Experimental work investigating novel material separation methods was conducted by researchers at the Singapore Institute of Manufacturing Technology (SIMTech), in collaboration with Rolls-Royce Fuel Cell Systems Limited.



(a) *End-of-life SOFC stack component*

(b) *Ceramic substrate after surface grinding*

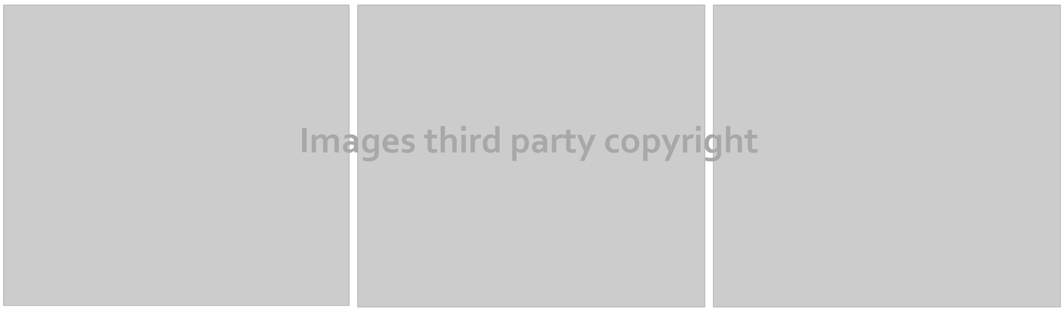
Figure 8.5: Illustration of a mechanical separation method. Surface grinding of the SOFC stack component *(a)* results in the removal of active layers from the ceramic substrate *(b)*. (Tay *et al.*, 2008).

8.4.2.1 Mechanical separation methods

Mechanical material separation of the active fuel cell layers from the substrate requires access to the surface of each ceramic plate component. Therefore, it is necessary to carry out disassembly option c (Figure 8.4), prior to any further processing. Various mechanical processes are potentially suitable for the removal of the printed fuel cell materials from the ceramic substrate. Figure 8.5 illustrates the use of mechanical grinding, which is effective in removing the fuel cell surface layer, resulting in a clean ceramic plate. Alternative methods, including the use of water jet, have been trialled with limited success.

The biggest challenge in using mechanical methods for material separation lies in the recovery of the removed fuel cell layers for further reprocessing and material recycling. Given the breakdown in value associated with the IP-SOFC stack design (Chapter 7), it is essential that the surface layers are recovered efficiently. In addition, the experimental work conducted on this process dealt only with small sections of fuel cell components. For a feasible industrial process a high degree of automation would be necessary. It is envisaged that, with appropriate investment, an automated system for surface grinding individual components could be developed, with the active fuel cell layers recovered from used grinding slurry. This material separation method was investigated in more detail in the case studies conducted in the research, and reported in Chapter 10 of the thesis.

Other mechanical processes were investigated as methods for the pre-treatment of end-of-life SOFC stacks, prior to recycling operations. Destructive processes, in particular milling, were found to be effective in treating whole SOFC components, such as the strip assembly shown in Figure 8.4. Removal of the metallic components (disassembly option a) is desirable, prior to the commencement of milling. The process was sufficient to pulverise even the dense ceramic components, and high recovery yields were obtained from a high volume trial (approximately 500 kg SOFC Stack). Process time, and associated energy requirements, could be reduced by



(a) *End-of-life SOFC stack component*

(b) *Ceramic substrate following chemical treatment*

(c) *Recovered fragments of active layer materials*

Figure 8.6: Illustration of a chemical separation method. Chemical treatment of the SOFC Stack component *(a)* results in the removal of fragmented active layers *(c)* from the surface of the ceramic substrate *(b).* (Tay *et al.*, 2008)

first removing the dense ceramic components. This destructive pre-treatment process has the benefit of destroying all intellectual property associated with the physical design of the IP-SOFC concept. This may be an attractive option for the SOFC manufacturer if there are significant concerns about the protection of the intellectual property contained within the materials sent to a third party for recycling.

8.4.2.2 Chemical separation methods

The different chemical properties of the ceramic substrate material, in comparison to the printed fuel cell layers, allow selective chemical attack to be engineered to facilitate the separation of these two material fractions. Chemical separation methods are potentially suitable for application to complete SOFC stack assemblies, such as the strip assembly shown in Figure 8.4; individual SOFC components, achieved by carrying out disassembly option c (Figure 8.4); or pulverised material achieved by milling, as described in Section 8.4.2.1 above. Figure 8.6 illustrates the result of experimental work carried out into alternative chemical separation methods. In this case, the active fuel cell layers were removed from the ceramic substrate following treatment with an acid solution, and the fragments could be readily recovered.

It is envisaged that more advanced chemical processes could be developed to allow the selective dissolution and subsequent precipitation of materials contained within the IP-SOFC stack. These processes were not investigated fully within the experimental work contributing to the research presented within the thesis. Chemical separation methods are not considered in the case studies presented in Chapter 10.

(a) Fragmented active layer materials *(b) Disintegrated ceramic substrate material* *(c) Fragmented dense components*

Figure 8.7: Illustration of a combined separation method. Following exposure to a pressurised steam environment, active layer fragments *(a)* and dense component fragments *(c)* can be separated from the bulk ceramic powder *(b)*. (Tay *et al.*, 2008)

8.4.2.3 Combined separation methods

Materials separation can also be achieved using a combination of methods. Within the experimental work which contributed to the research presented in the thesis, a materials separation method was developed, the results of which are illustrated in Figure 8.7. Initially, end-of-life SOFC Stack components were exposed to a pressurised steam environment. This resulted in chemical attack of the ceramic substrate. The ceramic substrate disintegrated in this environment into a fine powder, causing the active layers of the fuel cell to fragment. Differential particle size between the fine ceramic powder and the fragmented active layers allowed efficient recovery of the two material types by sieving of the dried material. The dense ceramic components were attacked in a similar manner to the ceramic substrate, causing them to break down into large fragments. This materials separation method was investigated in a case study, the results of which are presented in Chapter 10.

8.4.3 Recycling options for end-of-life SOFC stacks

For some of the materials within the end-of-life SOFC stacks, well-established recycling processes are commercially available. The recycling of these materials is therefore considered to be viable, with the adoption of existing methods and processes. Other materials, such as the low-value ceramic substrate, are suitable candidates for down-cycling, to be redistributed in low grade applications such as road-fill and as a structural filler. Recycling processes within the end-of-life scenarios investigated in the case studies are described in detail in Chapter 10. These are primarily concerned with the recovery of valuable materials from end-of-life SOFC stack components.

8.5 Redistribution of recovered materials

Redistribution is the final step in the end-of-life management process, as shown in Figures 8.1 and 8.3. Redistribution requires there to be a market for the material outputs from the reprocessing of end-of-life SOFC stacks. In the absence of such a market, disposal is the only remaining option.

8.5.1 Redistribution of recycled materials

As shown in Figure 8.3 various options are available for redistribution of recycled materials. In a closed-loop scenario, recycled materials are supplied directly back to the manufacturer of the SOFC stack, for reuse in the production of new SOFC stack assemblies. In a true closed-loop system the same material is reused continuously by the manufacturer. This could be achieved in a situation where a bespoke recycling plant is established to process waste from end-of-life SOFC stacks. In reality, most industrial recycling processes will combine input material from various sources, thus losing the identity of specific material flows. The viability of closed-loop recycling is heavily dependent on the geographic location of the recycler, in relation to the manufacturing plant. If the two locations are close together, it may be viable for the manufacturer to purchase material directly from the recycler. If the two sites are remote, it may be preferable for the SOFC manufacturer to source recycled material from a local supplier, and the recycler to supply recycled material from SOFC stacks to a local customer. This may eliminate economic and environmental impacts associated with transportation of materials.

Where the recycled material is redistributed for use in a higher value application, the term up-cycling is applicable. Up-cycling may potentially be realised for high value materials, such as precious metals, where material recovered from end-of-life SOFC stacks could be reused in the manufacture of jewellery or other value-added products. Down-cycling is likely to be realised for materials which are inherently low in value, or which are not re-processed to a high enough purity to render them suited to their original or equivalent application. In terms of the IP-SOFC Stack, the ceramic substrate material must be free from trace contaminants, in order to prevent chemical disruption to the electrochemical processes required for efficient operation of the fuel cells. Therefore, it is unlikely that a commercially available recycling process would deliver recycled ceramic suitable for reuse or even up-cycling. This low value material is likely to be down-cycled.

The economic gains achieved from the redistribution step of the end-of-life management of SOFC stacks will provide the majority of the “benefits” included in the cost-benefit analysis, described in Chapter 9. This step is therefore critical in defining the viability of alternative end-of-life scenarios.

8.5.2 Disposal options for end-of-life SOFC stacks

Without development of a suitable alternative end-of-life process, or the existence of suitable markets for the redistribution of recycled materials, disposal of end-of-life SOFC stacks constitutes the only available option open to SOFC manufacturers. As discussed in the review of legislation in Chapter 4, disposal to landfill is increasingly unacceptable, both from a regulatory perspective and based upon public perception. This is especially relevant to SOFC technology which will be marketed on its environmental credentials. In addition to the legislative climate, the nature of the materials contained within the SOFC stack act as a further barrier to disposing of the end-of-life product in landfill. In particular, the valuable material content provides a real incentive for at least some level of recycling to be carried out, and the hazardous materials present in the SOFC stacks only serve to increase the administrative burden associated with disposal. One of the primary aims of the research presented in the thesis is to support the development of an end-of-life process route for SOFC stacks which minimises the amount of material disposed of to landfill.

8.6 Scenario development for end-of-life management of solid oxide fuel cells

Three alternative scenarios for end-of-life processing of SOFCs have been developed (Figure 8.8) for investigation in the case studies presented in Chapter 10. These scenarios are based on the reprocessing options described in this chapter. Scenarios 1 and 2 incorporate disassembly and material separation process steps, in which the ceramic substrate material is separated from the fuel cell active layers. All three reprocessing scenarios use a commercially available recycling process for the recovery of valuable materials for subsequent redistribution. These scenarios have been developed based on laboratory-scale feasibility

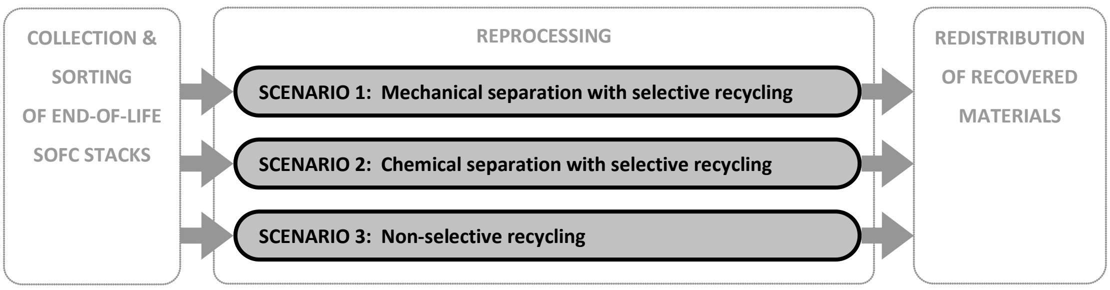


Figure 8.8: Overview of alternative end-of-life scenarios for SOFC stacks developed in the thesis

studies conducted by the Singapore Institute of Manufacturing Technology, in collaboration with Rolls-Royce Fuel Cell Systems Limited. Scenario 3 has been developed based on industrial trials conducted during the course of the research.

While it would have been possible within the research to combine the various disassembly, material separation and recycling process steps in different ways, thus creating a greater number of end-of-life scenarios, it was decided that a comparison of three distinct processes would be sufficient for the purposes of demonstrating the application of the framework for end-of-life management. However, the flexible nature of the framework is such that any number of alternative end-of-life process routes could be defined, evaluated and compared. In an industrial environment, it is likely that process comparison would be limited to a short-list of alternatives, based on initial feasibility studies including considerations such as the availability of suppliers to deliver the required processes. Thus it was decided that the development of only three end-of-life scenarios for evaluation in the case studies would demonstrate the application of the framework in a manner representative of its industrial application. This is consistent with the overall aim of the research which is not to define an optimised end-of-life solution for SOFC stacks, but rather to explore the issues involved in end-of-life management of this novel technology, and to present an approach by which these issues may be addressed.

8.6.1 Scenario 1: Mechanical separation with selective recycling

This scenario is illustrated in Figure 8.9. At the collection and sorting stage, the end-of-life stack is sorted into SOFC assemblies, where individual ceramic plates are joined together, and SOFC components consisting of individual ceramic plates. This scenario is not suited to treating SOFC components which are badly damaged at end-of-life.

The initial step in the reprocessing route is the disassembly of the large SOFC assemblies. Alternative processes may be suitable for application at this stage, and include cutting, either with blade, laser or water jet. Alternatively, force may be applied at the manifold-manifold bond to break the seal between individual plates. Cutting with a blade is considered to be the simplest and quickest method of disassembly at this stage, resulting in individual ceramic plates and a separate material stream comprising the dense ceramic manifold assemblies.

The individual SOFC components require further reprocessing steps to be applied. The initial process step is the removal of the printed active materials from the ceramic plates. In this scenario, a mechanical process is applied. Grinding has been selected as the most appropriate method available. The valuable material is collected in the slurry used in the grinding process, and as such the viability of this scenario is dependent on the development of a suitable material recovery process. This mechanical separation step results in the generation of two material streams; the high volume stream being the remaining ceramic plates, which now represents a clean and homogenous material composition, with the waste being in component form, and the low volume stream being the active materials from the anode, cathode, electrolyte and current collector components of the fuel cell. These active materials then require further processing in a precious metal recovery plant. A proportion of the ceramic substrate will be abraded with the active layers and will form part of the total material composition of this stream.

In this scenario four material streams are produced for redistribution. These comprise the

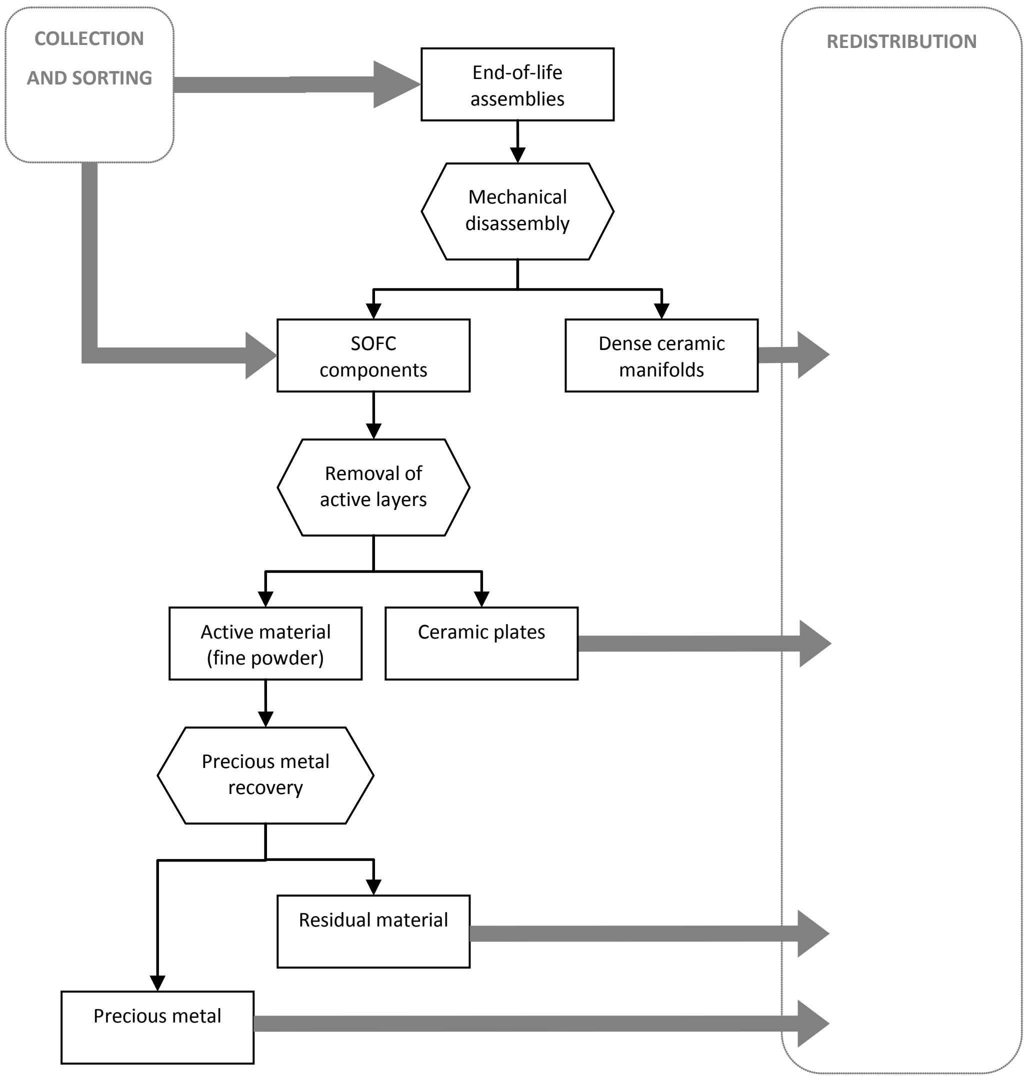


Figure 8.9: Scenario 1 reprocessing route.

dense ceramic components, the ceramic plates, the recovered precious metal, and the residual material from the precious metal recovery process.

8.6.2 Scenario 2: Chemical-mechanical separation with selective recycling

In the second scenario (Figure 8.10), the input to the reprocessing route can be complete end-of-life assemblies, individual SOFC components or fragmented SOFC components. The end-of-life SOFC stack is placed in a steam environment, under pressure and at an elevated temperature. The steam reacts with the ceramic substrate material and causes the physical structure of the ceramic to be broken down. The active layer materials are not affected by the steam, and become segregated from the ceramic bulk as flakes. The differential particle size resulting, following the steam treatment, allows the individual material streams to be segregated by sieving.

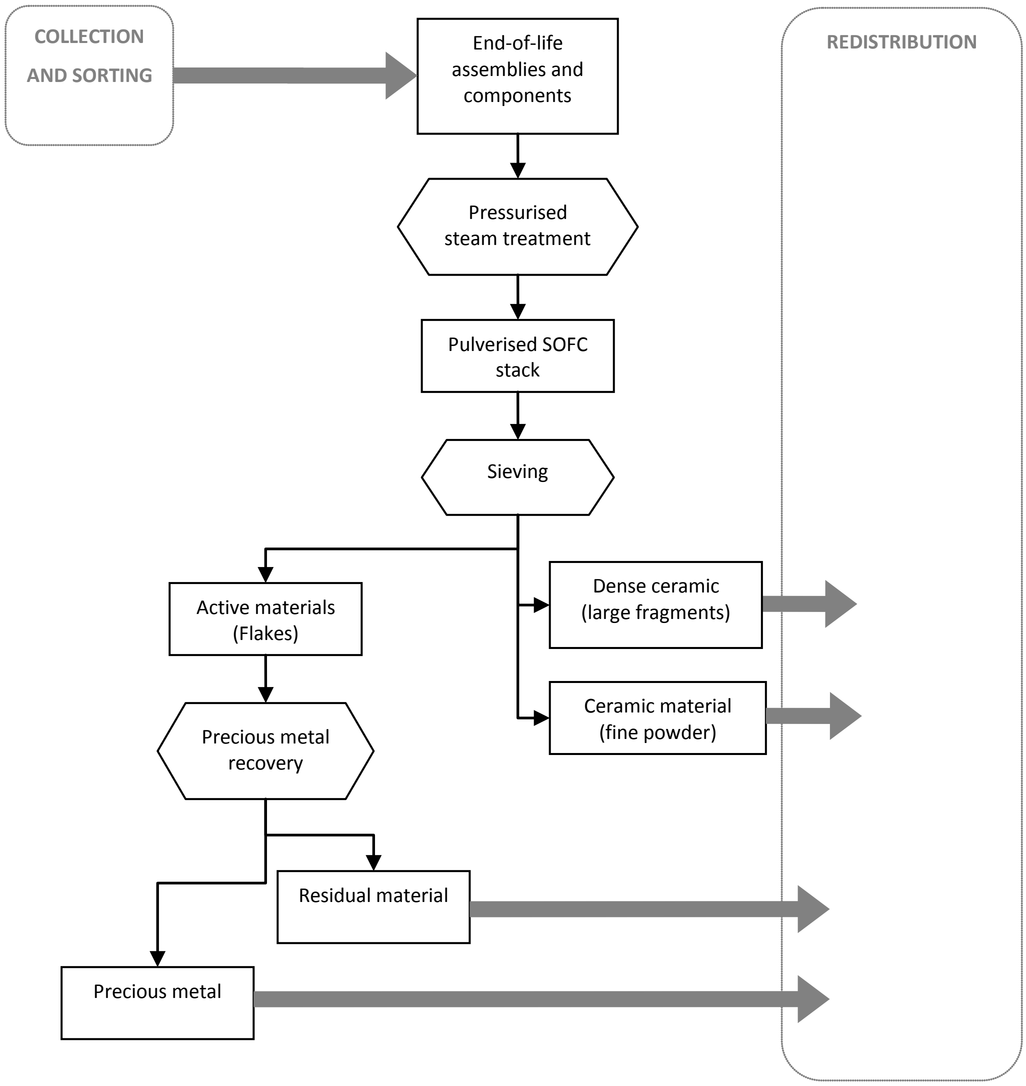


Figure 8.10: Scenario 2 reprocessing route.

The steam treatment has been demonstrated at laboratory scale, but may be facilitated at larger volume by the use of a large steam autoclave. Commercially available equipment would require adaptation to be suitable for industrial scale application of this reprocessing route.

8.6.3 Scenario 3: Non-selective recycling

The final scenario developed in the research is non-selective recycling of the end-of-life SOFC stacks. In this scenario (Figure 8.11), the end-of-life components are mechanically crushed into a fine powder, and then subjected to a conventional precious metal recovery process. This is a similar process to that utilised for the recovery of platinum group metals from ceramic-based catalytic converters. The process has been well developed to produce high yields of precious metal, and the resulting slag finds application in various down-graded material applications, such as in road-fill or in construction materials.

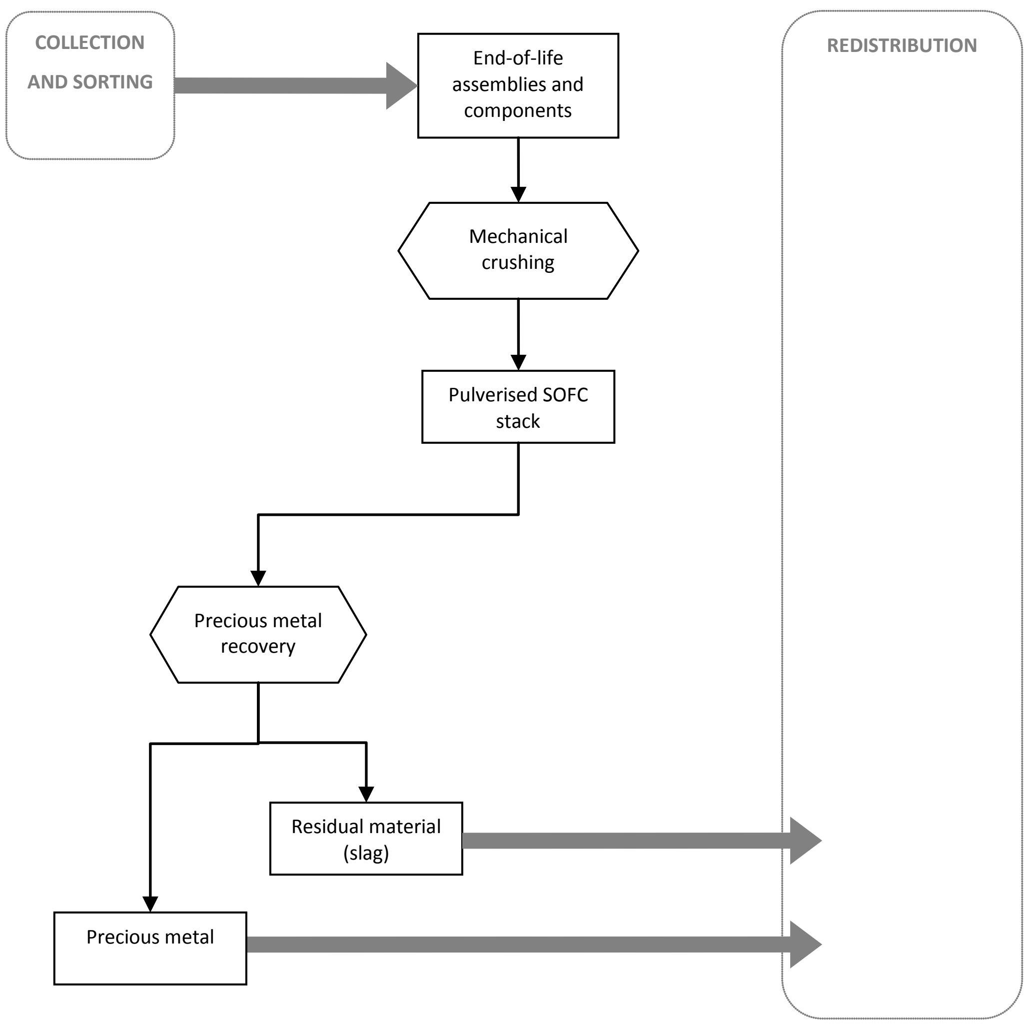


Figure 8.11: Scenario 3 reprocessing route.

8.6.4 Critical overview of alternative end-of-life scenarios for SOFCs

The three scenarios identified in Section 8.4 have different characteristics, and the results regarding their compliance with legislation, environmental and economic performance are presented and discussed in the case studies reported in Chapter 10. However, based on the descriptions presented in the current chapter, some initial observations can be made based on a comparison of the three process routes. These general observations are summarised in Table 8.1.

All three scenarios utilise a commercially available process for precious metal recovery as the final process step. The differences between the three scenarios therefore lie in the preceding treatment steps. With regard to the practical feasibility of the three scenarios, four aspects are identified as being significant.

The second aspect considered is process availability, which relates to the availability of suitable processing technology for application to the end-of-life management of SOFC stacks. In the process routes proposed for scenarios 1 and 2, equipment suitable for carrying out the individual process steps is commercially available, but would require adaptation before being suited to application at an industrial scale. In particular, the development of automated systems is envisaged to be necessary to allow these process routes to become practically viable.

Thirdly, process flexibility is considered, in particular with relation to the form of the input material. It is envisaged that the physical condition of end-of-life SOFC Stacks may vary, depending on the conditions to which they have been exposed during operation. Especially in the case of premature failure it is feasible that components may be broken. Disassembly of the SOFC Stack from the SOFC product may also result in breakages to components. Scenarios 2 and 3 are completely flexible with regard to the physical condition of the input material, since in both cases the initial step is destructive.

Finally the output from the process is considered, in terms of the number of different material streams arising from the processed end-of-life assemblies, as well as opportunities for redistribution of these material streams to profitable applications. In all cases, the precious metal fraction of the SOFC Stack is recovered for redistribution in high value applications. Scenarios 1 and 2 also yield a clean ceramic fraction, which may find application in mid value markets. In scenario 3 all materials, other than the precious metal, are combined in the slag from the recycling process and are unlikely to be suited to anything other than very low value applications.

Table 8.1: Comparison of end-of-life scenarios 1, 2 and 3 with respect to practical implementation.

	Scenario 1 ***Mechanical separation with selective recycling***	**Scenario 2** ***Chemical-mechanical separation with selective recycling***	**Scenario 3** ***Non-selective recycling***
Process complexity	• Three process steps required, prior to precious metal recovery. • Some specialist handling of components and assemblies required.	• Two process steps required, prior to precious metal recovery. • Non-specialist handling of components and assemblies required	• One pre-treatment step, prior to precious metal recovery. • Non-specialist handling of components and assemblies required
Process availability	• Technology is commercially available. • Development required to provide bespoke set-up, including automation.	• Technology is not currently commercially available. • Existing technology may be readily adapted for this application, with some development effort required.	• Technology is commercially available and currently in use. • No technology development required.
Process flexibility	• Input material can be in component or assembly form, but an initial disassembly step is required. • Process is dependent on components being whole, and retaining physical structure during processing.	• Input material can be in component or assembly form. • Physical condition of end-of-life components is not an influencing factor.	• Input material can be in component or assembly form. • Physical condition of end-of-life components is not an influencing factor.
Process output	Process produces • clean ceramic fraction (component form) • precious metal fraction • residual materials (amalgamated in slag from the precious metal recovery operation)	Process produces • clean ceramic fraction (powder/fragment form) • precious metal fraction • residual materials (amalgamated in slag from the precious metal recovery operation)	Process produces • precious metal fraction • all other SOFC Stack materials (amalgamated in slag from the precious metal recovery operation)

8.7 Scenario definition for evaluation and comparison

In order to quantitatively evaluate and compare alternative end-of-life scenarios, it is necessary to define each scenario specifically, in terms of input and output flows of materials, energy, waste and emissions. Each of these input and output flows will have an associated environmental and/or economic impact. Data to support the definition of parameters will be collated from a variety of sources, as illustrated in Figure 8.12. It is envisaged that theoretical or estimated data from the literature could be used initially to scope out new end-of-life scenarios. As the processes incorporated in these end-of-life scenarios become better understood, through practical trials at laboratory and then industrial scale, more robust data can be generated and utilised to provide a higher level of confidence in the output generated

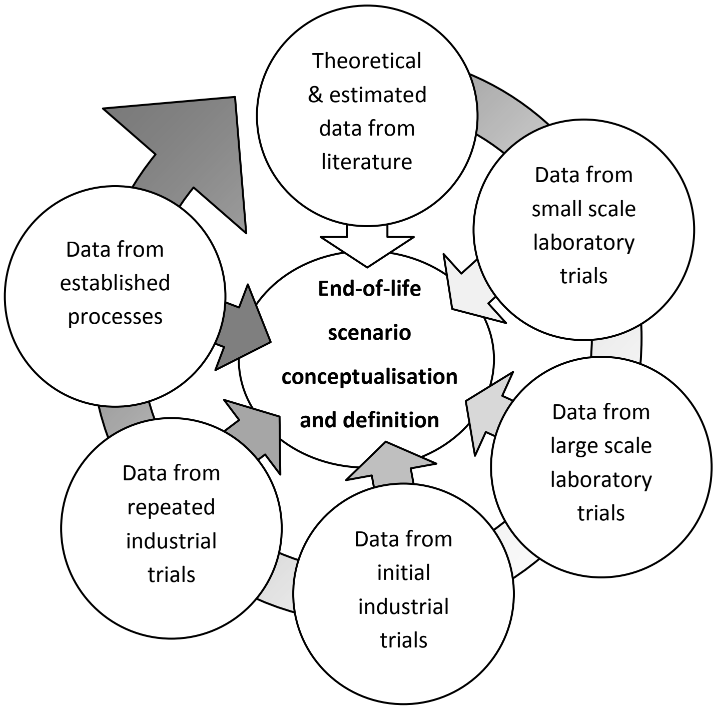


Figure 8.12: Data sources for definition of end-of-life scenarios, showing progression from initial concept to established process.

by the individual criteria evaluations and the decision support tool. The ability to apply the framework for end-of-life management of SOFCs to scenarios for which data availability is poor is essential in facilitating early consideration of alternative and novel end-of-life scenarios. Data collation and manipulation is performed in Excel, and all assumptions documented to maintain transparency. The quantitative definition of alternative end-of-life scenarios is exemplified through the completion of case studies, documented in Chapter 10.

8.8 Summary

This chapter has broken down the end-of-life management process into three principal steps, namely collection and sorting of end-of-life components; reprocessing of end-of-life components using a variety of disassembly, material separation and recycling processes; and redistribution of materials produced from the reprocessing operations. Specific examples have been provided of methods and approaches which may be applied to the development of practically feasible solutions for the management of end-of-life SOFC stacks. Three scenarios have been described, by which end-of-life SOFC stacks can be reprocessed into useful materials for redistribution. A method for defining each scenario, in terms of input and output flows, has been presented. The application of this method is demonstrated in Chapter 10, where case studies evaluate and compare the three scenarios described in this chapter, using the evaluation methodology described in Chapter 9.

CHAPTER 9 EVALUATION OF END-OF-LIFE MANAGEMENT SCENARIOS FOR SOLID OXIDE FUEL CELLS

9.1 Introduction

In this chapter the methods used to evaluate alternative end-of-life management options for the SOFC stack are developed. An evaluation methodology is defined, which includes a risk assessment method for the evaluation of legislative compliance; the use of life cycle assessment to evaluate environmental impact; and the use of cost-benefit analysis to evaluate economic impact. These individual evaluation methods and their application within the framework for end-of-life management of SOFC stacks are described. Finally, a multi-criteria decision support tool is presented, which has been developed within the research to support comparison of alternative end-of-life solutions within the framework.

9.2 Evaluation requirements for alternative end-of-life scenarios

The review of legislative requirements for end-of-life and waste management in Chapter 4 identified various aspects of relevance to the management of wastes arising from the end-of-life SOFC stack waste stream. Some requirements are applicable today, based on existing legislation. In addition to these existing requirements, the identification of trends in legislative development highlights a need to anticipate future requirements, likely to be introduced within the timescales required for full scale commercialisation of SOFC technology to be achieved. Any end-of-life option identified as failing to meet existing legislative requirements must be immediately discarded as unsuitable. Compliance with future legislative requirements cannot be evaluated with such clarity, since although future requirements can be predicted, their exact nature cannot be determined. Therefore an end-of-life option identified as running a low risk of future non-compliance would be favoured over an alternative option identified as high risk.

In addition to meeting legislative requirements, it is important that end-of-life waste from SOFC stacks is managed in a way which strives to minimise detrimental impacts on the local and global environment. This is necessary both to demonstrate good business practice on the part of the manufacturer, and to ensure that the attractive environmental benefits of the fuel cell product are not marred by a failure to deal with this waste stream in a responsible manner. Bad publicity regarding any aspect of the fuel cell product's life cycle may substantially damage market penetration.

To ensure that an end-of-life management option is realistic in a business environment it is also necessary that the cost of dealing with the end-of-life SOFC stack does not compromise the commercial feasibility of the product. One of the primary barriers to achieving full scale commercialisation of SOFC technology is cost. A good management solution for the end-of-life SOFC stack would therefore demonstrate a low cost-benefit ratio.

The requirement to consider all of the above when evaluating end-of-life options for the end-of-life SOFC stack is demanding: issues of compliance, environmental impact and cost are individually complex, and may conflict. A two-stage evaluation methodology has been developed, which assesses each criterion (compliance, environmental impact and cost) individually, and then combines the individual outcomes to provide a single performance score. The evaluation methodology is depicted in Figure 9.1.

In Stage 1 of the evaluation methodology shown in Figure 9.1, the three performance criteria (compliance, environmental impact and cost) are considered in parallel. Within the compliance evaluation, existing and future legislative requirements are considered separately. Since non-compliance with existing legislation cannot be accepted in an end-of-life management scenario, any options identified as being non-compliant must be discarded or revised, regardless of their environmental or economic performance. A risk assessment

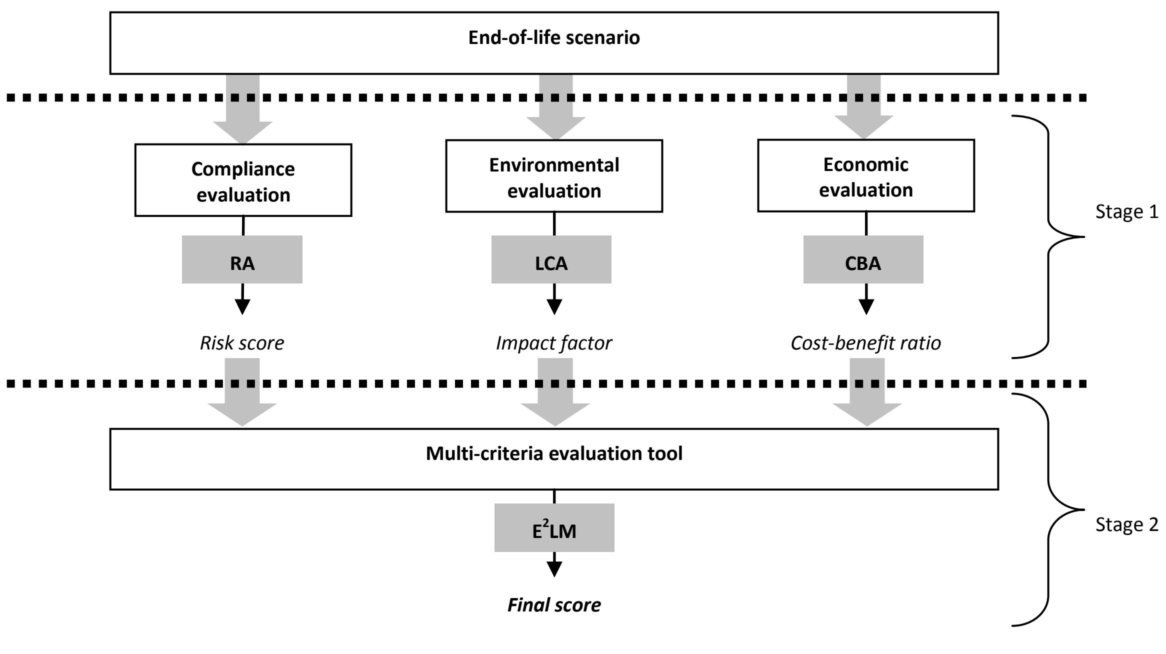


Figure 9.1: High level view of evaluation methodology for SOFC stack end-of-life management

method (RA) is used to identify the risk of non-compliance with future legislation. The development of this compliance evaluation tool is presented in Section 9.3. To evaluate environmental impact, the application of life cycle assessment (LCA) has been developed for use in this evaluation methodology, and is described in Section 9.4. In Section 9.5 a cost-benefit analysis (CBA) tool is presented as a means of conducting an economic evaluation of alternative end-of-life options.

The individual outputs from the RA, LCA and CBA tools provide three performance measures for an end-of-life scenario. When two or more end-of-life scenarios are compared, these performance measures may not readily identify a single preferred solution, since conflicts are likely to arise between the criteria. A multi-criteria evaluation method is therefore required to define priorities and combine the individual scores into a single performance parameter. The E^2LM tool (Environmental, Economic and Legislative Management at end-of-life) has been developed for this purpose and is presented in Section 9.6. This forms Stage 2 of the evaluation methodology shown in Figure 9.1. Application of the E^2LM tool, in combination with the Stage 1 evaluation tools, is demonstrated through case studies in Chapter 10.

Throughout this chapter, the formats in which results are presented from the various evaluation tools are illustrated using example data. It should be noted that the numerical values of these data have been generated for illustrative purposes only, and therefore do not relate to the evaluation of real end-of-life scenarios.

9.3 Evaluation of compliance using a risk-based model

Compliance with environmental legislation is the first of the three criteria evaluated within the methodology illustrated in Figure 9.1. A two-stage process is required for the evaluation of this performance metric. This two-stage process addresses the following two questions:

- Does the end-of-life scenario comply with existing legislation?
- What is the risk of the end-of-life scenario failing to comply with future legislation?

In the first instance, failure to comply with the requirements established by existing legislation identifies the end-of-life scenario as being unsuitable for further consideration. Some modification may be applied to the end-of-life scenario at this stage to address the non-compliance identified in the evaluation, or the scenario may simply be discarded. In the second instance, the evaluation considers compliance with future legislation: a risk-assessment evaluation tool has been developed to provide a systematic means of evaluating and quantifying the risk of non-compliance. A risk-based method was identified as being an appropriate approach to this part of the evaluation, since a substantial level of uncertainty remains as to the exact nature of future legislative requirements. Alternative quantitative methods, such as the monetisation of legislative risk, require the generation of numerical data, based on a range of assumptions. Therefore the outcomes maintain a high degree of uncertainty, which may be masked by the presentation of results in absolute monetary terms. For this reason, and based on the fact that risk assessment is a well-established process which is simple to perform and is a familiar tool in industries such as Rolls-Royce Fuel Cell Systems, the evaluation method described in Sections 9.3.1 and 9.3.2 were developed. An overview of the evaluation method for legislative compliance is shown in Figure 9.2.

9.3.1 Evaluation of compliance with existing legislation

The evaluation of compliance with existing legislation adopts a high level approach, with the intention of highlighting any significant non-compliance issues. This high level approach assumes that local health, safety and environment (HSE) regulations are adhered to. It is envisaged that SOFC manufacturers would have robust health, safety and environmental management systems in place for everyday operational activities, and that collaboration with industrial partners for implementation of end-of-life processes would be subject to the normal auditing process applied to the supply chain.

These assumptions are reflected in the questionnaire developed to evaluate compliance with existing legislative requirements, shown in Figure 9.3. The questionnaire is in two sections. The purpose of the first section of the questionnaire is to highlight any aspects of the end-of-

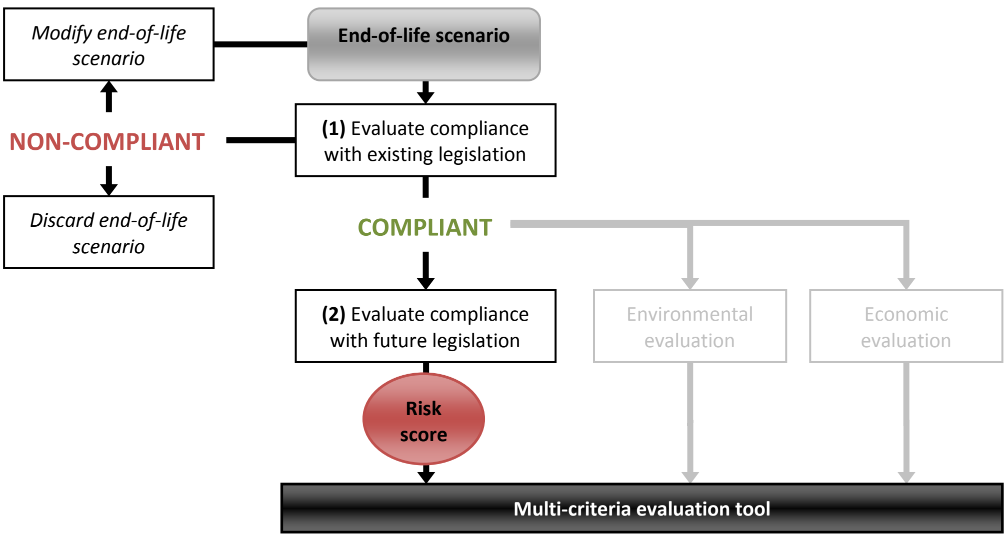


Figure 9.2: Detail of the evaluation method for legislative compliance.

life product or end-of-life process which are likely to require specific consideration when ensuring that local HSE procedures are adhered to. These primarily relate to the presence of hazardous materials and the management of hazardous waste. The use of hazardous materials in the SOFC stack, or in the end-of-life process, does not in itself represent non-compliance with existing legislative requirements, but does lead to a risk of non-compliance if local management procedures are not robust. In this section of the questionnaire, the questions are designed such that a negative response highlights a need for close management controls to be applied at the local level. These negative responses appear in amber, designed to represent a risk of non-compliance, as well as indicating an opportunity for improvement.

The second section of the questionnaire is concerned with specific compliance issues. In this section a negative response appears in red, indicating non-compliance. The overall result from this first step in the evaluation of legislative compliance designates the end-of-life scenario as being “COMPLIANT” or “NON-COMPLIANT”. “COMPLIANT” scenarios may contain a number of amber responses, highlighting the importance of local governance. Any scenario containing a red response is evaluated as being “NON-COMPLIANT”. According to the methodology shown in Figure 9.2, a “NON-COMPLIANT” result directs the user to discard or modify the end-of-life scenario under evaluation. A “COMPLIANT” result directs the user to the next step of the legislative risk assessment.

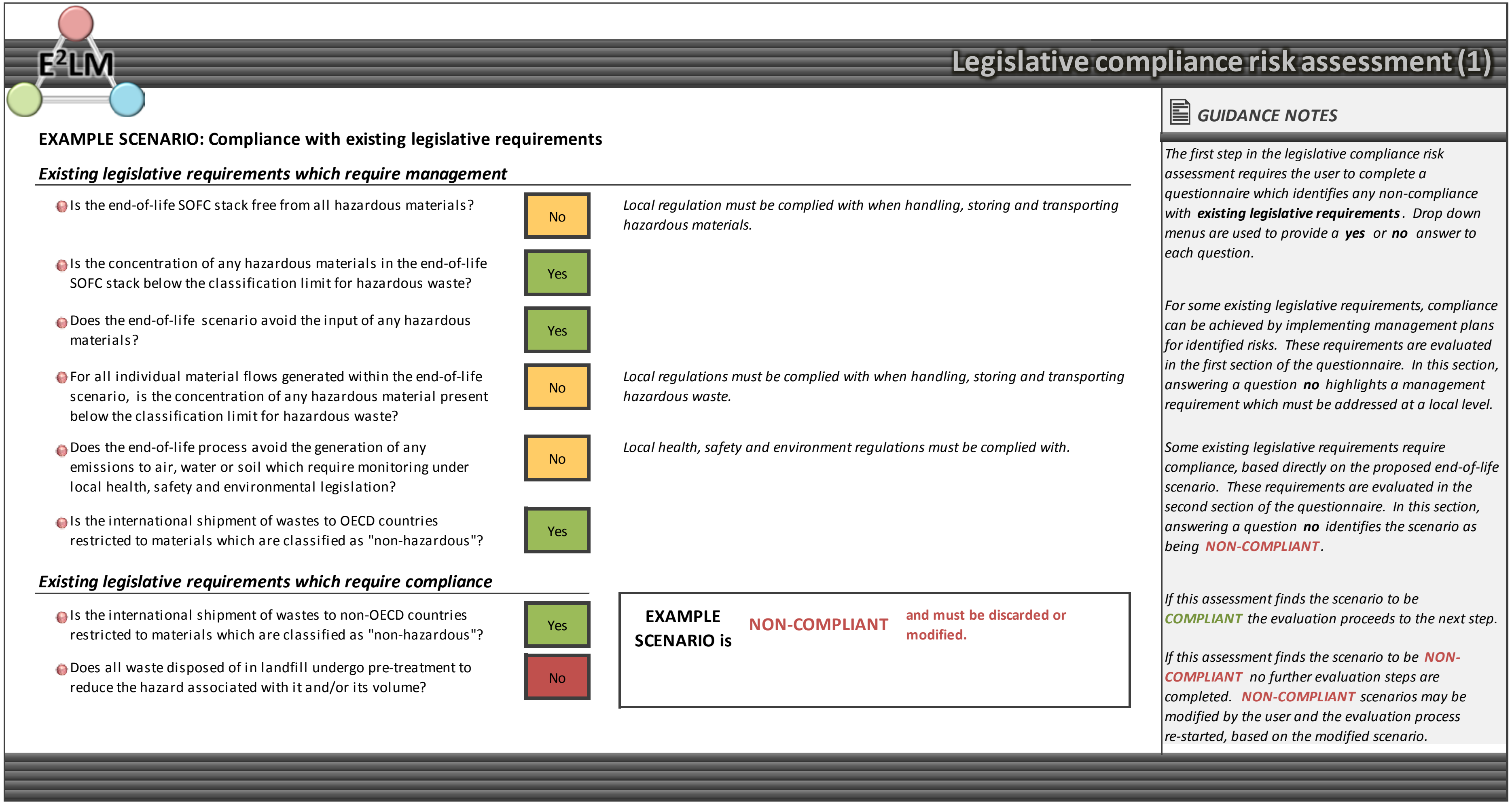


Figure 9.3: Standard questionnaire for the evaluation of compliance with existing legislative requirements.

9.3.2 A risk-assessment methodology for evaluating compliance with future legislation

Much of the legislation identified as being relevant to end-of-life management of SOFC stacks in the review documented in Chapter 4 of the thesis was classified as future legislation. This legislation establishes requirements which are not currently applicable to the management of end-of-life SOFC stacks, but which are considered likely to be relevant in the future. For example, EPR legislation exemplified by the WEEE Directive and End-of-life vehicles Directive does not include end-of-life waste from SOFC stacks. The technology is not included within the scope of any similar legislative measure; however, it would be unwise for SOFC developers to consider the technology immune from legislation encompassing the concept of EPR, and future developments in legislation should be anticipated.

In order to allow consideration of these potential future legislative requirements, a legislative risk assessment tool was developed. This tool aims to evaluate the risk of future non-compliance with legislation, based on predictions that can be made from today's existing legislative framework. The tool is required to evaluate whether a proposed end-of-life scenario represents a high risk of non-compliance or a low risk of non-compliance. Scenarios representing a low risk of non-compliance should be favoured over those representing a high risk of non-compliance.

The following terminology is adopted in the risk assessment tool:

- **Potential impact (*i*):** A specific impact which future legislation will potentially have on the end-of-life management of SOFC stacks.
- **Magnitude** of the potential impact (**M_i**)**:** Reflects the magnitude of the impact upon the end-of-life management of SOFC stacks. If the end-of-life scenario already addresses the future legislative requirements then the magnitude of the impact is small. If substantial modification is required in order to address the future legislative requirement then the magnitude of the impact is large. The scoring system used to evaluate M_i is defined in Table 9.1.
- **Probability** of the potential impact arising (**P_i**)**:** Reflects the likelihood of the future legislative requirement becoming directly relevant to the end-of-life management of SOFC stacks, based on current knowledge regarding the development of legislative trends. The scoring system used to evaluate P_i is defined in Table 9.2.

- **Risk** arising from the potential impact (***R_i***)**:** Calculated as the product of M_i and P_i. The designation of the final risk score as "high", "medium" or "low" is depicted in Figure 9.4.

In order to support the application of the legislative compliance risk assessment methodology within the evaluation methodology an Excel-based tool has been developed, and an output screen is shown in Figure 9.4. This tool illustrates the potential impacts from future legislation, defined based on the knowledge gained during the review of legislation documented in Chapter 4 of the thesis. For each impact the user provides a score for M_i and P_i based on his or her knowledge of the end-of-life scenario and the SOFC stack. The tool automatically calculates the risk associated with each impact (R_i). The overall risk of non-compliance for an evaluated scenario is calculated as the average of all the individual risk scores. Further description of the application of this method to the complete SOFC life cycle is provided in Wright *et al.* (2009).

The presentation of results from the legislative risk evaluation methodology, as shown in Figures 9.3 and 9.4 was developed through various iterations. Initially the tool was presented as a simple Excel spread sheet, however, it was found that this method of presentation lacked visual impact, and thus the appearance of the tool was improved, with the introduction of colour. Following discussions with various industrial contacts throughout the course of the research, a simple traffic light colour-coding system was found to provide a familiar visual representation of high, medium and low risk and was therefore adopted.

Table 9.1: Scoring system used to evaluate M_i in the legislative compliance risk assessment methodology

Score	Magnitude (M_i)
1	Will have minimal impact on the scenario proposed for the end-of-life management of SOFC stacks. The requirement is already met by the end-of-life scenario.
2	Will impact on the scenario proposed for the end-of-life management of SOFC stacks. Modifications to the end-of-life scenario in order to meet the requirement are feasible with some development effort.
3	Will have severe impact on the scenario proposed for the end-of-life management of SOFC stacks. Modifications to the end-of-life scenario in order to meet the requirement are substantial, and of unknown feasibility.

Table 9.2: Scoring system used to evaluate P_i in the legislative compliance risk assessment methodology

Score	Probability (P_i)
1	Low probability—general trend suggests potential future impact in >25 years.
2	Moderate probability—current or developing legislation is likely to impact within 5–25 years.
3	High probability—legislation currently impacts or is expected to impact in <5 years.

E²LM

Legislative compliance risk assessment (2)

EXAMPLE SCENARIO: Compliance with future legislative requirements

Potential impacts identified from future legislative requirements	M_i	P_i	R_i
Definition of hazardous waste becomes more stringent, such that all waste containing hazardous substances is classified as hazardous.	2	2	4
Recycling or recovery of up to 40% of the product (by weight) is required.	2	3	6
Recycling or recovery of 40 - 80% of the product (by weight) is required.	2	2	4
Recycling or recovery of more than 80% of the product (by weight) is required.	3	2	6
International transportation of hazardous wastes is prohibited.	1	2	2
International transportation of wastes is prohibited.	2	1	2
Disposal of all hazardous wastes to landfill is prohibited.	2	3	6
Disposal of all wastes to landfill is prohibited.	3	1	3

EXAMPLE SCENARIO: TOTAL RISK SCORE (R_T) = 4.13

TOTAL RISK SCORE (R_T) = $\sum R_i / n_i$

Where n_i is the total number of impacts evaluated.

- **HIGH RISK, $R_T > 4$**
- **MEDIUM RISK, $2 < R_T \leq 4$**
- **LOW RISK, $R_T \leq 2$**

GUIDANCE NOTES

The second step of the legislative compliance risk assessment evaluated the risk of non-compliance with future legislative requirements. The questionnaire identifies potential impacts arising from the development of existing legislative trends.
For each impact the user is required to evaluate the ***MAGNITUDE*** *of the impact* ***(M_i)*** *on the end-of-life scenario and the* ***PROBABILITY*** *of the impact arising* ***(P_i)****.*

SCORING FOR ***M_i***

1 *= Has minimal impact on the end-of-life scenario. The requirement is already met by the scenario.*

2 *= Will impact on the end-of-life scenario. Modifications to the end-of-life scenario in order to meet the requirement are feasible with some development effort.*

3 *= Will have severe impact on the end-of-life scenario. Modifications to the end-of-life scenario in order to meet the requirement are substantial, and of unknown feasibility.*

SCORING FOR ***P_i***

1 *= Low probability—general trend suggests potential future impact in >25 years.*

2 *= Moderate probability—current or developing legislation is likely to impact within 5–25 years.*

3 *= High probability—legislation currently impacts or is expected to impact in <5 years.*

Figure 9.4: Risk assessment tool for evaluating risk of non-compliance with future legislative requirements.

9.4 Evaluation of environmental performance using life cycle assessment

Life cycle assessment (LCA) is a standard methodology for evaluating the environmental impacts of products and processes, and has been reviewed in some detail in Chapter 4 of the thesis. During the early scoping phase of the research, it became apparent that the completion of full LCA, encompassing the complete SOFC life cycle, was not necessary for comparing the relative performance of alternative end-of-life scenarios. However, it was also believed that LCA provides a rigorous data-driven approach to the quantification of environmental impacts, which would support the development of a quantitative multi-criteria decision making methodology. Therefore a streamlined LCA approach, based on a restricted system boundary, was identified as an appropriate method to support the evaluation of the environmental impacts of alternative end-of-life scenarios for the SOFC stack, within the multi-criteria evaluation methodology.

A commercial LCA software package, GaBi4 (PE International GmbH, 2007) was utilised to support the environmental evaluation of alternative end-of-life scenarios. The environmental evaluation method developed in the research follows the four principal steps of LCA, as defined in ISO 14040 (ISO, 2006a) and summarised in Chapter 4 of the thesis (see Figure 4.4). These steps are highlighted in Figure 9.5, which provides an overview of the method. The method has been developed to minimise the requirement for the user to be involved in the operation of the GaBi4 software, which requires an element of specialist knowledge. GaBi4 is principally used to generate life cycle inventory data for individual material, energy, transport,

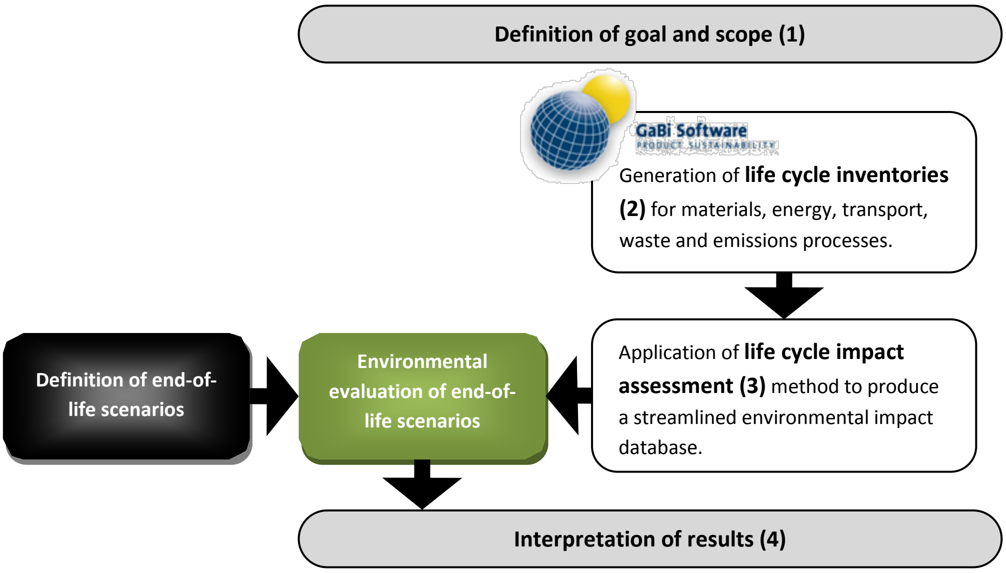


Figure 9.5: Overview of the method for environmental evaluation indicating the four principal steps of LCA methodology and the use of GaBi4 software.

waste and emissions processes, and then perform impact assessment calculations on these inventories using methods available within the software. This generates a streamlined environmental impact database, which, in combination with the definition of end-of-life scenarios (described in Chapter 8) provides the background data for the scenario evaluation. Results from the environmental evaluation are presented to the user, and the final environmental impact score provides one of the inputs to the multi-criteria decision support tool. Sections 9.4.1 – 9.4.4 provide a detailed description of the environmental evaluation method, following the four steps of LCA methodology.

9.4.1 Determination of goal and scope

The goal of the LCA within the multi-criteria evaluation methodology can be summarised in the following statement:

- To provide a comparative evaluation of the environmental impacts of alternative end-of-life scenarios for SOFC stacks.

The scope of the LCA is illustrated by the boundary definition shown in Figure 9.6. In defining this boundary, the following assumptions are made:

- The end-of-life phase of the SOFC stack life cycle does not influence the preceding stages (e.g. materials production, manufacture and use). These early steps of the life cycle will remain constant for alternative end-of-life scenarios and therefore are excluded from the scope of the LCA.

- Each end-of-life scenario comprises of collection and sorting, reprocessing and redistribution steps. Each of these steps may contribute to the total environmental impact of the end-of-life scenario.

- The principal input to the end-of-life scenario is end-of-life SOFC stacks. Other inputs include ancillary materials consumed during processing, energy and transportation. Outputs from the systems include emissions to air, water and soil, waste and recycled materials. Impacts of waste disposal are included within the system boundary.

- Recycled materials are considered as avoided impacts. Where X kg of a recycled material is produced by the end-of-life scenario, the impact of producing X kg of the equivalent virgin material is subtracted from the total environmental impact arising from the end-of-life scenario. This approach is only applied to recycled materials for

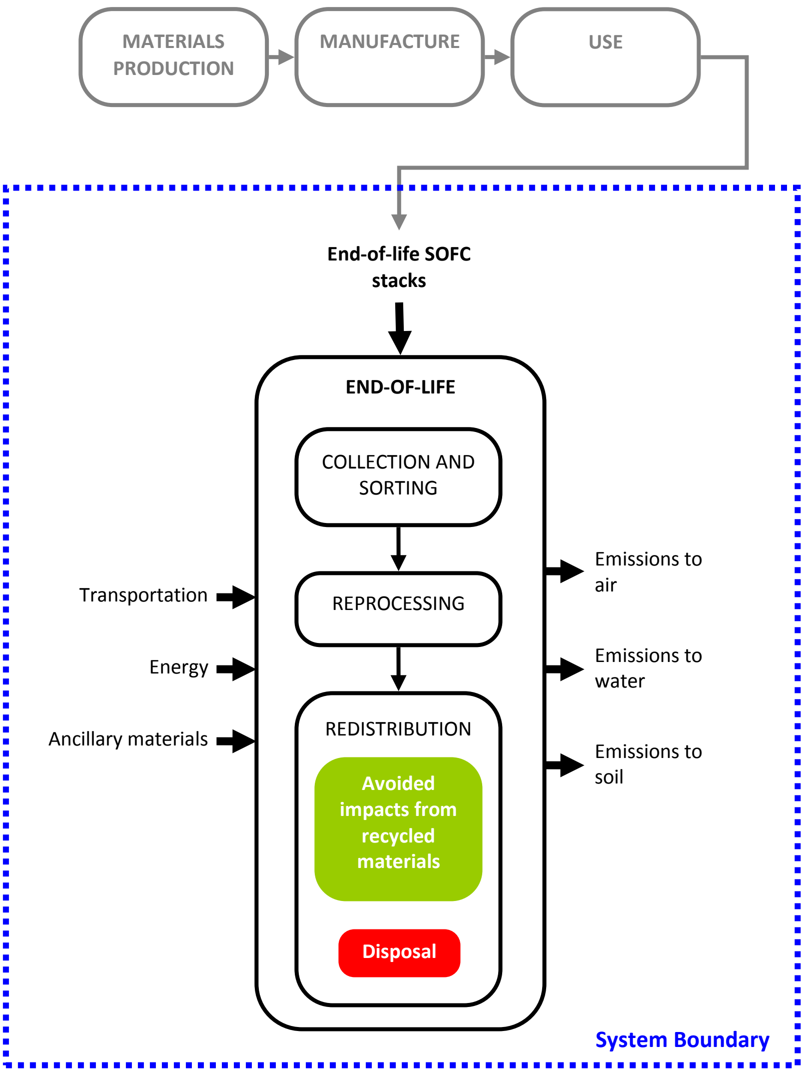


Figure 9.6: High level representation of the System Boundary for LCA within the multi-criteria evaluation framework.

which a known market exists. Transportation of the recycled material to the new user is not included within the system boundary.

The functional unit for the LCA is considered to be the weight of SOFC stack having a total electricity generating capacity of 1 kW. This value is based on theoretical output from the fuel cell stack operating at design point and does not take into account inefficiencies in power delivery from the fuel cell stack to the customer, nor those arising from non-optimal operating conditions. This approach to the functional unit links performance at end-of-life with performance during the operation phase of the life cycle. One of the primary goals for the development of SOFC technology is to increase the power density of the SOFC stack, expressed in terms of kW generating capacity per kg of SOFC stack. In order to support a life cycle approach to product design and improvement, especially in this pre-commercial phase of SOFC development, it is beneficial if the evaluation of the end-of-life phase reflects technological performance during operation.

9.4.2 Generation of a life cycle inventory

Inventory data for individual processes describing the production of ancillary materials; the generation of process energy; transportation; waste disposal; and emissions to air, water and soil are developed in GaBi4. Relevant processes are identified in the definition of alternative end-of-life scenarios, as defined in Chapter 8.

Figure 9.7 illustrates the user interface in GaBi4 whereby processes can be modelled. In the example, the process "transport by lorry" is modelled. This process requires both the production of the lorry (requiring inputs of materials and energy) and the operation of the lorry (where the principal input is fuel). The example is modelled using data available within GaBi4, taken from the Ecoinvent database, version 2.0 (Ecoinvent Centre, 2007). This database was used within the research to support the generation of inventories for many generic processes, including the production of materials, energy and transportation. GaBi4 also allows for user-specific processes to be modelled, based on data collected in the supply chain, from experimental work, or from the literature.

Following the development of a process model, such as that shown in Figure 9.7, GaBi4 calculates the inventory for the process, expressed in substance flows to and from the

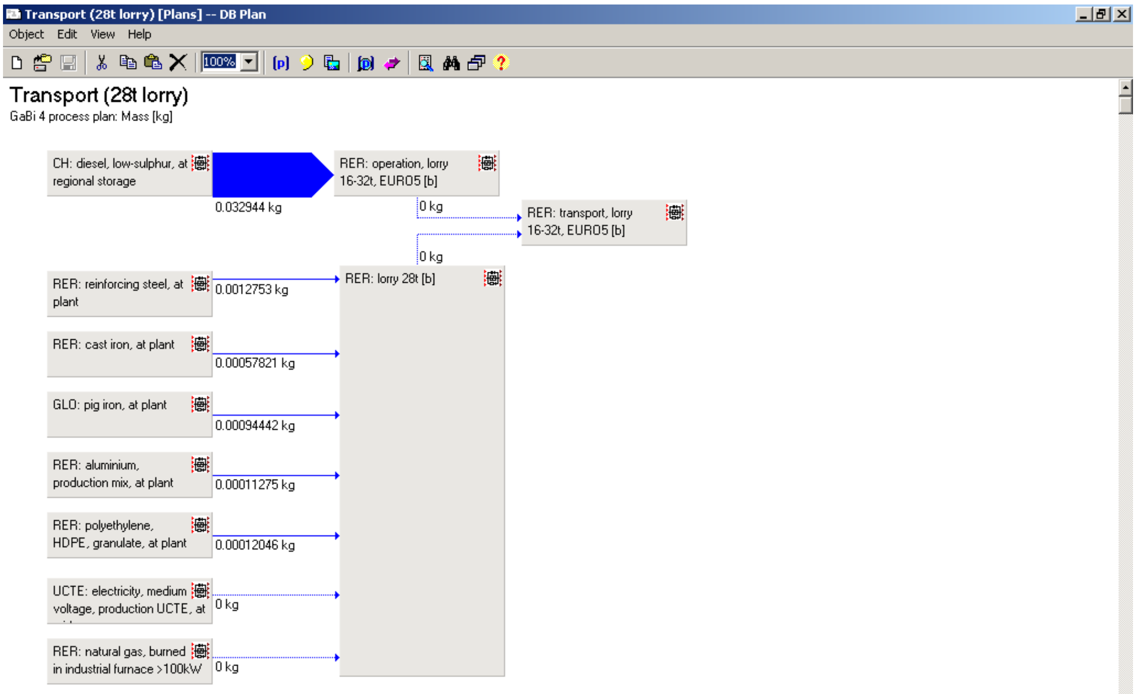


Figure 9.7: Example of process modelling in GaBi4 to support the generation of a process inventory.

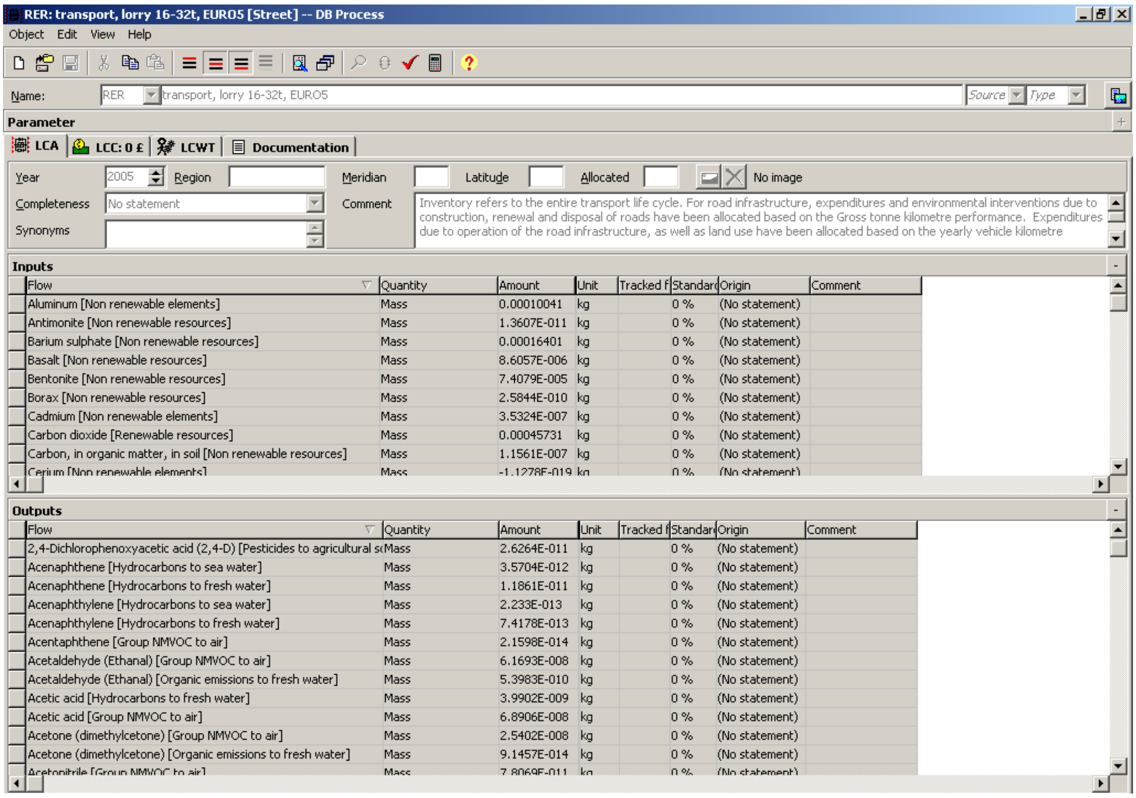


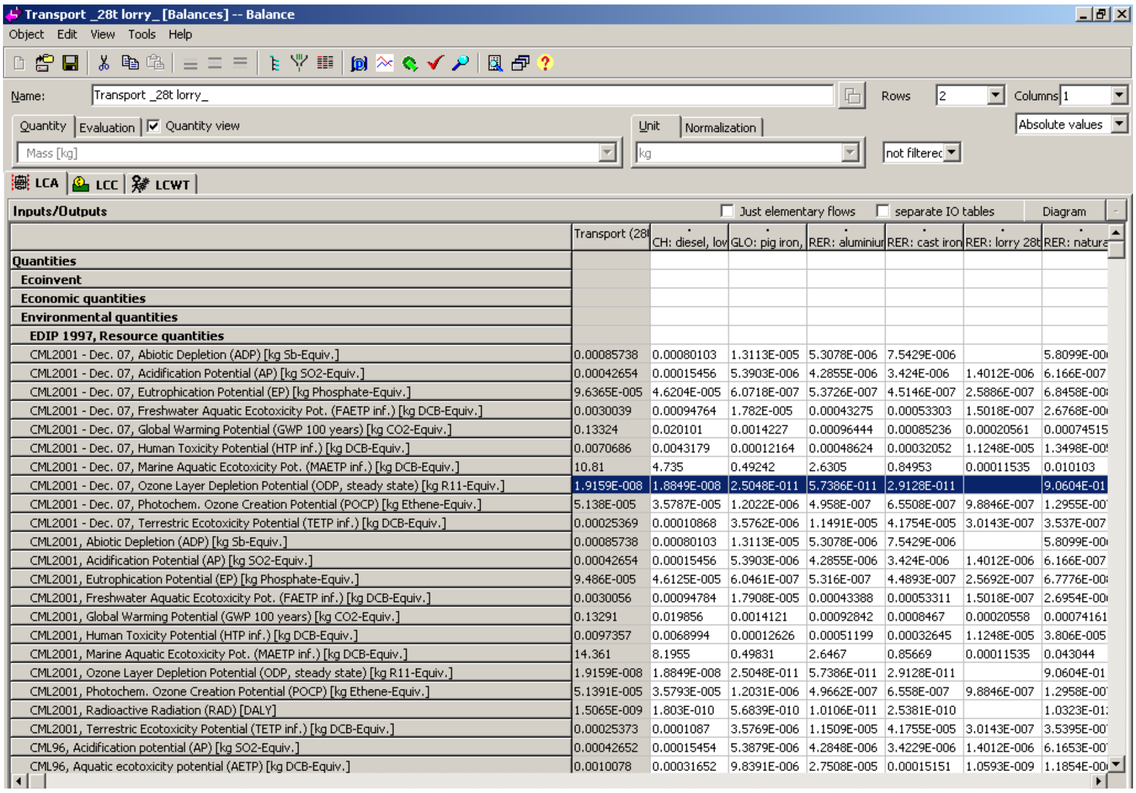
Figure 9.8: Example of a process inventory, generated in GaBi4.

environment. An example of such a process inventory is shown in Figure 9.8. The input and output flows identified in the inventory form the basis of the impact assessment step, described in Section 9.4.3.

Within the environmental evaluation method developed as part of the research, individual inventories are generated for each of the processes identified in the definition of end-of-life scenarios described in Chapter 8. These process inventories form the basis of the streamlined environmental impact database used in the environmental evaluation of alternative end-of-life scenarios, as depicted in Figure 9.5.

9.4.3 Evaluation of environmental impacts

Various impact assessment methods are available within GaBi4 to evaluate a range of environmental impacts. Figure 9.9 illustrates the presentation of impact assessment results for a single process in GaBi4. For the purposes of the multi-criteria evaluation methodology it was beneficial to select an impact assessment method which offers the facility to generate a single score representation of the environmental impacts of an end-of-life scenario. The CML2001 – Dec. 2007 method was selected as an appropriate method. This is a well-established method, which was updated within the GaBi4 software in December 2007. As well as including within its scope a full range of environmental impacts, the method has been



	Transport (28	CH: diesel, low	GLO: pig iron,	RER: aluminiur	RER: cast iron	RER: lorry 28t	RER: natura
Quantities							
Ecoinvent							
Economic quantities							
Environmental quantities							
EDIP 1997, Resource quantities							
CML2001 - Dec. 07, Abiotic Depletion (ADP) [kg Sb-Equiv.]	0.00085738	0.00080103	1.3113E-005	5.3078E-006	7.5429E-006		5.8099E-00
CML2001 - Dec. 07, Acidification Potential (AP) [kg SO2-Equiv.]	0.00042654	0.00015456	5.3903E-006	4.2855E-006	3.424E-006	1.4012E-006	6.166E-007
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	9.6365E-005	4.6204E-005	6.0718E-007	5.3726E-007	4.5146E-007	2.5886E-007	6.8458E-00
CML2001 - Dec. 07, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	0.0030039	0.00094764	1.782E-005	0.00043275	0.00053303	1.5018E-007	2.6768E-00
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0.13324	0.020101	0.0014227	0.00096444	0.00085236	0.00020561	0.00074515
CML2001 - Dec. 07, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	0.0070686	0.0043179	0.00012164	0.00048624	0.00032052	1.1248E-005	1.3498E-00
CML2001 - Dec. 07, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	10.81	4.735	0.49242	2.6305	0.84953	0.00011535	0.010103
CML2001 - Dec. 07, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	1.9159E-008	1.8849E-008	2.5048E-011	5.7386E-011	2.9128E-011		9.0604E-01
CML2001 - Dec. 07, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	5.138E-005	3.5787E-005	1.2022E-006	4.958E-007	6.5508E-007	9.8846E-007	1.2955E-00
CML2001 - Dec. 07, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	0.00025369	0.00010868	3.5762E-006	1.1491E-005	4.1754E-005	3.0143E-007	3.537E-007
CML2001, Abiotic Depletion (ADP) [kg Sb-Equiv.]	0.00085738	0.00080103	1.3113E-005	5.3078E-006	7.5429E-006		5.8099E-00
CML2001, Acidification Potential (AP) [kg SO2-Equiv.]	0.00042654	0.00015456	5.3903E-006	4.2855E-006	3.424E-006	1.4012E-006	6.166E-007
CML2001, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	9.486E-005	4.6125E-005	6.0461E-007	5.316E-007	4.4893E-007	2.5692E-007	6.7776E-00
CML2001, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	0.0030056	0.00094784	1.7908E-005	0.00043388	0.00053311	1.5018E-007	2.6954E-00
CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0.13291	0.019856	0.0014121	0.00092842	0.0008467	0.00020558	0.00074161
CML2001, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	0.0097357	0.0068994	0.00012626	0.00051199	0.00032645	1.1248E-005	3.806E-005
CML2001, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB-Equiv.]	14.361	8.1955	0.49831	2.6467	0.85669	0.00011535	0.043044
CML2001, Ozone Layer Depletion Potential (ODP, steady state) [kg R11-Equiv.]	1.9159E-008	1.8849E-008	2.5048E-011	5.7386E-011	2.9128E-011		9.0604E-01
CML2001, Photochem. Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	5.1391E-005	3.5793E-005	1.2031E-006	4.9662E-007	6.558E-007	9.8846E-007	1.2958E-00
CML2001, Radioactive Radiation (RAD) [DALY]	1.5065E-009	1.803E-010	5.6839E-010	1.0106E-011	2.5381E-010		1.0323E-01
CML2001, Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	0.00025373	0.0001087	3.5769E-006	1.1509E-005	4.1755E-005	3.0143E-007	3.5395E-00
CML96, Acidification potential (AP) [kg SO2-Equiv.]	0.00042652	0.00015454	5.3879E-006	4.2848E-006	3.4229E-006	1.4012E-006	6.1653E-00
CML96, Aquatic ecotoxicity potential (AETP) [kg DCB-Equiv.]	0.0010078	0.00031652	9.8391E-006	2.7508E-005	0.00015151	1.0593E-009	1.1854E-00

Figure 9.9: Life cycle impact assessment data calculated in GaBi4.

developed in GaBi4 to allow the application of normalisation and weighting to the impact assessment data, providing the opportunity of presenting the results as a single impact score.

The normalisation and weighting steps available in GaBi4 for the CML2001 – Dec.07 method can be applied to a set of six impact categories:

- Abiotic depletion (AD)
- Acidification potential (AP)
- Eutrophication potential (EP)
- Global warming potential (GWP)
- Ozone layer depletion potential (ODP)
- Photochemical ozone creation potential (POCP)

This set of impact categories, defined in Table 4.3, was therefore selected for application to the inventory data developed for individual processes.

After developing impact assessment data for each individual process, based on the inventories described in Section 9.4.2, these datasets were exported to Excel, forming a streamlined database of environmental impacts.

This database forms the basis of the environmental impact assessment included within the multi-criteria evaluation methodology used to compare alternative end-of-life scenarios for SOFC stacks. Based on the defined end-of-life scenario, as described in Chapter 8, the impacts associated with each input and output flow of material, energy, transportation, waste and other emissions, are added together. This stage in the evaluation method requires the use of data collected from experimental work and/or commercial process trials, or simulated data representing proposed end-of-life scenarios. Specific issues concerning data availability at this stage of the evaluation method are explored further within the case studies, reported in Chapter 10.

The calculation of individual environmental impact scores provides a detailed view of the environmental performance of the alternative end-of-life scenarios. However, in order to be able to use the environmental impact as part of a multi-criteria evaluation tool, a single score output was required. The CML2001 Experts IKP (Northern Europe) evaluation method, available within GaBi4 was selected to combine the individual outputs from each of the impact categories described above (PE International GmbH, 2007). The method applies weighting, according to a panel decision, to each of the impact categories. In addition a normalisation step is required, which normalises the calculated impact score against the average annual impact for a given geographical region of population. In this case the northern European average was used (PE International GmbH, 2007). The weighting assigned under this method is shown in Table 9.3. While useful in supporting decision-making, the application of normalisation and weighting to the output from the impact assessment stage of the LCA is optional in the ISO 14044 methodology (ISO, 2006b).

Table 9.3: Weighting factors applied in the life cycle impact assessment evaluation method CML2001 – Dec. 07, Experts IKP (Northern Europe) (PE International GmbH, 2007)

Environmental impacts (CML2001 – Dec. 07 method)	**Units**	**Weighting**
Abiotic Depletion (ADP)	kg Sb-Equiv.	1.5
Acidification Potential (AP)	kg SO_2-Equiv.	4
Eutrophication Potential (EP)	kg Phosphate-Equiv.	7
Global Warming Potential (GWP 100 years)	kg CO_2-Equiv.	10
Ozone Layer Depletion Potential (ODP, steady state)	kg R11-Equiv.	4
Photochem. Ozone Creation Potential (POCP)	kg Ethene-Equiv.	1.5

The generation of individual environmental impact results, prior to the application of normalisation and weighting factors, provides a level of transparency which is lost through the calculation of an amalgamated single score result. In addition, the expression of individual environmental impact scores as absolute values allows an expert to interpret the results within a wider context, based on his or her expert knowledge of the absolute environmental impacts arising from other processes. However, for the purposes of supporting decision making in a practical way, and potentially within an industrial environment where expert knowledge cannot be guaranteed, it is useful to remove the complexity inherent to a set of six individual scores through the generation of a single figure result. Despite the simplification that this additional step in the impact assessment methodology brings, the single figure result could be disputed by an expert, on the grounds that the normalisation and weighting factors used in its generation were not representative or accurate. Therefore, and as shown in the following section, the output from the LCA evaluation method includes one screen showing individual environmental impacts, expressing as absolute values, and a second screen showing the amalgamated results following the application of normalisation and weighting factors.

9.4.4 Interpretation of results

The required input for the multi-criteria evaluation tool is the single-figure impact score, calculated following the application of normalisation and weighting to the impact assessment data. While this is useful in supporting decision-making, an element of transparency is lost with regard to the individual impact categories investigated, and their connection with different stages in the end-of-life process. For this reason, the output from the environmental evaluation is provided in two formats. On the first results screen, a set of charts is presented to the user, identifying the impact assessment results for each of the six impact categories. These impacts are categorised according to the three stages within the end-of-life management process, with impacts from the reprocessing stage further categorised as arising from transportation or material processing. These results are presented for a single comparison, and represent the impact assessment results, prior to any normalisation or application of weighting factors. Figure 9.10 provides an illustrative screenshot of this first results page, generated using example data.

The final results page provides normalised, weighted results for all scenarios under comparison. As well as providing the numerical single-figure score, a chart is provided showing the contribution of each of the end-of-life stages to the overall score. An example of the format in which results are presented is shown in Figure 9.11.

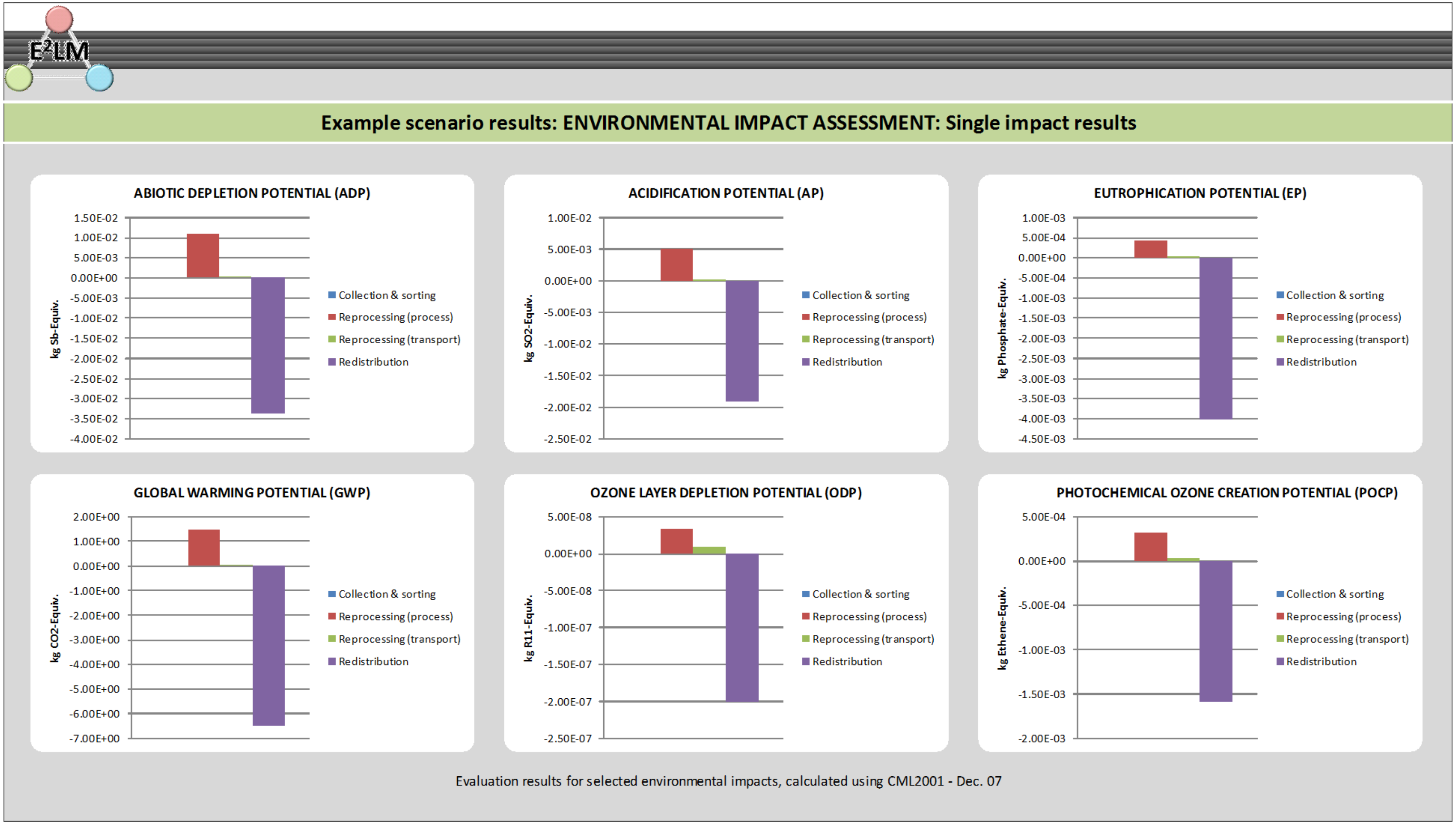


Figure 9.10: Initial presentation of results from the environmental evaluation, showing results for a single scenario for individual impact categories, prior to any normalisation or weighting.

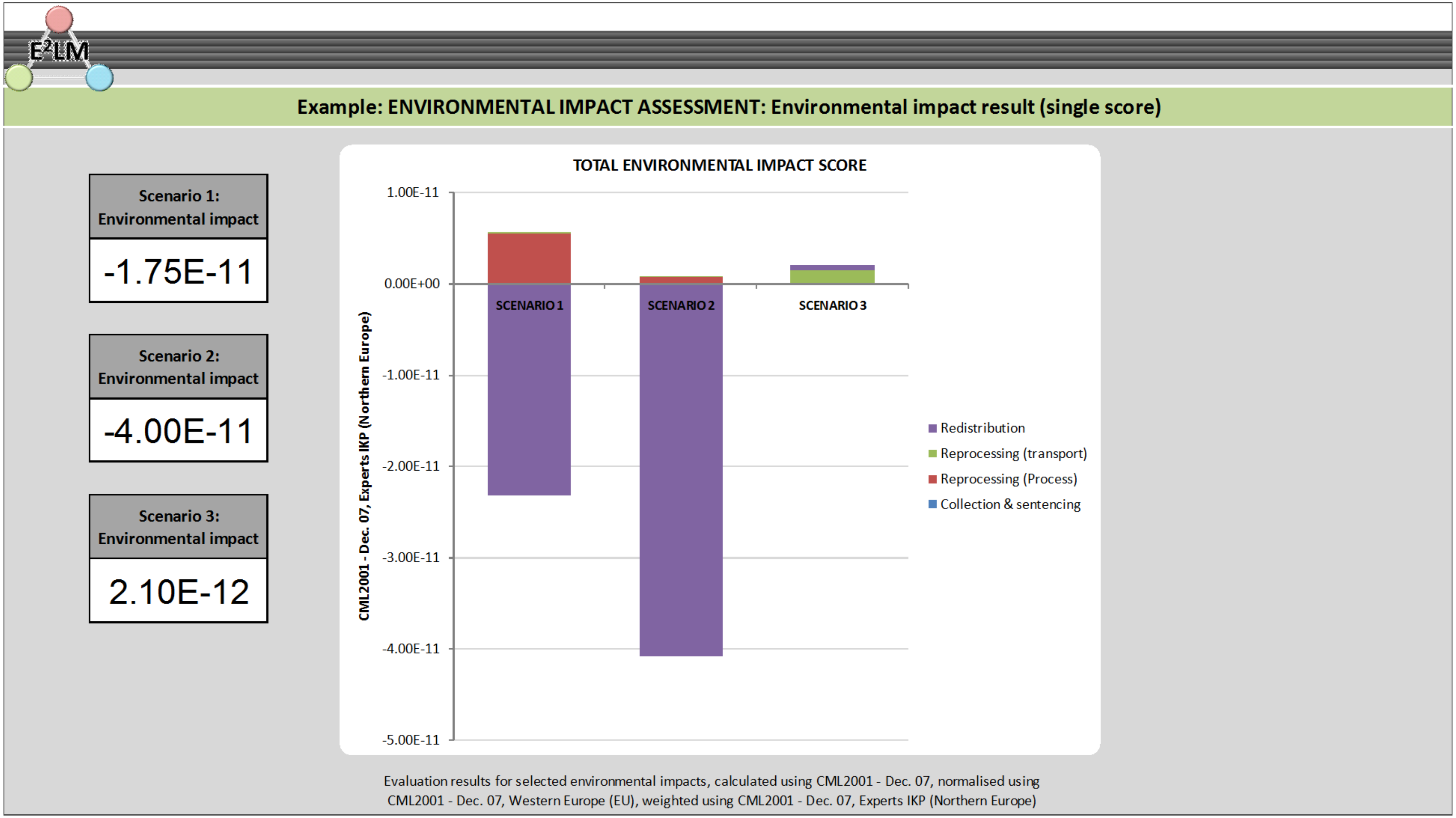


Figure 9.11: Final presentation of results from the environmental evaluation, showing a single-figure environmental impact for each scenario, and a chart showing the breakdown of impacts arising.

9.5 Evaluation of economic performance using a parametric cost-benefit ratio approach

A cost-benefit analysis (CBA) approach is adopted in the evaluation methodology in order to provide an economic performance metric for alternative end-of-life scenarios. CBA is used to support decision-making across a broad range of situations, including the development of environmental and social policy as well as in the adoption of new technologies or processes. In contrast to traditional accounting methods, CBA originally evolved to provide a means by which external effects, i.e. those of a social or environmental nature, may be captured within economic analysis, alongside merely commercial considerations (Hanley and Spash, 1993). CBA therefore allows a holistic approach to the evaluation of economic performance by extending economic analysis to include both direct and indirect benefits and costs (Doeleman, 1985). However, in the evaluation methodology adopted in the research, CBA is used only as a simple method to quantify direct benefits and costs. The other elements of the methodology, namely the legislative risk assessment tool and the use of LCA, support evaluation of other aspects of the end-of-life scenario.

Unlike for LCA, which has a standardised methodology documented in the ISO14000 series of international standards (ISO, 2006a and 2006b), the CBA method is founded on some fundamental principles, which may be applied in many different ways to a broad range of situations. Some examples of the application of CBA, in particular with respect to the evaluation of end-of-life management, are provided in the review of the literature reported in Chapter 4.

The fundamental principles on which CBA are founded require the quantification of all relevant costs (C) and revenues, or benefits (B), associated with the scenario under evaluation. Quantification of these values is considered in terms of present value (PV), which incorporates a discount rate (i) to reflect changes in monetary value over time (t). The equations used to express the total costs and revenues associated with a given scenario are adapted from Hanley and Spash (1993) and are shown in Equations 9.1 and 9.2 respectively:

$$PV\ (C) = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \qquad Equation\ 9.1$$

$$PV\ (B) = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t} \qquad Equation\ 9.2$$

where $PV(C)$ = present value of costs

$PV(B)$ = present value of benefits

i = discount rate

t = time in years

n = number of years

Within the research, it is assumed that alternative end-of-life scenarios are applied according to the same timescales, and that costs and benefits quantified within the streamlined CBA approach adopted in the evaluation method are immediate. This provided justification for removing the time element associated with the CBA method, such that i = 0 and t = 0. A similar approach was adopted by Staikos (2007). This provides the simplified expressions:

$$PV\ (C) = \sum_{m=1}^{n} \frac{C_m}{(1+0)^0} = \sum_{m=1}^{n} C_m \qquad Equation\ 9.3$$

$$PV\ (B) = \sum_{m=1}^{n} \frac{B_m}{(1+0)^0} = \sum_{m=1}^{n} B_m \qquad Equation\ 9.4$$

where $PV(C)$ = present value of costs

$PV(B)$ = present value of benefits

C_m = individual cost associated with the scenario, for $m = 1, 2, 3, ..., n$.

B_m= individual revenue associated with the scenario for $m = 1, 2, 3, ..., n$.

Results from CBA are typically expressed as a ratio of the summed costs and revenues, and can be presented either as a cost-benefit ratio (CBR) or benefit-cost ratio (BCR). In the evaluation methodology developed in the research, it is necessary that the results from the economic evaluation tool are consistent in form with the results from the legislative risk assessment and LCA evaluations. For both of these other evaluation methods, high value result indicates poor performance (i.e. high risk of non-compliance and high environmental impact, respectively). Thus, it was decided to calculate the CBA results in terms of a cost-benefit ratio. Therefore an unfavourable scenario with high associated cost and low associated benefit yields a high numerical result. Conversely, a favourable scenario with low associated costs and high associated benefit yields a low numerical result. Calculation of the cost-benefit ratio (CBR) is according to the formula:

$$CBR = \frac{PV(C)}{PV(B)} = \frac{\sum_{m=1}^{n} C_m}{\sum_{m=1}^{n} B_m} \qquad Equation\ 9.5$$

This generic formula is used to define parametric cost-benefit models for alternative end-of-life scenarios, within the economic evaluation method applied as part of the multi-criteria evaluation methodology.

9.5.1 Definition of parametric cost-benefit models for end-of-life scenarios

In order to evaluate alternative end-of-life scenarios, a parametric cost-benefit model is required for each scenario, encompassing all costs and revenues arising throughout the end-of-life management process. In order to illustrate this approach, an illustrative parametric cost model has been developed for the first end-of-life scenario defined in Chapter 8. A summary of the terminology used in the development of these models is presented in Table 9.4.

Example: Scenario 1 - Mechanical separation with selective recycling

The cost-benefit ratio for scenario 1 (CBR_{MECH}) is defined as:

$$CBR_{MECH} = \frac{\sum_{m=1}^{n} C_m}{\sum_{m=1}^{n} B_m} \qquad Equation\ 9.6$$

The total costs associated with end-of-life scenario 1 (C_{MECH}) arise from the transportation of end-of-life SOFC stacks from the operating site to the initial treatment facility (C_{trans1}), the operating costs of the mechanical material separation process (C_{op1}), transportation of the recyclable material fraction to the recycling facility (C_{trans2}) and the operating costs of the final recycling process (C_{op2}). In addition, the disposal of the non-recyclable material fraction (C_{disp}) contributes.

This gives a parametric model for the costs associated with scenario 1 as:

$$\begin{aligned} C_{MECH} = {} & C_{trans1} + C_{op1} + C_{trans2} + C_{op2} + C_{disp} \\ & = (W_{trans1} \times P_{trans1}) + \left(W_{op1} \times P_{op1}\right) + (W_{trans2} \times P_{trans2}) \\ & + \left(W_{op2} \times P_{op2}\right) + \left(W_{disp} \times P_{disp}\right) \end{aligned} \qquad Equation\ 9.7$$

Scenario 1 yields two output flows with redistribution value: ceramic plates from the mechanical separation process (R_{CER}), and precious metal from the final recycling step (R_{PM}). The total benefits associated with scenario 1 (B_{MECH}) are calculated as the sum of all revenues generated by the recovery of these valuable materials. This gives a parametric model for the benefits associated with scenario 1 as:

$$B_{MECH} = R_{CER} + R_{PM} = (CER_{weight} \times CER_{value}) + (PM_{weight} \times PM_{value})$$

Equation 9.8

Similarly, parametric cost-benefit models may be developed for any alternative end-of-life scenario.

Table 9.4: Summary of terminology used in defining parametric cost-benefit models for end-of-life scenarios.

COSTS	DEFINITION
$C_{trans} = W_{trans} \times P_{trans}$	Cost of collection of end-of-life product or part-processed material from its original location and transportation to the necessary processing site, in £. One or more collection and transportation costs may be included in a scenario, depending on the number of process steps involved and their location.
W_{trans}	Weight of end-of-life product or part-processed material requiring collection or transportation, in kg.
P_{trans}	Price for collection and transportation of 1 kg end-of-life product or part-processed material, in £ per kg.
$C_{op} = W_{op} \times P_{op}$	Operating costs for a treatment step within the end-of-life process, in £. One or more operating costs may be included in the scenario, depending on the number of treatment steps and the extent to which cost data is broken down by the data provider.
W_{op}	Weight of end-of-life product, or part-processed material stream requiring treatment, in kg.
P_{op}	Price for treatment step, in £ per kg.
$C_{disp} = W_{disp} \times P_{disp}$	Disposal costs for residual material remaining after all treatment processes have been completed, in £. Residual material may originate directly from the end-of-life product or may arise from ancillary materials used in the treatment of wastes. Disposal costs may be incorporated in operating costs or provided separately.
W_{disp}	Weight of end-of-life product or residual material requiring disposal, in kg.
P_{disp}	Price for disposal of residual material, in £ per kg.
BENEFITS	**DEFINITION**
$R_M = M_{weight} \times M_{value}$	The revenue recovered from the recovery of valuable material, in £. For any scenario one or more valuable material streams may be recovered.
M_{weight}	The weight of valuable material recovered in a form suitable for resale, in kg.
M_{value}	The market value of recovered material in £ per kg.

9.5.2 Evaluation of cost-benefit ratios for end-of-life scenarios

In order to conduct an economic evaluation of alternative end-of-life scenarios, the parametric models defined in Section 9.5.1 are used. Values for each of the required parameters are developed from available data, originating from a variety of primary and secondary sources. The challenges and limitations associated with data collection for the economic evaluation are illustrated and discussed through the case studies reported in Chapter 10.

9.6 E^{2}LM: a multi-criteria decision support tool

A multi-criteria evaluation tool has been developed to allow the output from the legislative risk assessment, LCA and CBA to be combined into a single score. The single score encompasses legislative compliance, environmental impact and economic impact for each evaluated scenario, and as such supports decision making, with respect to the selection of the end-of-life scenario demonstrating best overall performance.

The tool developed as part of the research to support multi-criteria decision making is called **E^{2}LM**, which stands for **E**nvironmental, **E**conomic and **L**egislative impact **M**odel for end-of-life management. The tool was developed in Excel to provide a user-friendly interface and to allow integration with the single-criterion evaluation methods described in the previous sections of this chapter.

Various approaches to multi-criteria decision making are available and have been briefly reviewed in Chapter 4 of the thesis. However, at the outset of the development of the multi-criteria decision support tool it was identified that the requirements for this tool were relatively simple. One principal requirement was the ability to apply weighting factors to the three evaluated criteria in order to incorporate the perceived relative significance of legislative risk, environmental impact and economic impact. A Weighted Sum Method (WSM) was identified as meeting this requirement, and was therefore applied in the research. This method is one of the oldest and simplest approaches to multi-criteria decision making (Triantaphyllou, 2000) and can be expressed in the equation (Fishburn, 1967):

$$A^*_{WSM\ score} = \min(i) \sum_{j=1}^{n} a_{ij} w_j \qquad for\ i = 1, 2, 3, \dots, n. \qquad Equation\ 9.9$$

where, for the evaluation of *m* scenarios against *n* criteria:

$A^*_{WSM\ score}$ = the WSM score of the best scenario

$\min(i)$ = the minimum WSM score, for scenario i

a_{ij} = the actual value of the scenario i, in terms of criterion j

w_j = the weight of importance assigned to criterion j

This equation describes the “minimisation” case, in which a low scoring scenario is preferential to a high scoring scenario.

The application of the WSM approach to a multi-criteria decision support tool for end-of-life management of SOFC stacks is described in Sections 9.6.1 – 9.6.6 below. The main limitation of this method is that the summation of values requires all individual criteria to be expressed using the same units. This is not directly achieved using the evaluation methods described in Sections 9.3 – 9.5; the results from the application of the legislative risk assessment tool, LCA and CBA bear no relation to each other. In order to overcome this problem, a normalisation step is conducted on the individual evaluation results, before the multi-criteria decision method is applied. Since E^2LM is a comparative tool, the results values can be normalised using a simple relative normalisation method. This method is performed in Step 3 of the method, as outlined in Section 9.6.3 below.

9.6.1 Step 1: Define alternative end-of-life scenarios

The first stage in the E^2LM methodology requires the user to identify the end-of-life scenarios under evaluation. The methodology is comparative and thus a minimum of two scenarios must be entered to provide meaningful results. The simple name assigned to each scenario in the single criterion evaluation steps is used for identification purposes and is imported, together with the scores produced by the legislative risk assessment, environmental impact assessment and economic impact assessment. Within the example shown in Figure 9.12, illustrative values are provided for three end-of-life scenarios which are to be compared within the E^2LM tool. Values of the results for the three individual evaluation methods differ significantly and have no relationship to each other. This disparity is eliminated in the subsequent normalisation step, which allows the three performance metrics to be combined eventually into a single score for each scenario. The only similarity between the values for the individual criterion evaluation methods is that a low value represents a favourable outcome, with respect to scenario performance.

9.6.2 Step 2: Define evaluation criteria weightings

In the second step of the E^{2}LM methodology, the relative importance of each of the individual performance criteria is defined. At least one of the performance criteria must be allocated a weighting factor of 1, which is the highest value allowable. The other two weighting factors may be equal to 1, where all performance criteria are considered to be equally important, or may be assigned values less than 1. In the example provided in Figure 9.12, legislative compliance is assigned a weighting factor $Leg_f = 1$. Environmental impact is considered to be slightly less important than legislative compliance and as such is assigned a weighting factor $Env_f = 0.8$. Economic impact is considered to be only half as important as legislative compliance and is assigned a weighting factor $Eco_f = 0.5$.

Weighting factors should be defined by an individual or group, based on expert opinion. The ability for the user to define customised weighting factors gives the tool added flexibility. Weighting priorities may change over time, depending on business requirements, technology maturity, external pressures and other factors.

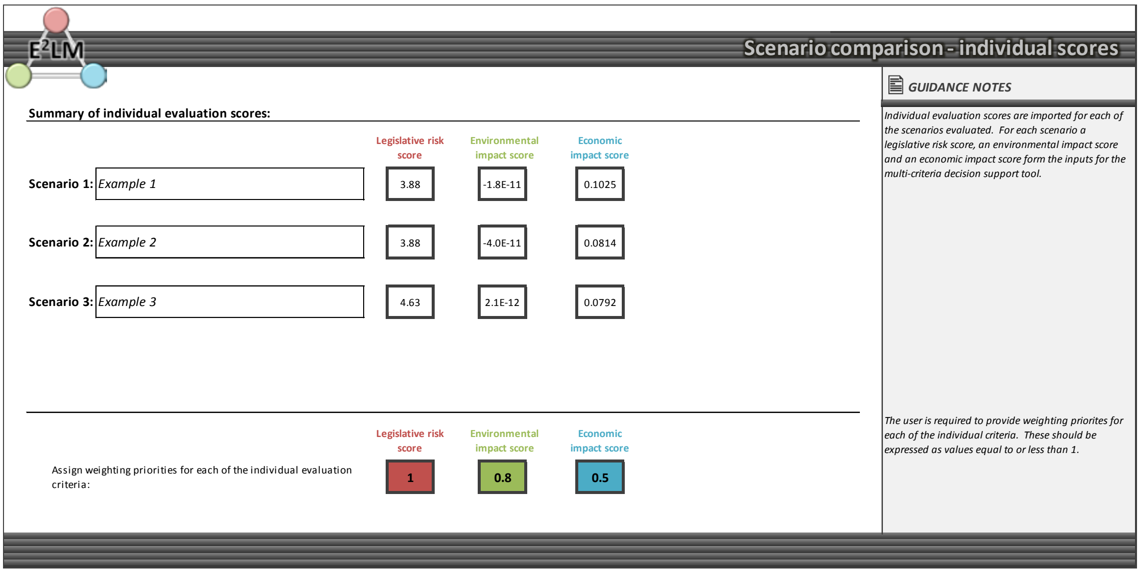


Figure 9.12: User interface for Steps 1 and 2 of the E^{2}LM methodology in which the results from single criterion evaluation methods are imported, and weighting priorities are defined.

9.6.3 Step 3: Normalise single score results

The third step of the E^{2}LM methodology requires normalisation of the single score results. Normalised scores are expressed as a fraction of the largest score for each criterion, according to equations *9.10, 9.11* and *9.12*:

$$Leg_{nx} = {}^{Leg_x}/_{Leg_{max}} \qquad \qquad Equation\ 9.10$$

$$Env_{nx} = {}^{Env_x}\!/_{Env_{max}} \qquad \textit{Equation } 9.11$$

$$Eco_{nx} = {}^{Eco_x}\!/_{Eco_{max}} \qquad \textit{Equation } 9.12$$

Where Leg_{nx}, Env_{nx} and Eco_{nx} represent the normalised scores for scenario x for legislative risk, environmental impact and economic impact respectively; Leg_x, Env_x and Eco_x represent the original scores for scenario x for legislative risk, environmental impact and economic impact respectively; Leg_{max}, Env_{max} and Eco_{max} represent the maximum score from all scenario results for legislative risk, environmental impact and economic impact respectively.

The example in Figure 9.13 provides an illustration of how these normalised scores are presented in the E[2]LM tool. Normalised scores are calculated automatically and are presented as numerical values. Bar charts are automatically produced to allow comparison of the scenarios across each of the three evaluation criteria.

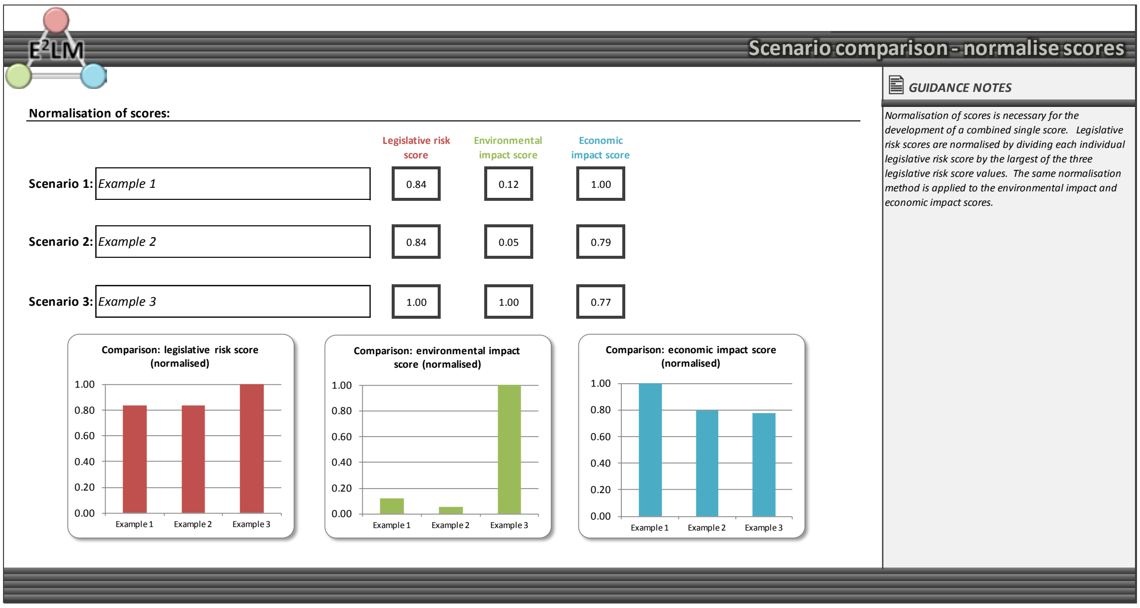


Figure 9.13: User interface for Step 3 of the E[2]LM methodology in which normalised scores are calculated and plotted.

In Figure 9.13, scenario 1 has the highest economic impact, but has a legislative risk score equal to scenario 2, and the second highest environmental impact of the three scenarios. Whilst scenario 3 performs worst in terms of legislative risk and environmental impact, its economic impact is the lowest. None of the scenarios shows superior performance across all three performance criteria, and based upon the numerical values and visual representations provided in Figure 9.13 the identification of the "best" end-of-life solution is not immediately obvious.

9.6.4 Step 4: Apply weighting factors

In Step 4 of the E[2]LM methodology weighting factors, as defined by the user in Step 2, are applied to the normalised scores. The user defined weighting factors are applied as simple multipliers, with:

$$Leg_{wx} = Leg_{nx} \times Leg_f \qquad \text{Equation 9.13}$$

$$Env_{wx} = Env_{nx} \times Env_f \qquad \text{Equation 9.14}$$

$$Eco_{wx} = Eco_{nx} \times Eco_f \qquad \text{Equation 9.15}$$

Where Leg_{wx}, Env_{wx} and Eco_{wx} are the weighted normalised scores for scenario x for legislative risk, environmental impact and economic impact respectively; Leg_{nx}, Env_{nx} and Eco_{nx} are the normalised scores calculated in Step 3; Leg_f, Env_f and Eco_f are the user defined weighting factors specified in Step 2. These weighted values are plotted on a radar chart, shown in Figure 9.14, and form the basis of the calculations for a single-score result.

9.6.5 Step 5: Compare scenarios

The comparison of alternative end-of-life scenarios is achieved by combining the normalised, weighted results from the individual evaluation methods into a single representation of overall performance. In order to achieve this, the E[2]LM decision support tool presents the final results for the three evaluated scenarios as a triangular radar plot (Figure 9.14). The axes for the plot represent legislative risk, economic impact and environmental impact. This visual representation of results provides the user with a clear picture of the relative contribution of each of these individual performance criteria to the overall performance of the scenario. From the example provided in Figure 9.14 it can be seen that the scenario "Example 3" has the

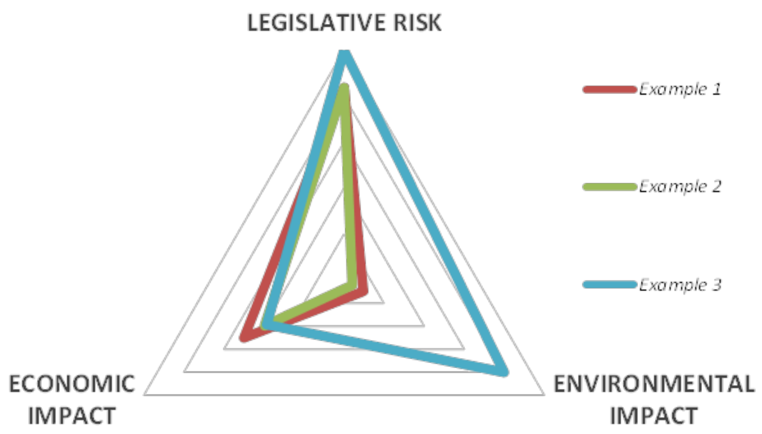


Figure 9.14: Detail of the multi-criteria evaluation output used for comparison of three example end-of-life scenarios.

highest legislative risk, while the scenario “Example 1” has the greatest economic impact.

While this visualisation is useful as a comparison tool there is a possibility of some ambiguity remaining regarding the identification of the scenario with the overall “best” or “worst” performance.

In order to overcome this potential ambiguity, this final stage in the evaluation methodology includes the calculation of a single numerical performance score, which combines all three performance criteria. This score is defined as the area represented by the triangle, plotted on the triangular radar graph exemplified in Figure 9.14. The overall impact score for scenario x ($Impact_x$) can therefore be calculated by:

$$Impact_x = 0.5 \times \sin(120) \times [(Leg_{wx}) \times (Env_{wx}) + (Env_{wx}) \times (Eco_{wx}) + (Eco_{wx}) \times (Leg_{wx})]$$

$$Equation\ 9.16$$

Figure 9.15 illustrates the user interface for Steps 4 and 5 of the E^2LM methodology, showing the triangular plot of results. In addition the calculated impact scores are quantified and visualised in a bar chart in the bottom right hand corner of the E^2LM user interface to allow clear identification of the relative performance of each of the defined end-of-life scenarios. In the example shown in Figure 9.15 it is clear that the scenario called *“Example 3”* has highest overall impact, and thus would be the least desirable end-of-life solution. The scenario *“Example 2”* in this case achieves the lowest overall impact score and as such would be the preferred solution.

It is a deliberate feature of the scenario comparison results screen (Figure 9.15) that the triangular plot of results is provided, alongside the numerical single score result for each evaluated scenario. It was identified that the distillation of results to a single score provides a useful tool to support decision making, especially when the outcome from an evaluation methodology has to be presented to a non-expert audience, as may be the case in an industrial setting. In this case, a single score can provide clear direction. On the other hand, it is recognised that the process of generating a single score result removes a degree of transparency, which can be detrimental to the decision-making process. The triangular plot therefore provides a clear, visual representation of the relative strengths and weaknesses of the individual scenarios under evaluation. It should be noted that this total impact score provides a relative value only, and could not be used for comparison with scenarios considered in a separate evaluation.

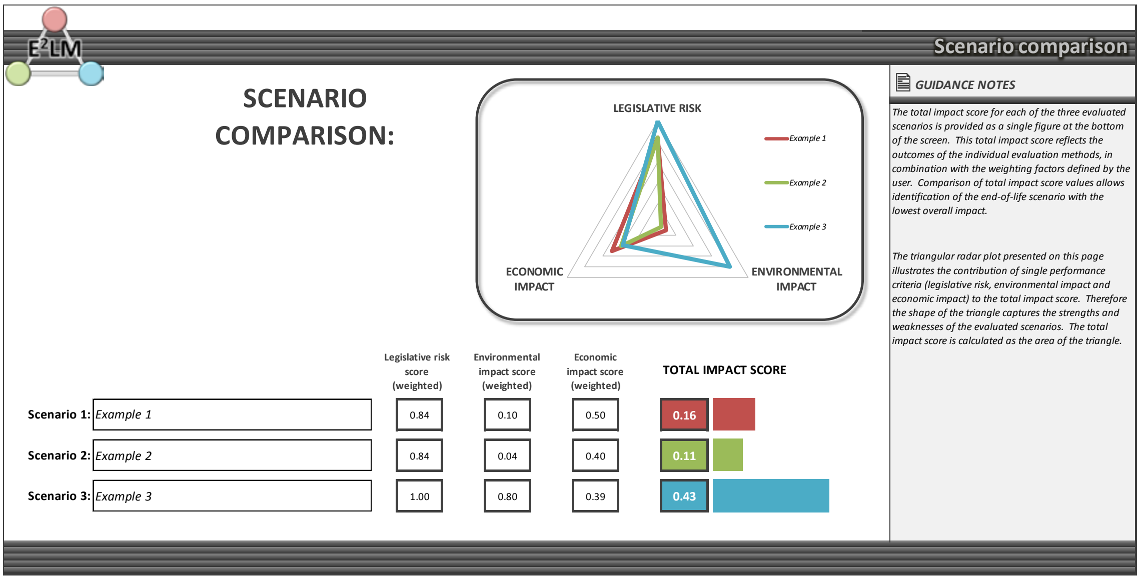


Figure 9.15: User interface for the final evaluation step of the E^2LM methodology in which the overall impact score is presented for each scenario.

9.6.6 Step 6: Sensitivity analysis

The final stage in the E^2LM methodology allows the user to investigate the sensitivity of the single-score result obtained to the weighting factors applied to the three individual evaluation criteria. Figure 9.16 illustrates the application of revised weighting factors to the results shown in Figure 9.15. In the example provided in Figure 9.13, the revision of weighting values does not change the scenario with the lowest overall impact score: in both cases *"Example 2"* would be selected as having the lowest overall impact score.

It is believed that this ability to test the weighting factors adopted within the E^2LM methodology is an essential part of the tool, since it supports the validation of decision-making which might otherwise be based on weighting factors incorporating a high degree of subjectivity. However, it is recognised that the final results generated by the multi-criteria evaluation tool could be sensitive to many other factors, beginning with the accuracy of data collected from individual end-of-life process steps, through the application of LCA characterisation factors, cost data and subjective influences arising in the legislative risk assessment. Therefore, in order to develop a more rigorous understanding of the sensitivity of results to these factors, much more extensive sensitivity analysis is required. However, given the commercial availability of software applications to support a statistical approach to sensitivity analysis, it suggested that improvements to this aspect of the evaluation methodology could be implemented at a later date.

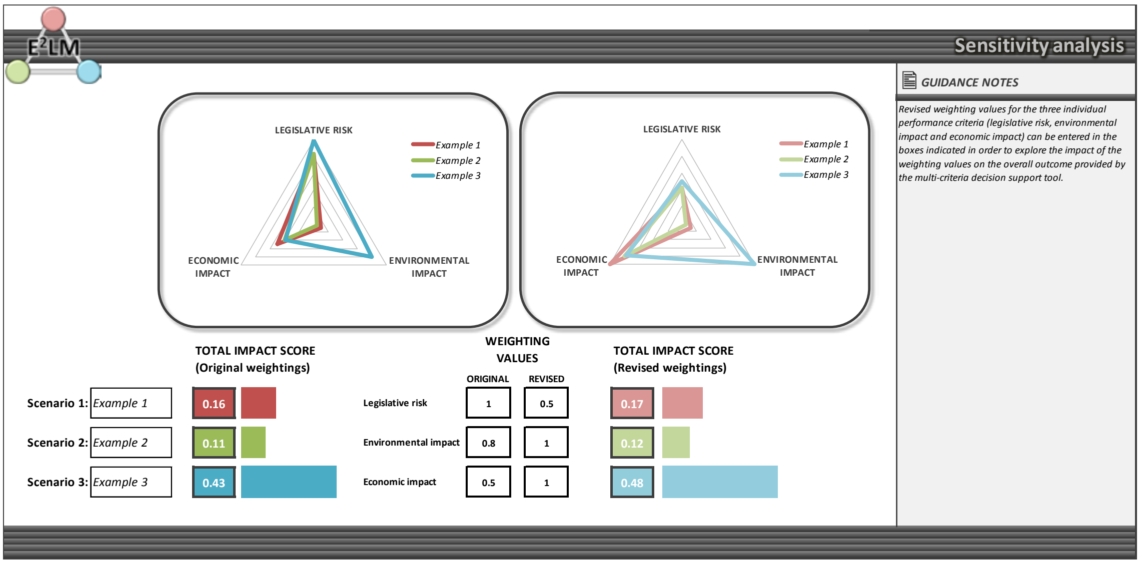


Figure 9.16: User interface for the sensitivity analysis step in the E^{2}LM methodology, in which revised weighting values can be tested to investigate their impact on the final result.

9.7 Summary

Methods have been described for the evaluation of end-of-life scenarios for SOFC stacks according to three performance criteria. A novel method for evaluating the risk of non-compliance with existing and future legislative requirements has been developed. For the evaluation of environmental impact, an LCA-based approach has been adopted, which utilises commercially available LCA software to support the generation of life cycle inventories for alternative scenarios and the application of a selected impact assessment method. Economic impacts associated with alternative end-of-life scenarios are quantified using a simplified CBA method. Together, these evaluation methods provide inputs to a multi-criteria evaluation methodology which has been developed to support decision making during the development of end-of-life management processes for the SOFC stack. The application of this evaluation methodology in supporting decision making is explored further in the case studies, reported in the following chapter. Based on the findings from these case studies, the benefits and limitations of the evaluation methodology are discussed in Chapter 11.

CHAPTER 10 END-OF-LIFE MANAGEMENT OF SOLID OXIDE FUEL CELLS: CASE STUDIES

10.1 Introduction

This chapter documents two case studies which have been selected to demonstrate the application of the research reported in the thesis. The chapter begins with an overview of the case studies, followed by a systematic description of their completion. Results from both case studies are reported and analysed, in order to draw some conclusions regarding the validity of the framework and evaluation methods reported in the thesis in supporting end-of-life management of SOFCs.

10.2 Overview of selected case studies

Two case studies have been selected in order to demonstrate the application of the framework for end-of-life management of SOFCs as described in Chapter 6 of the thesis. These case studies reflect two different modes of applying the framework in order to support the development of an end-of-life management solution which demonstrates compliance with end-of-life legislation, low environmental impact and low economic impact. In the first case study, the framework is used to support the identification of a preferred end-of-life scenario, based on a comparison of three alternatives. This case study demonstrates a reactive approach to end-of-life management. The second case study demonstrates the ability of the framework in supporting a more proactive approach to end-of-life management. In this case study, the impact of a design modification to the SOFC stack on the selection of a preferred end-of-life scenario is investigated.

A wide range of research concepts are addressed in this thesis. These two case studies have been selected to demonstrate and test the following concepts:

Case study 1

- Application of the framework for end-of-life management according to a reactive approach, focusing on the evaluation of alternative processes for material recovery and recycling.

- Implementation of the multi-criteria evaluation methodology to identify an end-of-life scenario demonstrating legislative compliance, low environmental impact and low economic impact, when compared with alternatives.

Case study 2

- Exploration of the proactive application of the framework for end-of-life management through the consideration of a design modification to the SOFC stack, and the resulting impact on the evaluation results for alternative end-of-life scenarios.
- Validation of the end-of-life framework as a flexible tool to support the development of a more sustainable product design for SOFC stacks, based on impacts arising at the end-of-life stage.

A visual overview of both of the case studies is provided in Figure 10.1.

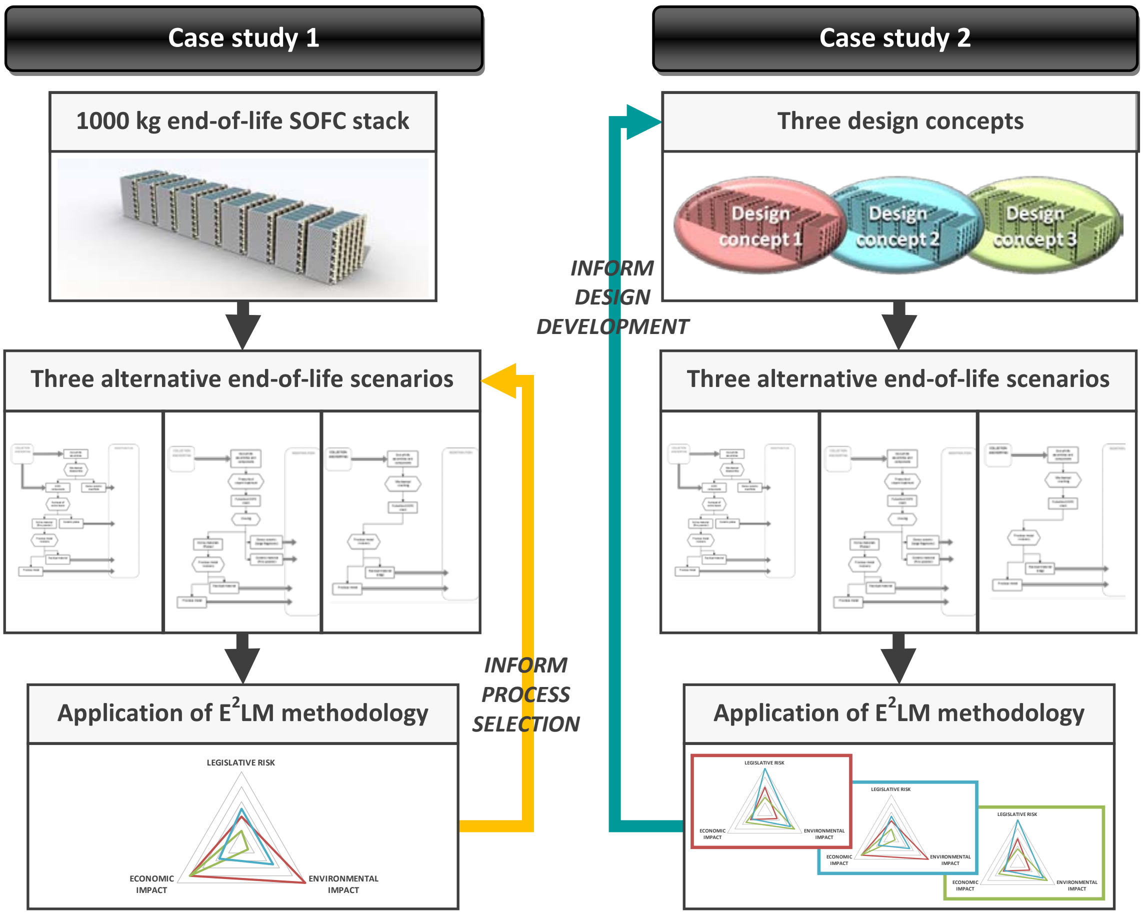


Figure 10.1: Visualisation of case studies 1 and 2.

10.3 Case study 1

During the course of the research reported in this thesis, Rolls-Royce Fuel Cell Systems Limited was involved in a collaborative project with the Singapore Institute of Manufacturing Technology (SIMTech) to investigate alternative process routes for material separation and recovery from end-of-life SOFC components. The project explored a number of approaches based on small scale laboratory experiments. During the same period, a commercially available process was identified for the recovery of precious metals from SOFC components which had been manufactured for development purposes. These components had used valuable materials in the current-collecting layer of the SOFC stack to facilitate electrochemical testing and other technology development requirements. There was a desire by the company to recover the value contained in this inventory of components. An initial industrial trial was conducted, based on a 500 kg batch of SOFC components, in order to evaluate the efficiency and suitability of this commercially available process.

From the laboratory and industrial trials described above, various process routes have been identified as being feasible for the recovery and recycling of materials from the SOFC stack. These process routes are equally relevant for the management of components which have been manufactured for technology development purposes and which are no longer required, as for end-of-life SOFC stack components which will arise in the future from the maintenance and decommissioning of commercial products. In order to prioritise further development efforts concerned with the optimisation of the most suitable end-of-life process route, it is necessary to compare the alternative options in terms of their legislative, environmental and economic performance. Development effort can then be directed towards the process which performs best, according to these criteria. This comparison of alternative end-of-life scenarios is the subject of the first case study.

It is recognised that this case study would benefit from the availability of more specific data, with regard to the end-of-life scenarios investigated. The scenarios investigated in the case study represent conceptual processes, for which a level of feasibility has been demonstrated through the practical work described above: however, these processes have not been optimised for end-of-life management of SOFC stacks, nor have they been fully validated. The case study therefore represents a first attempt at evaluating alternative end-of-life options, and paves the way for further, more rigorous, investigation of end-of-life processes as SOFC technology proceeds towards commercialisation.

The case study follows the four stages of the framework for end-of-life management of SOFC stacks, as described in Chapter 6 of the thesis, namely:

1. Characterisation of the product stream
2. Definition of end-of-life scenarios
3. Single criterion scenario evaluation
4. Multi-criteria evaluation and comparison of scenarios

Sections 10.3.1 and 10.3.2 below document the first two stages of the framework as applied to case study 1. Sections 10.3.3 and 10.3.4 describe data collection and other aspects of the implementation of the case study and the application of the evaluation methodology. Results from the single and multi-criteria evaluation methods are analysed in section 10.3.5.

10.3.1 Characterisation of the product stream for case study 1

The product stream considered in this case study comprises end-of-life SOFC stacks, based on the Integrated Planar SOFC concept under development at Rolls-Royce Fuel Cell Systems. The following assumptions underline the characteristics of the product stream identified as being relevant to the end-of-life management process:

- The SOFC stack has a material composition as defined for the IP-SOFC concept in Chapter 7. The end-of-life stacks have been used for pre-commercial technology development and utilise a palladium-based current collector, instead of the lower-cost lanthanum-based material. The palladium content of the end-of-life SOFC stack is approximately 1% by weight.
- The material composition of the SOFC stack components has not changed during the operational life of the SOFC stack.
- 1000 kg of end-of-life SOFC stack components are available for processing.
- The generation of 1 kW electricity requires 3.5 kg of SOFC stack components for a product operating at design point.
- The end-of-life SOFC stack components arise from installations in Derby, UK.
- The end-of-life SOFC stack has been disassembled from the SOFC product system.
- The end-of-life SOFC stack is physically intact, with no damage arising to individual components during operation, shut-down or disassembly from the SOFC product system.

10.3.2 Definition of end-of-life scenarios for case study 1

Based on the laboratory and industrial trials investigating alternative end-of-life processing routes, three end-of-life scenarios have been identified as feasible solutions for the end-of-life management of the SOFC stack. These scenarios have been outlined previously in Chapter 8. Summaries of the data developed to define each of these scenarios during the completion of the case study are provided in Tables 10.1 – 10.3. The assumptions underlying these data are explained below. Scenarios are defined in terms of the three principal stages in end-of-life management defined in Chapter 8 of the thesis, namely:

A. Collection and sorting
B. Reprocessing
C. Redistribution

10.3.2.1 Scenario 1: Mechanical separation and selective recycling

The end-of-life process route developed as scenario 1 is represented graphically in Figure 8.9 of the thesis, and is defined in detail in this section.

A. COLLECTION AND SORTING

- Collection and sorting is conducted at the site where the end-of-life components arise. No additional transportation is required to the location of the first process step.
- All of the end-of-life SOFC stack components (1000 kg) are suitable for reprocessing. None are reused or repaired.

B. REPROCESSING

- The reprocessing route has three principal process steps:
    1. Mechanical disassembly of SOFC stack
    2. Mechanical removal of active fuel cell printed layers from the surface of individual SOFC components
    3. Precious metal recovery from the removed active fuel cell layers.
- Process steps 1 and 2 are conducted at a site within the UK, where specialist equipment is available. Process step 3 is conducted at a location in Belgium. Transport requirements are derived from calculated distances between locations (Google Maps, 2011).
- Mechanical disassembly of the SOFC stack is carried out using abrasive water jet cutting (Figure 10.2). No practical trials have been conducted to evaluate the

feasibility of this method; however, it is widely accepted that this method is suitable for cutting a broad range of materials, including ceramics. A cutting speed of up to 7.5 m min^{-1} is quoted for cutting of reinforced plastics (Kalpakjian and Schmid, 2008); however, given the relative hardness of the ceramic material from which the SOFC stack is made, and the complexity of the structure, a cutting time of 5 minutes is assumed for each strip assembly, with an additional 5 minutes required for setting up each strip assembly for cutting. An additional 15 minutes time is also required for cleaning equipment after processing 500 kg of end-of-life SOFC stack. Material and energy inputs are assumed to be 10 litres $hour^{-1}$ of water, 36 kg $hour^{-1}$ of abrasive, with the operation of the water jet cutting system requiring 35 kW electricity (Tesko Laser Division, 2005). It is assumed that a closed-loop system is employed (e.g. Jet Edge Waterjet Systems, 2011) such that in effect no water or abrasive are consumed during the cutting process. A yield of 95% for the recovery of individual fuel cell components is assumed, allowing for a level of component breakage resulting in the production of damaged components which would not be suitable as inputs to the grinding process.

- Mechanical removal of active fuel cell printed layers is carried out using a mechanical grinding process. Limited practical trials of this process have been conducted by collaborators at SIMTech, but were not pursued far enough to obtain quantitative data. Therefore, the Ecoinvent database was used to provide energy consumption data representative of a mechanical process. Data for chipping processes (such as drilling and milling) of metals indicate an energy requirement of approximately 0.2 – 2.4 MJ for the removal of 1 kg of material. Given the relative hardness of ceramic materials compared with metal, a value of 10 MJ is assumed as the energy requirement for the removal of 1 kg active material from the surface of the ceramic plates. It is assumed that a closed system is in operation to recover the ground layers,

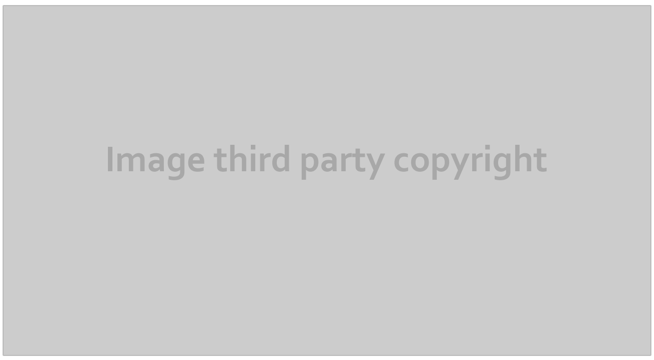


Figure 10.2: Illustration of cutting by abrasive water jet (Flowwaterjet.com, 2011)

thus eliminating dust emissions. A yield of 85% for the recovery of active material is assumed for this process step since it is likely that a relatively high proportion of the ground material will be lost in the grinding media.

- Precious metal recovery from the removed active material is based on data from the Ecoinvent database (Ecoinvent Centre, 2007), reflecting the recovery of precious metals from used autocatalysts. Some small scale practical trials have been conducted in collaboration with Rolls-Royce Fuel Cell Systems Limited and SIMTech, proving the feasibility of this process, as applied to end-of-life SOFC stack components. Input materials and energy are related to the quantity of precious metal produced from the process, and are calculated accordingly. Similarly, emissions from the process are calculated, based on known emissions for the production of 1 kg of secondary palladium as documented in the Ecoinvent database (Ecoinvent Centre, 2007). A recovery rate of 97% is assumed, based on the lower end of efficiency estimates quoted by a range of industrial recyclers.

C. REDISTRIBUTION

- The principal outputs from the three process steps are dense ceramic components; ceramic plates; and precious metals and residual materials from the precious metal recovery operation.
- The dense components are scrapped as non-hazardous ceramic waste.
- The ceramic plates are sold to a ceramics supplier for use as raw material. The market value of the plates is identified as being lower than the cost of the original raw material since some crushing and decontamination processes will need to be applied, before the material is suitable for reuse as a high purity ceramic. It is unlikely that the material will be suitable for direct reuse in SOFC components, given likely contamination with species which may disrupt the electrochemical performance of the fuel cell; however, it is assumed that the material would be suitable for use in a high value application.
- The precious metal is recycled in closed loop model and retains the original market value.

The definition of scenario 1 is summarised in Table 10.1.

Table 10.1: Data definition for scenario 1.

	Collection & Sorting	**Reprocessing Step 1** Abrasive water jet cutting	**Reprocessing Step 2** Surface grinding	**Reprocessing Step 3** Precious metal recovery
	Yield = 100%	Yield = 95%	Yield = 85%	Yield = 97%
Material inputs	End-of-life SOFC stack 1000 kg	End-of-life SOFC stack 1000 kg Water 0 kg* SiC abrasive 0 kg*	End-of-life SOFC components 816 kg	Active material 57 kg Lime 626 kg Copper 7.8 kg
Energy inputs	None	Electricity 162 MJ	Electricity 665 MJ	Electricity 30408 MJ Natural gas 6069 MJ
Transport inputs	None	Road transport 75 tkm	None	Road transport 31 tkm Rail transport 3 tkm
Material outputs	End-of-life SOFC stack for reprocessing 1000 kg	End-of-life SOFC components 816 kg	Active material 57 kg	None
Redistribution	None	Dense ceramics 134 kg Scrap components 50 kg	Ceramic plates 637 kg Scrap components 122 kg	Palladium metal 7.8 kg Process waste (hazardous) 56.7 kg Process waste (non-hazardous) 626 kg

**Closed loop system is assumed.*

10.3.2.2 Scenario 2: Chemical-mechanical separation and selective recycling

The end-of-life process route developed as scenario 2 is represented graphically in Figure 8.10 of the thesis, and is defined in detail in this section.

A. COLLECTION AND SORTING

- Collection and sorting is conducted at the site where the end-of-life components arise. No additional transportation is required to the location of the first process step.

B. REPROCESSING

- The reprocessing route has three principal process steps:
    1. Pressurised steam treatment to break down the SOFC stack components.
    2. Material separation, using sieving process.
    3. Precious metal recovery from the recovered active material fraction.

- Process steps 1 and 2 are conducted in Derby, UK, at the site where collection takes place. Process step 3 is conducted at a location in Belgium. Transport requirements are derived from calculated distances between locations (Google Maps, 2011).

- Pressurised steam treatment to break down the SOFC stack components has been proven at the laboratory level by collaborative work conducted by SIMTech, using a domestic pressure cooker. At a larger scale, industrial autoclaves (Figure 10.3) provide a pressurised steam environment commonly used for the treatment of municipal and hazardous wastes (Sterecycle, 2008; Babcock International Group Plc, 2011; Mott MacDonald Group, 2011). Energy requirements for a large-scale process are calculated based on the reported value for the treatment of 1000 kg of municipal waste (Friends of the Earth, 2008). Trials at SIMTech indicated a five hour treatment time was required to fully break down the ceramic SOFC stack, whereas domestic waste can be treated in around one hour (Friends of the Earth, 2008): energy data are scaled accordingly. It is assumed that 1000 kg of end-of-life SOFC stack can be processed as a single batch. A yield of 98% is assumed for this process step, allowing for some material loss during the recovery of treated material from the autoclave.

- Material separation using a sieving process has been proven at SIMTech at the laboratory scale with a manual process. A large-scale process would require the use of an automated, high-volume sieving system, such as that described by Nordson Corporation (1999), which has a power rating of 0.75 kW, and can process around 500

Figure 10.3: Example of an industrial autoclave for waste treatment (OnSite Sterilization LLC, 2011)

kg of powder in 1 hour. These data are used to calculate energy requirements for the sieving process step in scenario 2. A yield of 70% is assumed for this process step, since it is not known that the accuracy of the sieving process is high for this application.

- Precious metal recovery from the recovered material is based on data from the Ecoinvent database (Ecoinvent Centre, 2007), reflecting the recovery of precious metals from used autocatalysts. Some small scale practical trials have been conducted in collaboration with Rolls-Royce Fuel Cell Systems Limited and SIMTech, proving the feasibility of this process, as applied to end-of-life SOFC stack components. Input materials and energy are related to the quantity of precious metal produced from the process, and are calculated accordingly. Similarly, emissions from the process are calculated, based on known emissions for the production of 1 kg of secondary palladium as documented in the Ecoinvent database (Ecoinvent Centre, 2007). A recovery rate of 97% is assumed, based on the lower end of efficiency estimates quoted by a range of industrial recyclers.

C. REDISTRIBUTION

- The principal outputs from the three process steps are large fragments of dense ceramic components; a fine ceramic powder; and precious metals and residual materials from the precious metal recovery operation.

- The dense ceramic fragments are scrapped as non-hazardous ceramic waste.

- The fine ceramic powder is sold to a ceramics supplier for use as raw material. The market value of the powder is identified as being lower than the cost of the original raw material since some additional reprocessing will need to be applied, before the material is suitable for reuse as a high purity ceramic. It is unlikely that the material will be suitable for direct reuse in SOFC components, given likely contamination with species which may disrupt the electrochemical performance of the fuel cell; however, it is assumed that the material would be suitable for use in a high value application. As such, the market value of the recovered powder is identified as being lower than the cost of the original raw material (see Table 7.3), but higher than the value of the ceramic plates recovered in scenario 1.
- The precious metal is recycled in a closed loop model and is produced at sufficient purity to be re-sold at their original market value (see Table 7.3)

The definition of scenario 2 is summarised in Table 10.2.

Table 10.2: Data definition for scenario 2.

	Collection & Sorting	Reprocessing Step 1 Pressurised steam treatment	Reprocessing Step 2 Sieving	Reprocessing Step 3 Precious metal recovery
	Yield = 100%	Yield = 98%	Yield = 70%	Yield = 97%
Material inputs	End-of-life SOFC stack 1000 kg	End-of-life SOFC stack 1000 kg Water 0 kg*	Pulverised SOFC stack 980 kg	Active material 48 kg Lime 532 kg Copper 6.6 kg
Energy inputs	None	Electricity 56 MJ Gas 396MJ	Electricity 0.82 MJ	Electricity 25833 MJ Natural gas 5156 MJ
Transport inputs	None	None	None	Road transport 23 tkm Rail transport 3 tkm
Material outputs	End-of-life SOFC stack 1000 kg for reprocessing	Pulverised SOFC stack 980 kg	Active material 48 kg	None
Redistribution	None	Process waste (non-hazardous) 20 kg	Ceramic powder 569 kg Dense fragments 363 kg	Palladium metal 6.7 kg Process waste (hazardous) 48.4 kg Process waste (non-hazardous) 532 kg

A closed system is assumed, such that net water consumption is nil.

10.3.2.3 Scenario 3: Non-selective recycling

The end-of-life process route developed as scenario 3 is represented graphically in Figure 8.11 of the thesis, and is defined in detail in this section.

A. COLLECTION AND SORTING

- Collection and sorting is conducted at the site where the end-of-life components arise. No additional transportation is required to the location of the first process step.

B. REPROCESSING

- The reprocessing route has two principal process steps:
  1. Mechanical crushing of the SOFC stack.
  2. Precious metal recovery from the pulverised material.

- Process step 1 is conducted in Buxton, UK. Process step 2 is conducted at a location in Belgium. Transport requirements are derived from calculated distances between locations (Google Maps, 2011).

- Mechanical crushing of the SOFC stack has been proven at an industrial scale level, using a ball milling process (Figure 10.4); however, specific data from the process trials are not available for quantifying energy and other process requirements. Therefore data are taken from the Ecoinvent database (Ecoinvent Centre, 2007). The production of limestone, as documented in the Ecoinvent database, includes two separate process steps for crushing and then milling. Energy requirements for these two process steps are combined, and multiplied by a factor three, based on known differences in the hardness of the materials being processed. From observation of the industrial trials it is clear that the dense components in the SOFC stack slow down the crushing process, thus indicating an overall requirement for more process energy.

- Precious metal recovery from the recovered material is based on data from the Ecoinvent database (Ecoinvent Centre, 2007), reflecting the recovery of precious metals from used autocatalysts. Some small scale practical trials have been conducted in collaboration with Rolls-Royce Fuel Cell Systems Limited and SIMTech, proving the feasibility of this process, as applied to end-of-life SOFC stack components. Input materials and energy are related to the quantity of precious metal produced from the process, and were calculated accordingly. Similarly, emissions from the process are calculated, based on known emissions for the production of 1 kg of secondary

Figure 10.4: Example of an industrial ball mill, suitable for processing end-of-life SOFC stacks. (NSI Equipments Ltd, 2011)

palladium as documented in the Ecoinvent database (Ecoinvent Centre, 2007). A recovery rate of 97% is assumed, based on the lower end of efficiency estimates quoted by a range of industrial recyclers.

C. REDISTRIBUTION

- The principal outputs from the three process steps are precious metals and residual materials from the precious metal recovery operation.
- The precious metals are recycled in a closed loop model and are produced at sufficient purity to retain their original market value (Table 7.2)
- Compared with scenarios 1 and 2, the composition of the material input to the precious metal recovery process is much higher in inert ceramic content. As such it is assumed that the majority (80%) of this ceramic material is suitable for application as low-grade structural filler. In the case study no revenue is associated with this material stream at the redistribution stages since it is assumed that the inherent low value of the recovered material results in its redistribution being cost neutral.

The definition of scenario 3 is summarised in Table 10.3.

Table 10.3: Data definition for scenario 3.

	Collection & Sorting		**Reprocessing Step 1 Mechanical crushing**		**Reprocessing Step 2 Precious metal recovery**	
	Yield = 100%		Yield = 98%		Yield = 97%	
Material inputs	End-of-life SOFC stack	1000 kg	End-of-life SOFC stack	1000 kg	Pulverised SOFC stack Lime Copper	980 kg 759 kg 9.5 kg
Energy inputs	None		Electricity	16.7MJ	Electricity Natural gas	36904 MJ 7365 MJ
Transport inputs	None		Road transport	20 tkm	Road transport Rail transport	608 tkm 59 tkm
Material outputs	End-of-life SOFC stack for reprocessing	1000 kg	Pulverised SOFC stack	980 kg	None	
Redistribution	None		Process waste (non-hazardous)	20 kg	Palladium metal Ceramic for structural filler Process waste (hazardous) Process waste (non-hazardous)	9.5 kg 707 kg 273 kg 759 kg

10.3.3 Data for case study 1

High level data defining each of the end-of-life scenarios evaluated in case study 1 are captured in the Tables 10.1 – 10.3. These data are collated from various sources, and developed from real data and assumptions, as described in Section 10.3.2. In order to apply the evaluation methods to these three scenarios, more detailed data are required regarding the environmental and economic attributes of the process steps described.

10.3.3.1 Data to support legislative compliance risk assessment

Data to support legislative compliance risk assessment is obtained from knowledge regarding the composition of the integrated-planar SOFC stack concept described in Chapter 7 of the thesis, as well as a high level knowledge of the alternative end-of-life scenarios defined in Section 10.3.2. Results from the application of this evaluation method are reported in Section 10.3.5.1.

10.3.3.2 Data to support evaluation of environmental impact

The evaluation of environmental impact requires the application of LCA methodology, as described in Chapter 9. Data to support the development of a life cycle inventory for each end-of-life scenario are obtained from the Ecoinvent database (Ecoinvent Centre, 2007). Table 10.4 summarises the principal datasets used in the case study. Manipulation of the data to obtain inventories is carried out using GaBi4 software (PE International GmbH, 2007). The datasets summarised in Table 10.4 are identified as providing the closest representation of the processes utilised in the end-of-life scenarios, in the absence of process-specific data.

10.3.3.3 Data to support evaluation of economic impact

As described in Chapter 9, the evaluation of economic impact using cost-benefit analysis (CBA) requires the quantification of all costs and revenues arising during the end-of-life management process. Cost data to support the case study is available from various sources.

For each of the scenarios evaluated, the final process step is for the recovery of precious metal from the SOFC stack material. Cost data were obtained for this process from various precious metal recycling companies, located in the UK, Europe and Singapore, during the course of practical trials conducted at Rolls-Royce Fuel Cell Systems. The data used in the case study reflect an average cost profile for this process, based on these commercial data. The principal costs associated with the precious metal recovery process step are summarised in Table 10.5.

Table 10.4: Summary of data used to support evaluation of the environmental impact of alternative end-of-life scenarios in case study 1.

Material inputs	Units	Name of dataset	Source
Water	Kg	RER: tap water, at user	Ecoinvent database, version 2.0
Abrasive	Kg	RER: silicon carbide, at plant	Ecoinvent database, version 2.0
Lime	Kg	CH: lime, hydrated, loose, at plant	Ecoinvent database, version 2.0
Copper	Kg	RER: copper, at regional storage	Ecoinvent database, version 2.0
Energy inputs			
Electricity	MJ	BE: Powermix, GB: Powermix	Ecoinvent database, version 2.0
Natural gas	MJ	RER: natural gas, burned in industrial furnace >100kW	Ecoinvent database, version 2.0
Transport inputs			
Transport by lorry	Tkm	RER: transport, lorry 16-32t, EURO5	Ecoinvent database, version 2.0
Transport by rail	Tkm	RER: transport, freight, rail	Ecoinvent database, version 2.0
Material outputs (avoided impact)			
Palladium	Kg	RER: palladium, at regional storage	Ecoinvent database, version 2.0
Ceramic plates	Kg	Ceramic material production	Developed with ceramic material suppliers to RRFCS.
Ceramic powder	Kg	Ceramic material production	Developed with ceramic material suppliers to RRFCS.
Residual structural filler	Kg	CH: gravel, crushed, at mine	Ecoinvent database, version 2.0
Waste			
Waste to inert material landfill	Kg	CH: disposal, inert waste, 5% water, to inert material landfill	Ecoinvent database, version 2.0
Waste to hazardous material landfill	Kg	DE: disposal, hazardous waste, 0% water, to underground deposit	Ecoinvent database, version 2.0

Similarly, commercial cost data are available for crushing end-of-life SOFCs – required as the first process step in scenario 3.

With regard to scenarios 1 and 2, no commercial cost data are available, since these processes have not been practically trialled at volume. However, cost estimates are generated based on assumptions regarding process energy requirements and process time. A summary of these cost estimates is presented in Table 10.6.

Revenues from the end-of-life management of the SOFC stack arise from the production of useable material, with a market value. The assumptions underlying the calculation of revenues for the case study are summarised in Table 10.7.

Table 10.5: Cost data for precious metal recovery step

Cost element	Range of commercial values	Value used in case study 1
Lot charge	£30 - £500	£500
Processing charge per kg material	£4 - £6	£5
Refining charge per kg precious metal	£170 - £250	£190
Precious metal accountability *Initial analysis of material provides a theoretical precious metal concentration from which the amount repayable to the waste supplier is derived. The refinery does not repay 100% of this value, but repays a percentage, based on a pre-defined "accountability" percentage.*	90% - 98% depending on precious metal concentration	Specified in results for individual scenario evaluation

Table 10.6: Development of cost data for unknown processes

Process	Estimated operator time	Estimated cost rate	Energy requirements (per 1000 kg)	Energy unit cost*
Water jet cutting	5 minute setup time per 10 kg 5 minute cutting time per 10 kg 15 minute clean-up time per 500 kg	£50 per hour	162 MJ electricity	£0.07 per kWh
Surface grinding	1 minute per 0.125 kg 30 minute clean-up time per 200 kg	£50 per hour	665 MJ electricity	£0.07 per kWh
Pressurised steam treatment	30 minutes setup per 1000 kg 30 minutes clean-up per 1000 kg	£50 per hour	56 MJ electricity 396 MJ natural gas	£0.02 per kWh
Sieving	30 minute setup per 1000 kg 30 minute clean-up per 1000 kg	£50 per hour	0.81 MJ electricity	£0.07 per kWh

**Estimated, based on data within Department of Energy and Climate Change, 2011*

Table 10.7: Data for calculation of revenue from end-of-life scenarios in case study 1

Recovered material	Assumed market value (£ per kg)	Source
Palladium	£15000	Johnson Matthey, 2011
Ceramic plates (from surface grinding)	£0.50	Estimated, based on market value of £1 per kg for ceramic raw material (alibaba.com, 2011f) assuming some reprocessing required prior to reuse
Ceramic powder (from sieving)	£0.70	Estimated, based on market value of £1 per kg for ceramic raw material (alibaba.com, 2011f) , assuming some reprocessing required, prior to reuse
Structural filler (from precious metal recovery, scenario 3)	Cost neutral	Estimated

10.3.4 Implementation of case study 1

Case study 1 was implemented using the data and assumptions generated by the application of the first two stages of the framework, definition of product stream and definition of end-of-life scenarios, described in Sections 10.3.1 – 10.3.3 above. The third and fourth stages of the framework were applied, following the evaluation methodology developed in Chapter 9 of the thesis. Each of the three end-of-life scenarios was evaluated to determine legislative risk, environmental impact and economic impact (Figure 10.5). Legislative risk was evaluated using the novel risk assessment tool described in Chapter 9 of the thesis. Environmental impact was evaluated using GaBi4 software to perform LCA of each end-of-life scenario, according to the goal, scope and system boundaries described in Chapter 9. Microsoft Excel was used to manipulate the results generated in GaBi4 in order to generate a graphical representation of results. A cost-benefit spreadsheet was generated in Microsoft Excel in order to support the

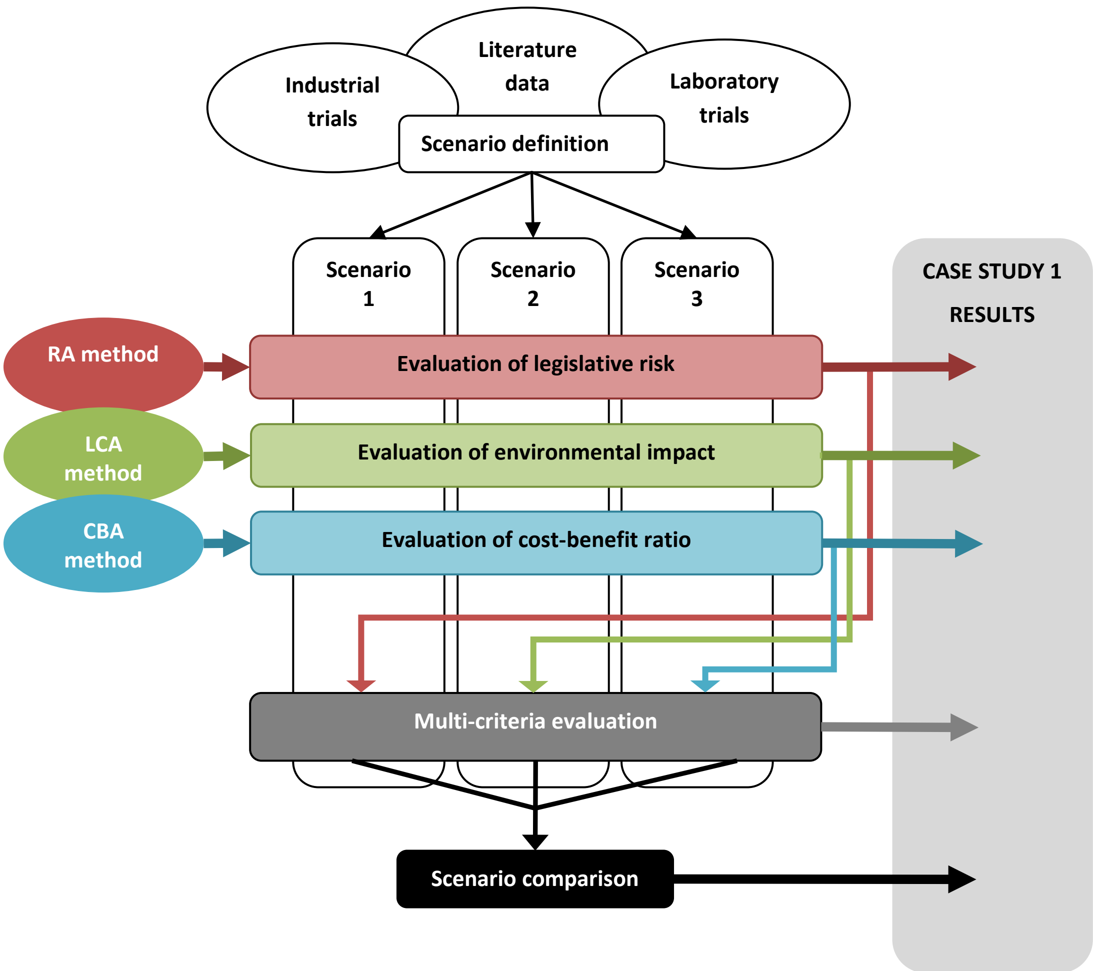


Figure 10.5: Implementation of case study 1.

parametric cost-benefit analysis (CBA) described in Chapter 9, and again to generate a graphical representation of results. The numerical results from the individual evaluation methods were used as the input to the E^2LM decision support tool.

10.3.5 Analysis of results for case study 1

The following sections present the results obtained from the individual evaluation methods for legislative compliance, environmental impact and economic impact. In addition, the application of the multi-criteria decision support tool, E^2LM, is applied to support identification of the preferred end-of-life scenario.

10.3.5.1 Legislative compliance risk assessment results

Figures 10.6 – 10.8 show the results from the legislative compliance risk assessment for each of the scenarios under evaluation in the case study.

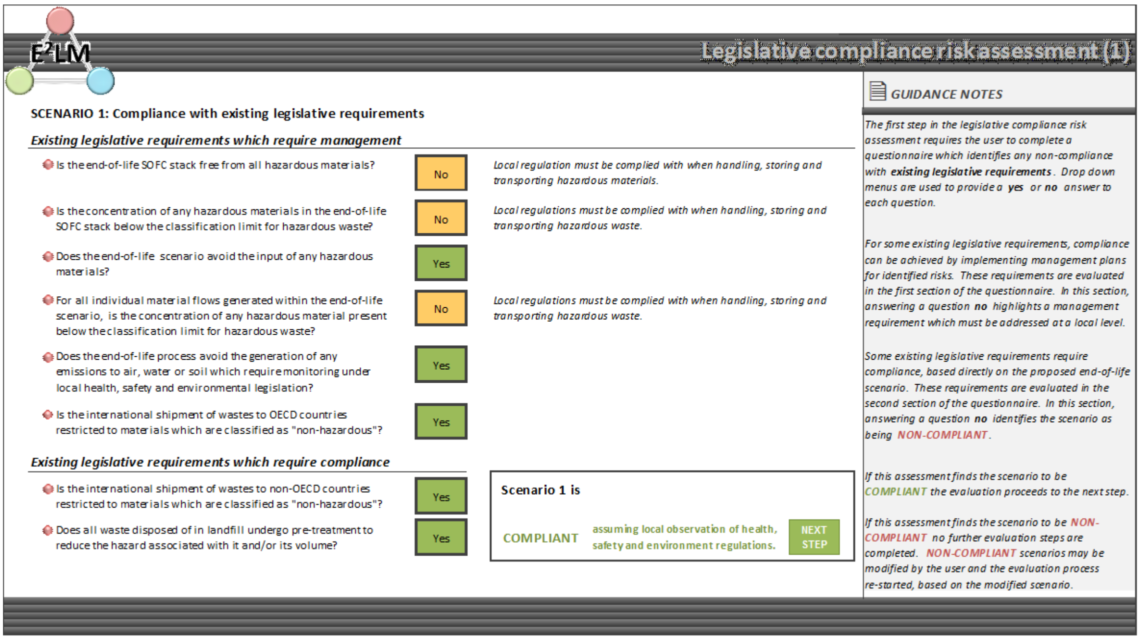
All three scenarios are shown to have the same performance with regard to compliance with existing legislation. The presence of various hazardous materials within the SOFC stack is indicated. These hazardous substances, as discussed in Chapter 7, are present in very small concentrations in the manufactured SOFC stack, and as such the SOFC stack waste stream would not be classified in its entirety as hazardous waste. The exception to this is nickel oxide, which, as a category 1 carcinogen, has a concentration limit of 0.1% by weight, over which waste containing this substance is classified as hazardous waste. Within the SOFC stack, nickel oxide is converted to nickel metal during operation, on exposure to a hydrogen-rich environment. However, this transformation is reversible, depending on the conditions under which the SOFC stack is shut down. If the SOFC stack is shut down in an oxygen-rich environment, then nickel oxide re-forms. If, however, the SOFC stack is shut down in a hydrogen-rich environment, then nickel remains in the metallic form. Nickel, in the metallic form, is allowed in concentrations up to 1% by weight before a waste stream is classified as hazardous.

Based on the low concentration of nickel oxide within the SOFC stack, it is possible therefore, that the answer to the question *"Is the concentration of any hazardous materials in the end-of-life SOFC stack below the classification limit for hazardous waste?"* would only be answered "YES", if it could be guaranteed that the SOFC stack has been shut down in a non-oxidising environment. For each of the three scenarios it is assumed that such controls are not currently in place, and so a negative response is entered on the risk assessment form.

None of the scenarios, as defined in the case study, require the input of hazardous materials, however, individual process steps result in the generation of small quantities of hazardous waste, principally arising from the concentration of the small quantities of hazardous materials contained within the SOFC stack. Similarly, emissions of dust and contamination of waste water will require monitoring under local health, safety and environment regulations, with appropriate controls implemented.

With regard to the international transportation of waste, all scenarios require the shipment of hazardous waste overseas, based on the assumptions made within the case study regarding the state of the nickel within end-of-life SOFC stacks. Under controlled shut-down conditions, scenario 3 would not require the shipment of hazardous waste overseas. The initial material separation steps conducted in scenarios 1 and 2 result in the removal of the bulk ceramic material, prior to shipment of waste for precious metal recovery. As such, this concentrated material fraction for scenarios 1 and 2 would be classified as hazardous, regardless of whether the nickel was in metal or oxide form.

The results from the risk assessment step of the legislative evaluation indicate that scenarios 1 and 2 achieve an equal score of 3.88. The evaluation method identifies two areas of “high” risk. The first area relates to the weight percentage of the end-of-life SOFC stack which is recycled. Scenarios 1 and 2 both achieve recycling rates of between 55% and 70% of the input material. A requirement to recycle a higher percentage would require significant improvement to be achieved in the material separation steps of the end-of-life processes. The disposal of hazardous waste to landfill also introduces a high level risk for scenarios 1 and 2. Development of legislation to prohibit disposal of all hazardous wastes to landfill would require alternative solutions to be developed for the low levels of residual hazardous waste arising from the processing of end-of-life SOFC components. Similarly, the prohibition of disposal of non-hazardous wastes would require significant modification of the end-of-life scenarios; however, this development in legislation is identified as having only a low probability, such that a medium risk is identified.



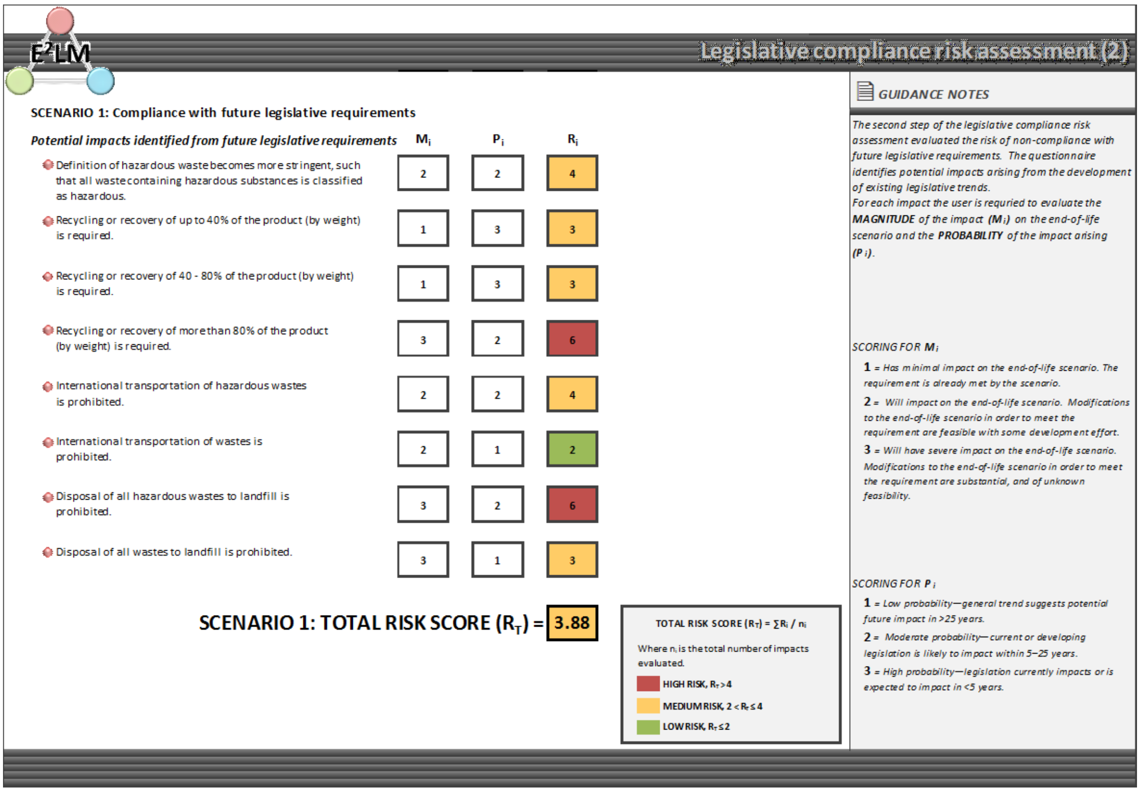


Figure 10.6: Case study 1 results from legislative risk assessment for scenario 1

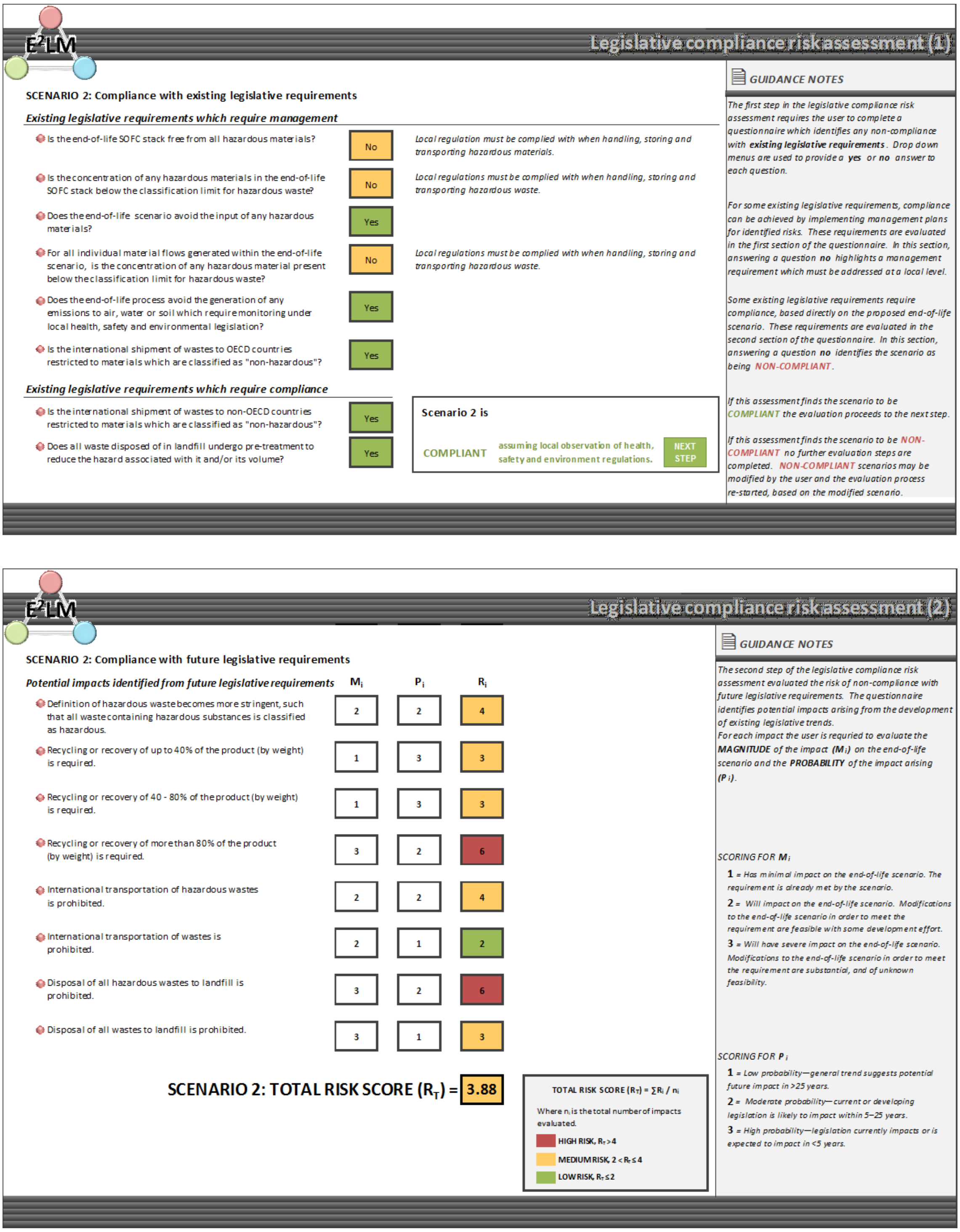


Figure 10.7: Case study 1 results from legislative risk assessment for scenario 2

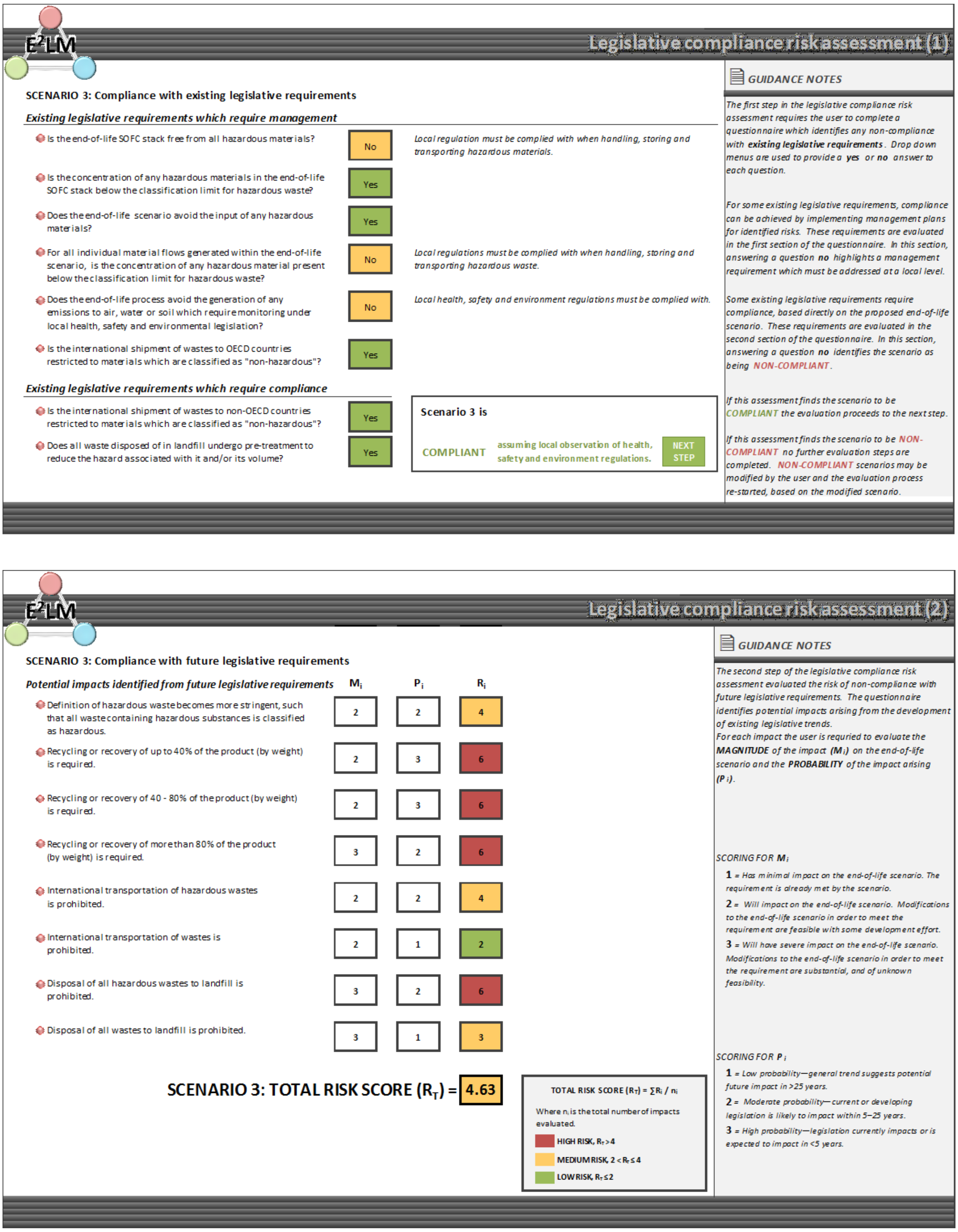


Figure 10.8: Case study 1 results from legislative risk assessment for scenario 3

For scenario 3, two additional areas of high risk are identified, leading to a higher risk score of 4.63. In scenario 3, the majority of the weight of material recycled from the end-of-life SOFC stack is in the form of residual waste from the precious metal recovery process step, which is used as low-grade structural filler. While this has been considered within the case study to be recycled material, with associated avoided environmental impacts, its definition as such is tenuous, and no market value has been assigned during the evaluation of economic impact. If this material fraction were to be classified as waste rather than recycled material then significant modification to the end-of-life scenario would be required to achieve recycling rates greater than that attributed to the recovery of precious metal (which is at most 1% by weight).

Overall, the results from the legislative risk assessment in case study 1 highlight the risks introduced at end-of-life when hazardous materials are present within a product. These risks could be alleviated by substitution of hazardous materials with less hazardous alternatives. In addition, the comparison of the results obtained for scenarios 1 and 2 with that of scenario 3 illustrate the value of early separation of materials within the end-of-life SOFC stack, in supporting higher overall levels of material recycling.

10.3.5.2 Environmental impact results

Results from the evaluation of environmental impact are shown in Figures 10.9 – 10.12. These results were obtained by applying the streamlined LCA method, described in more detail in Chapter 9. Results indicate the environmental impact associated with the end-of-life management of a SOFC stack capable of producing 1 kW of electrical power when operating at design point.

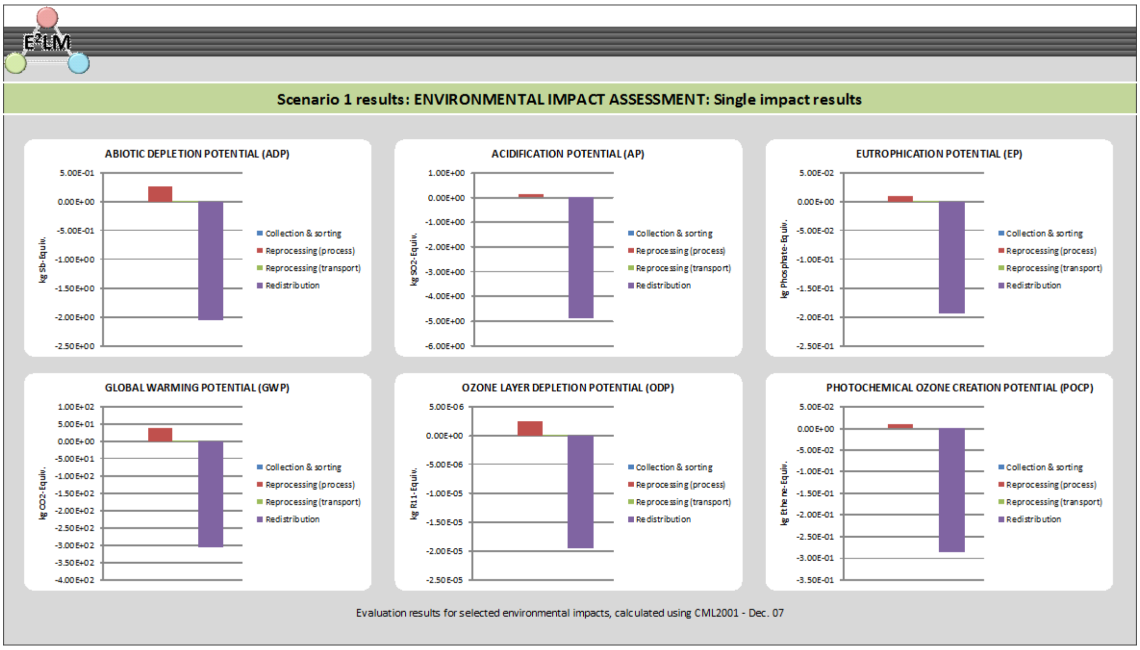
When examining the results from the three alternative scenarios, it is immediately clear that similar patterns can be observed, with regard to the distribution of environmental impacts across the three stages of the end-of-life process (collection and sorting; reprocessing; redistribution). Graphical representations of the single impact results, for each of the six impact categories included within the scope of the evaluation, indicate that the environmental benefits arising from the redistribution stage in all cases substantially outweigh the cumulated detrimental effects of the other stages.

The benefits at the redistribution stage arise from the avoided impacts assigned to the production of recycled palladium metal, as well as recycling of ceramic materials in scenarios 1 and 2. This effect reflects the high environmental impacts associated with the production of virgin palladium, especially considering the low concentration of palladium present in the SOFC stack. It should be noted that a complete life cycle assessment of the SOFC components examined in this case study would also take into account the detrimental environmental impacts of palladium production in the manufacturing phase of the SOFC product life cycle. None-the-less, the results from the case study indicate that these high impacts during manufacture would be alleviated if efficient recovery of material at end-of-life was routinely achieved.

It is also clear from the results presented in Figures 10.9 to 10.11 that the collection and sorting step of end-of-life management makes an insignificant contribution to the overall environmental impact of any of the scenarios evaluated. Also, the impacts of transportation during the reprocessing step were found to be negligible. All three scenarios investigated in this case study were limited in their geographical scope, with all process steps being conducted within Europe, which is at present relatively close to the point of origin of the end-of-life SOFC stacks. Given the intention of Rolls-Royce Fuel Cell Systems Limited to enter a global market, it is possible that the impacts of transportation would be more prevalent in the future, depending on the proximity of recycling processing plants to the installed SOFC products.

By the application of normalisation and weighting factors, the aggregated scores can be used to compare performance more clearly across the three scenarios, as shown in Figure 10.12. All three scenarios have an overall score which is a negative number, which indicates that in all cases the proposed reprocessing routes would be beneficial within the complete product life cycle. With an overall impact value of -2.13×10^{-9}, scenario 3 provides the greatest environmental benefits. This is directly related to the high efficiencies associated with the recovery of palladium metal. Scenario 3 demonstrates the least complex process route, and as such material losses associated with initial material separation steps are minimised. In contrast, scenario 2 incurs high losses during the sieving separation step, resulting in a smaller amount of palladium being recovered in the final process step. This scenario performs the least well of the three, with an overall impact of -1.53×10^{-9}.

These environmental impact results illustrate that investing in the end-of-life management of SOFC stacks is of benefit with regard to the environmental impact of the technology. This is especially significant in cases such as this where environmentally damaging materials are used in the production of components.



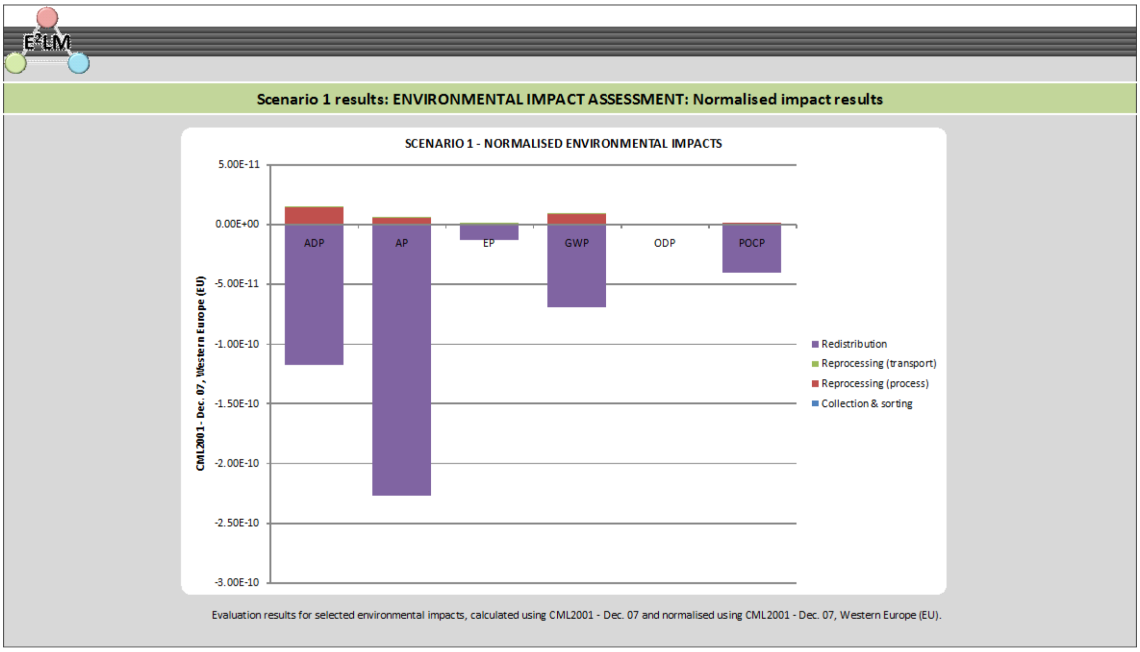
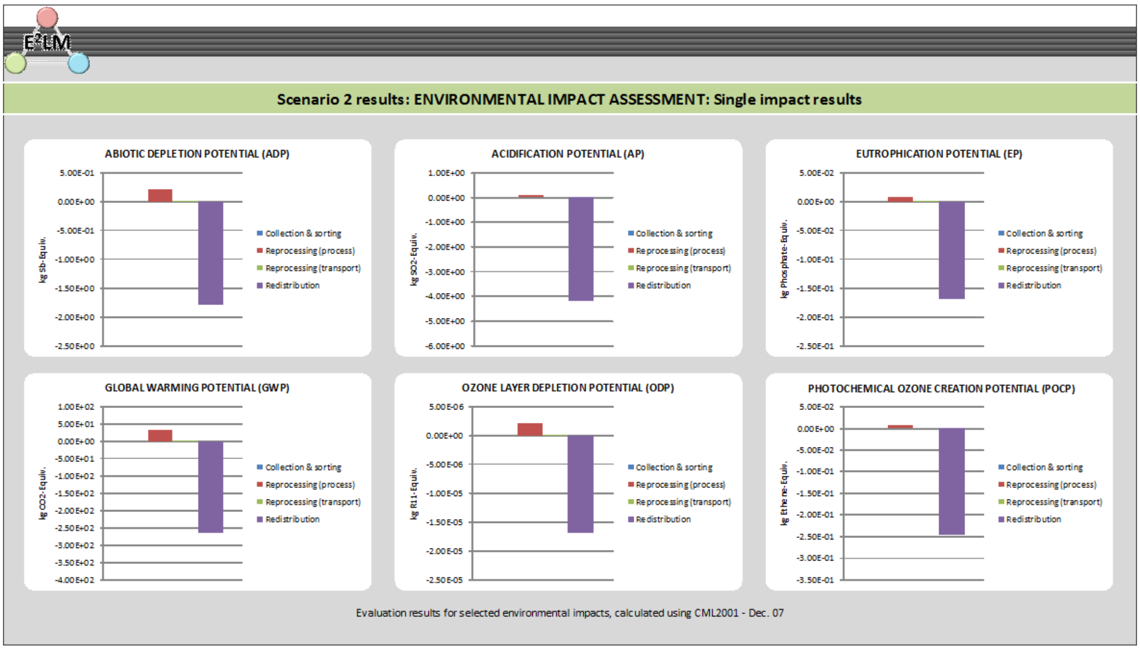


Figure 10.9: Case study 1 results from environmental impact assessment for scenario 1



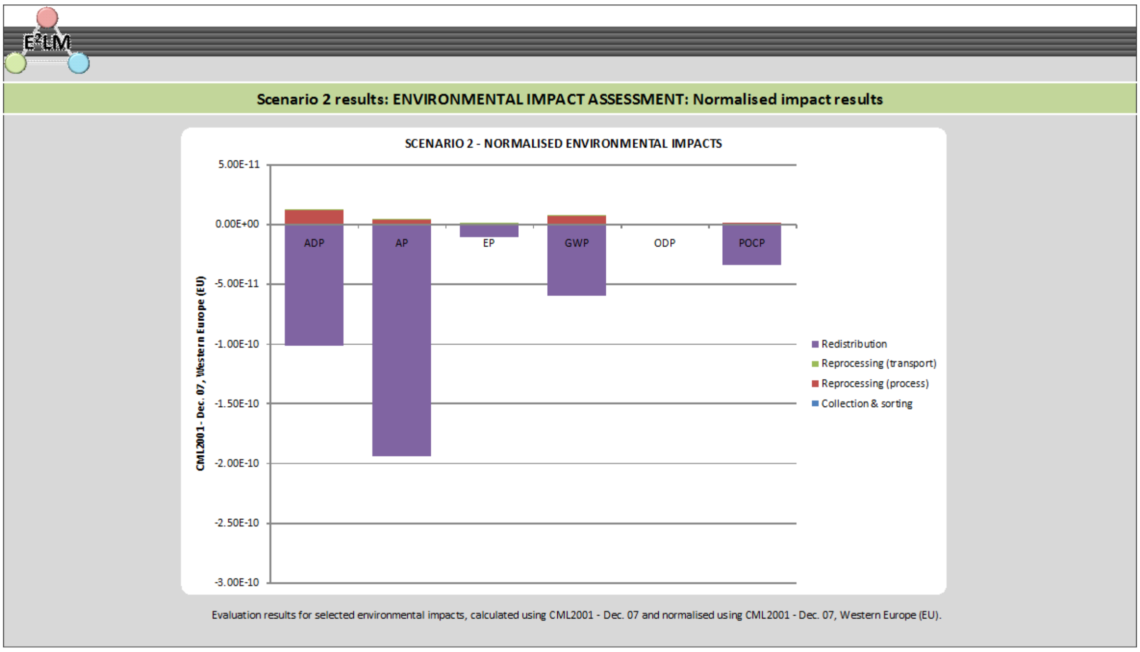
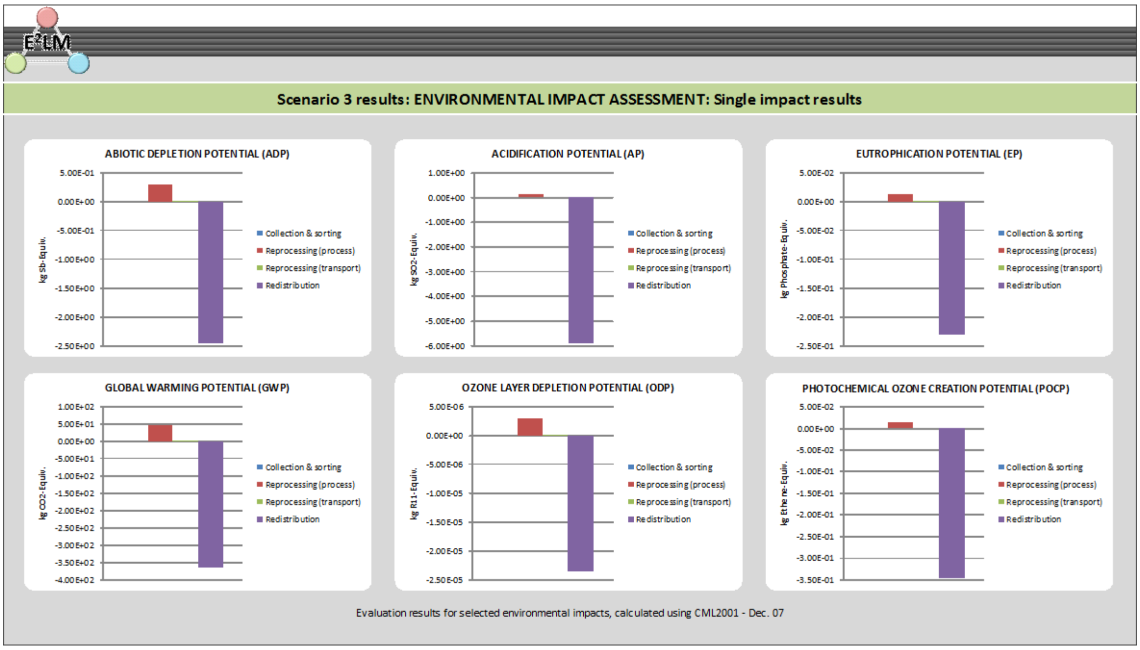


Figure 10.10: Case study 1 results from environmental impact assessment for scenario 2



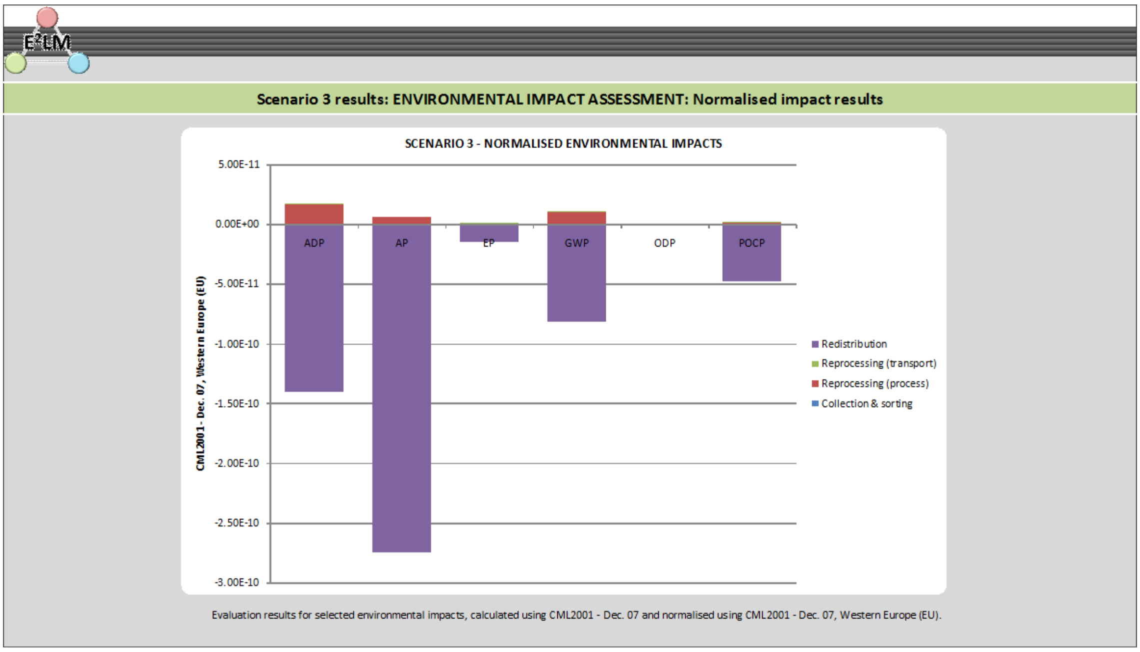


Figure 10.11: Case study 1 results from environmental impact assessment for scenario 3

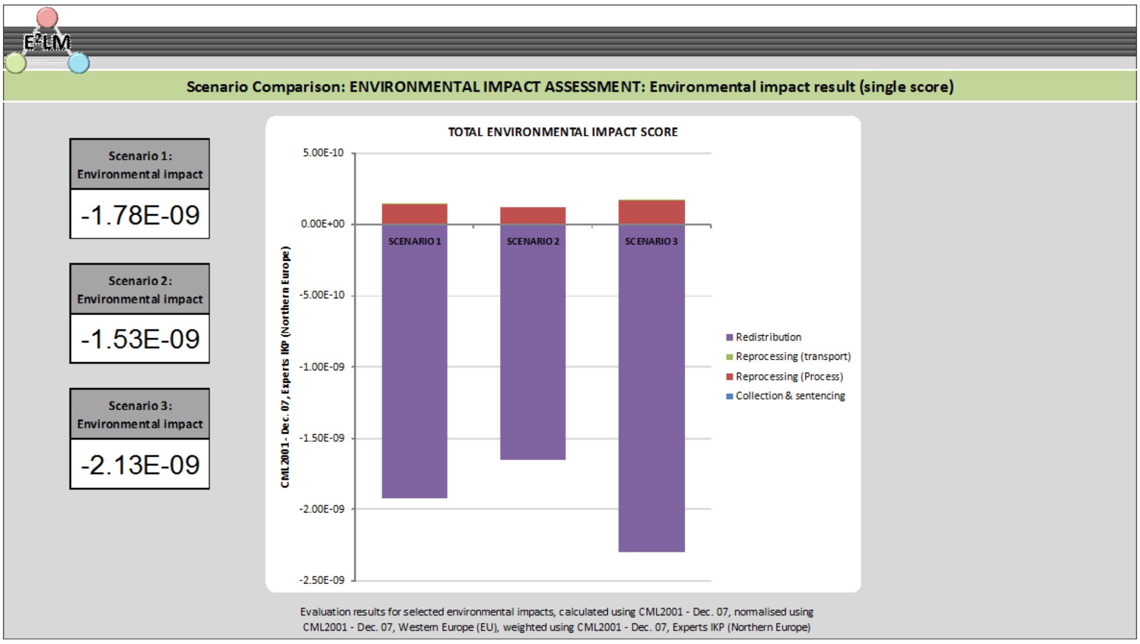


Figure 10.12: Single score results from the evaluation of environmental impact for the three scenarios investigated in case study 1.

10.3.5.3 Economic impact results

The results from the economic impact evaluation are presented in Figure 10.13, with costs displayed as negative values, and revenues displayed as positive values. It is immediately clear from the results that the value of the recycled materials dominates the performance of all three scenarios. The recovery efficiency for palladium in scenario 2 is lower than scenarios 1 and 3, due to inefficiencies in the sieving process step. Scenario 3 has the highest recovery efficiency for palladium.

The costs associated with all three scenarios are marginal in comparison with the revenues recovered from recycled materials. Scenario 2 has the lowest costs associated with it, based on the assumptions defined in Sections 10.2 and 10.3. In contrast, scenario 1 has higher costs associated with the initial material separation stages of the process.

The cost-benefit ratio provides a single figure result for the economic impact evaluation. A low cost-benefit ratio value represents a low economic impact. In all cases the cost-benefit ratio associated with the end-of-life scenarios is less than one, indicating than an overall economic benefit is realised. The results from the case study indicate that scenario 2 performs best economically, while scenario 1 has the highest economic impact.

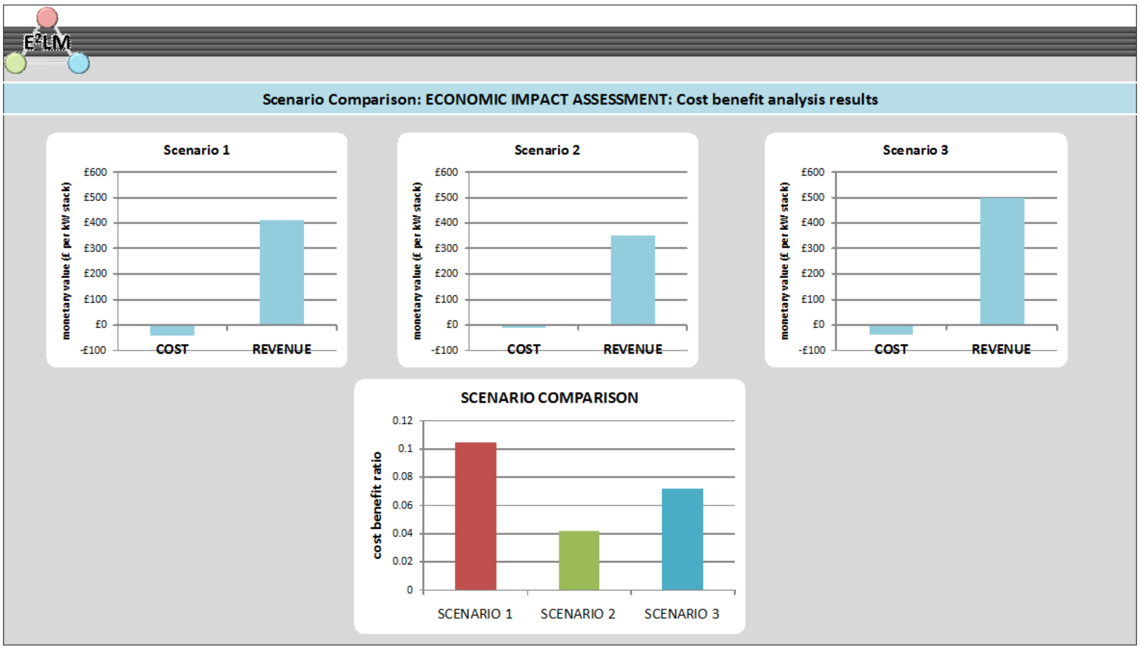


Figure 10.13: Results from the evaluation of economic impact for the three scenarios investigated in case study 1.

10.3.5.4 Multi-criteria decision making

Individual results from the evaluation methods presented in the previous sections were imported into the E^2LM multi-criteria decision support tool, and results were normalised.

Results from the multi-criteria evaluation method are shown in Figures 10.14 – 10.17. Figure 10.16 shows the final outcome for the comparison between the three scenarios evaluated in case study 1. Scenario 2 is identified as being the preferred end-of-life option, based on the single score calculated using the weightings for individual performance criteria. Scenario 1 performs least well, when all performance criteria are considered together.

A sensitivity analysis was performed on the results generated using the multi-criteria decision support tool, as shown in Figure 10.17. Weighting levels were changed to represent a situation where legislative compliance is considered to be half as important as environmental and economic impact, which are considered equal. Results from the application of these revised weightings show the same order of preference to be obtained for the three end-of-life scenarios evaluated.

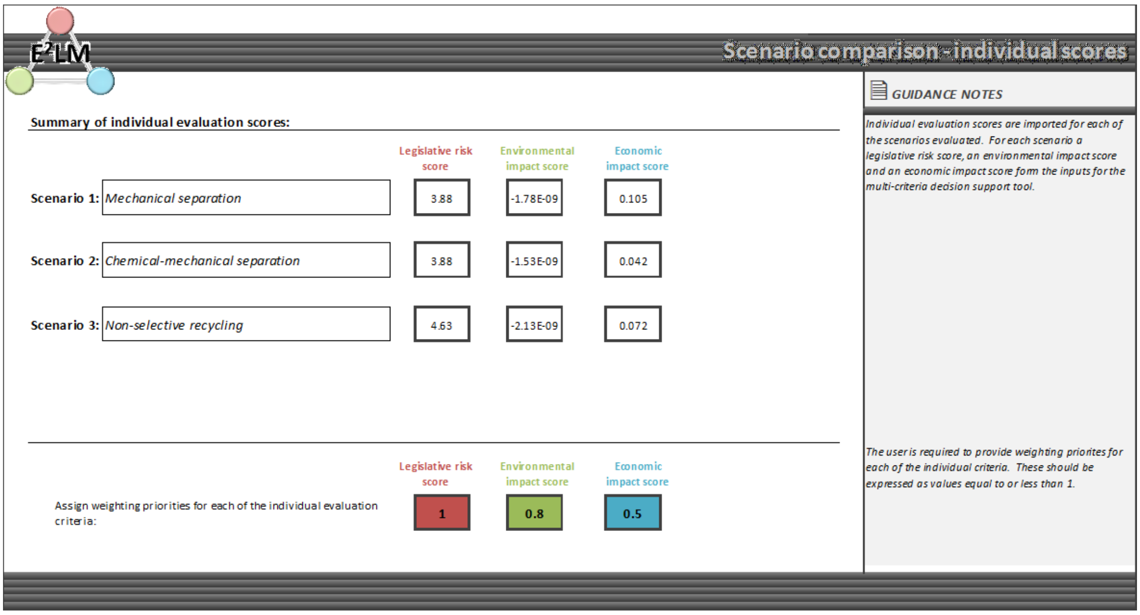


Figure 10.14: Individual performance scores are imported to the multi-criteria decision support tool, and weightings are defined for case study 1.

Figure 10.15: Normalised results from the individual evaluation methods for case study 1.

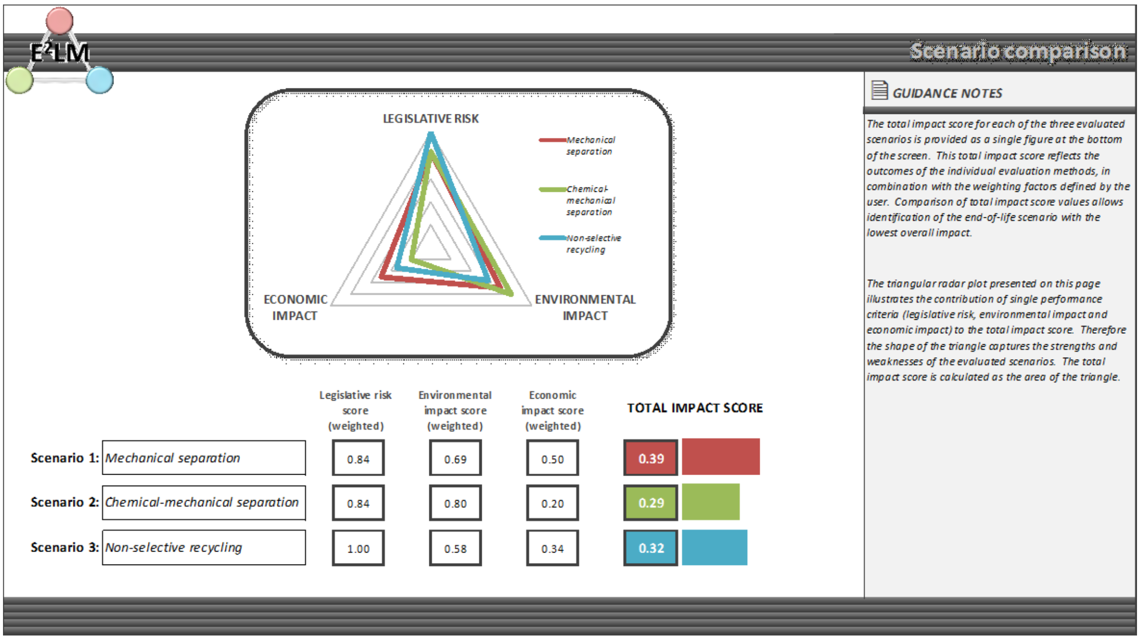


Figure 10.16: Final comparison of scenarios 1, 2 and 3 investigated in case study 1.

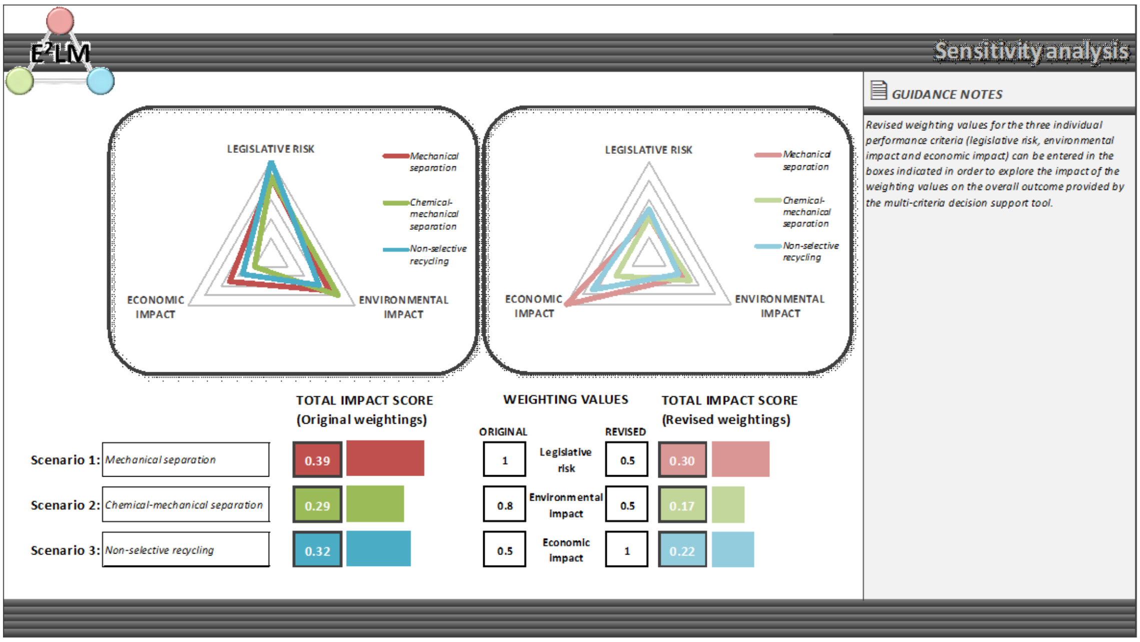


Figure 10.17: Sensitivity analysis showing the results of applying revised weightings in the multi-criteria evaluation method used in case study 1.

10.3.6 Conclusions from case study 1

Case study 1 demonstrates the application of the framework for end-of-life management of SOFC stacks, as developed in the research presented in this thesis. The results from the individual evaluation methods are summarised qualitatively in Figure 10.18. These results indicate that evaluation of individual performance criteria does not necessarily provide a clear selection of a preferred end-of-life scenario from several alternative options. In case study 1, none of the three scenarios evaluated was found to perform “best” against all three performance criteria: similarly there was not a clear worst performer. As such, this highlights the paramount importance of the multi-criteria decision support tool. The application of this tool in this case study identifies scenario 2 as providing the best overall performance, relative to the other two end-of-life options.

This final conclusion from the case study is interesting. At present, only scenario 3 represents a commercially “ready” process for the treatment of end-of-life SOFC components, but has not been tailored to meet the specific requirements of this end-of-life waste stream. Scenarios 1 and 2 have been developed based on preliminary feasibility studies. The results from case study 1 indicate that improvements on the commercially available process route could potentially be achieved, through development of a new end-of-life process (scenario 2): however, the results also indicate that poor process selection could result in the impact of end-of-life management being increased (scenario 1), rather than decreased.

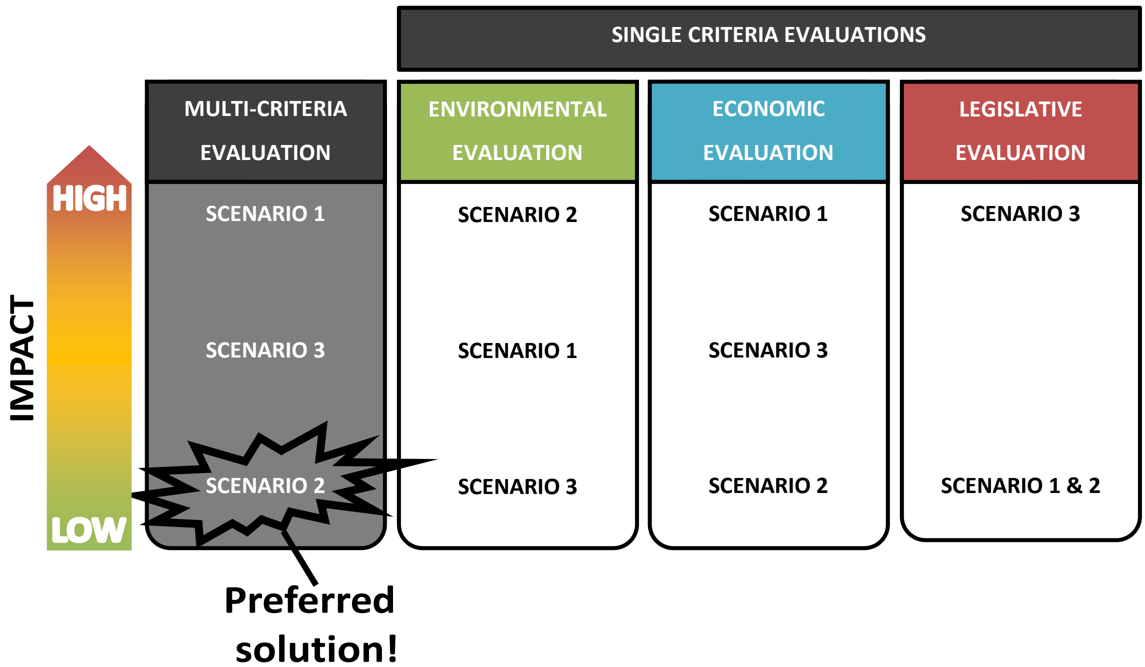


Figure 10.18: Summary of results from case study 1.

10.4 Case study 2

The results from case study 1 indicate the dominance of the palladium content of the end-of-life SOFC stack with respect to the overall environmental and economic impact associated with its end-of-life management. However, the end-of-life SOFC stack considered in case study 1 consists of pre-commercial components, manufactured during the development of manufacturing processes, and prototyping of the technology. As such, the material composition of the SOFC stack considered in case study 1 is unrepresentative of the material composition of commercial product, since the use of precious metals, such as palladium, is considered to be necessary only for product development and testing purposes. Alternative materials with lower market value are available to replace the use of palladium in the IP-SOFC design.

Therefore, case study 2 investigates the impact of reducing the palladium content of the SOFC stack on the end-of-life phase of the life cycle. Case study 2 builds on the results obtained in case study 1, and so is subject to the same data limitations as described in Sections 10.2 and 10.3. The intention of case study 2 is to demonstrate the application of the end-of-life framework developed in the thesis to inform decisions regarding the design of the SOFC stack, thus supporting a more proactive approach to end-of-life management.

10.4.1 Characterisation of the product stream for case study 2

Three variations of product stream were investigated during this case study, reflecting changes in material composition effected by modification of the SOFC stack design. One of the principal design challenges for fuel cell developers is cost reduction. As such the use of expensive materials is constantly being reviewed, and their use minimised wherever possible. However, valuable material content is an attractive attribute of end-of-life products, since the revenues recovered often contribute to the economic feasibility of the recycling process. In order to investigate this apparent conflict between design requirements and end-of-life requirements, three different design concepts were evaluated:

- Design concept 1: High palladium content – this material composition was the subject of case study 1, representing pre-commercial products where the use of noble metals, such as palladium, is useful for performance testing. Palladium content is assumed to be 1%, by weight, of the SOFC stack.
- Design concept 2: Medium palladium content – this material composition represents a significant reduction in the use of palladium. Palladium is partially replaced with a

ceramic current collecting material, similar to the SOFC cathode. Palladium content is assumed to be 0.1%, by weight, of the SOFC stack.

- Design concept 3: Trace palladium content – almost all precious metal is removed from the SOFC stack, and is replaced with a ceramic current collector material, similar to the SOFC cathode. Palladium content is assumed to be 0.01%, by weight.

All other assumptions regarding the characterisation of the product stream are the same as those documented for case study 1 in Section 10.3.1.

10.4.2 Definition of end-of-life scenarios for case study 2

The end-of-life scenarios investigated for case study 2 are the same as those previously defined in case study 1 in Section 10.3.2.

10.4.3 Data for case study 2

In general the data requirements for case study 2 are the same as those for case study 1 and the data utilised in case study 2 are the same as those defined in Sections 10.3.2 and 10.33. Data are only adapted to reflect changes in palladium content of the SOFC stack. All other design and process parameters are assumed to remain the same.

10.4.4 Implementation of case study 2

The implementation of case study 2 followed the same process as depicted in Figure 10.5, repeated three times for each of the design concepts investigated. Further to supporting a comparison of three alternative end-of-life scenarios, case study 2 had an additional purpose of exploring the link between the product design and end-of-life stages.

10.4.5 Analysis of results for case study 2

The following sections present the results obtained from the individual evaluation methods for legislative compliance, environmental impact and economic impact. Finally, the application of the multi-criteria decision support tool, E^2LM, is applied to support identification of the preferred end-of-life scenario.

10.4.5.1 Legislative compliance risk assessment results

Changes to the palladium content of the SOFC stack were not found to impact upon the risk of non-compliance with legislative requirements. Therefore the results for the legislative risk assessment are the same for all three design concepts, and are the same as the results presented in case study 1, in Figures 10.6 – 10.8.

10.4.5.2 Environmental impact results

Environmental impact results for the three design concepts are shown in Figures 10.19 – 10.21, with each figure showing a comparison of the results obtained for all three end-of-life scenarios. It can be seen that even with elimination of all but a trace quantity (0.01%) of palladium, the benefits of the material recycling continue to outweigh the detrimental impacts of the reprocessing step, as shown in Figure 10.21. However, in this third design concept, the benefits of recycling ceramic material in addition to the precious metal become apparent, illustrated by the superior benefits offered by scenarios 1 and 2.

These results from case study 2 indicate that for the first design concept (1% palladium) scenario 3 provides the greatest environmental benefit, while scenario 2 performs least well. This same order is observed for the second design concept (0.1% palladium), although the variation in performance for the three scenarios is much less marked. However, for the final design concept evaluated (0.01% palladium), scenario 3 provides the greatest environmental benefit, while scenario 1 would be the least preferred option from an environmental perspective.

These results indicate that a design modification, such as that defined in case study 2, can play a significant role at the end-of-life stage of the product life cycle. In this case study example, the outcome of the selection of an end-of-life solution for the SOFC stack based on environmental impact alone would differ for design concepts 1 and 3.

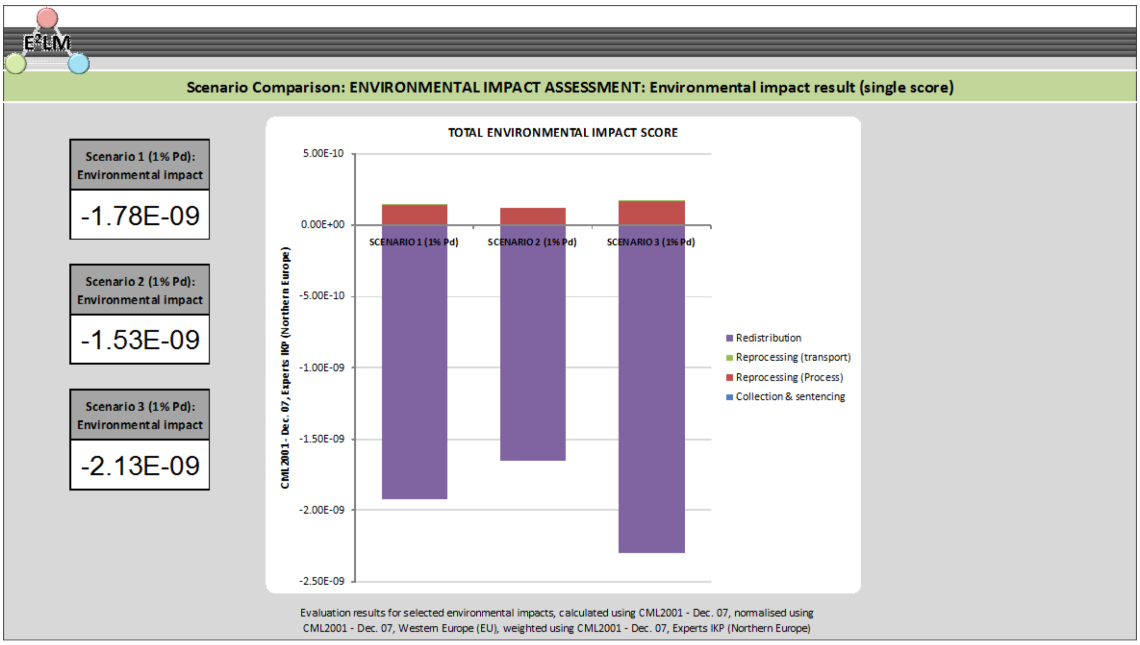


Figure 10.19: Single score results from the evaluation of environmental impact arising from the end-of-life management of Design Concept 1 (1% Palladium) by three alternative scenarios.

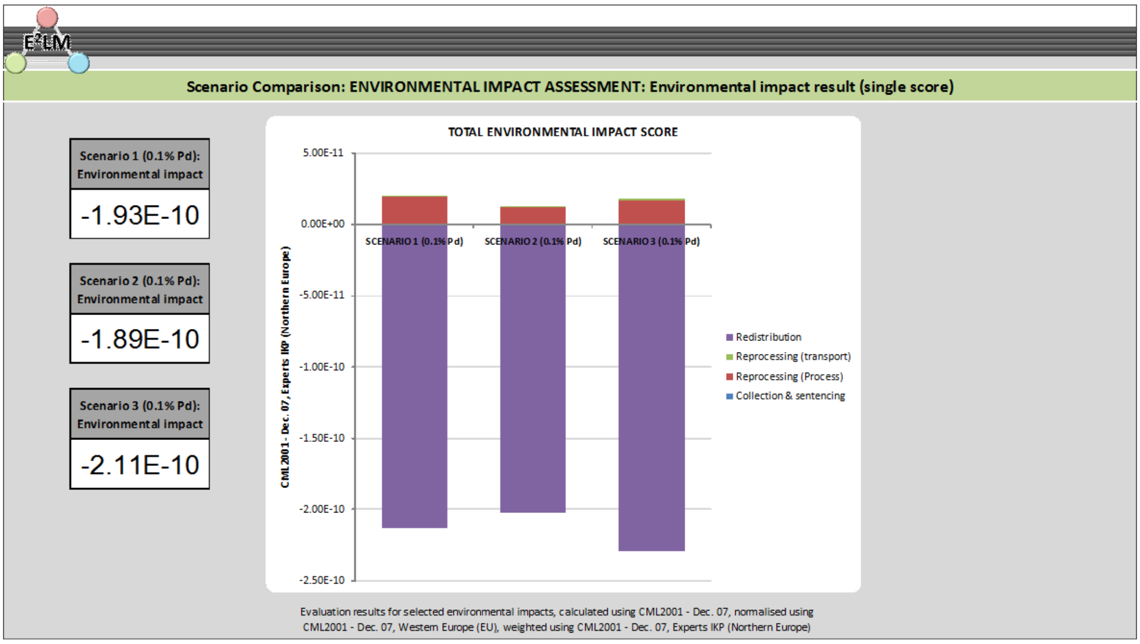


Figure 10.20: Single score results from the evaluation of environmental impact arising from the end-of-life management of Design Concept 2 (0.1% Palladium) by three alternative scenarios.

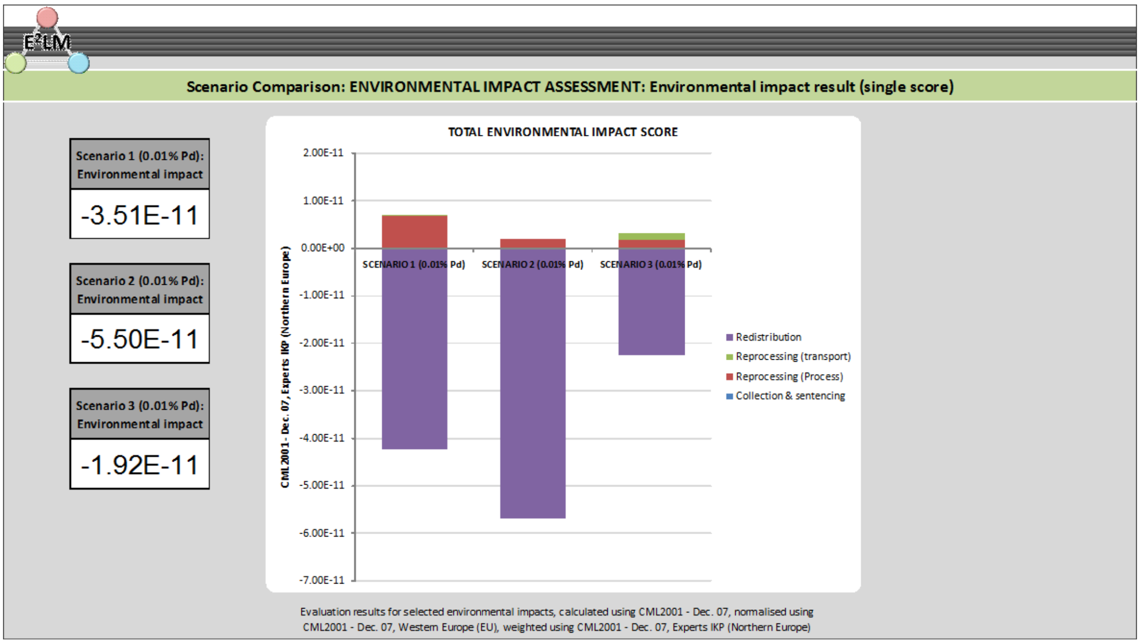


Figure 10.21: Single score results from the evaluation of environmental impact arising from the end-of-life management of Design Concept 3 (0.01% Palladium) by three alternative scenarios.

10.4.5.3 Economic impact results

Economic impact results for the three design concepts are shown in Figures 10.22– 10.24, with each figure showing comparison of results obtained for each of the end-of-life scenarios. It can be seen that for the first two design concepts, with 1% and 0.1% palladium respectively, the revenues recovered from the recycling process outweigh the total costs of end-of-life management for all three scenarios. This is indicated by cost-benefit ratio values of less than one. For the third design concept (0.01% palladium), the recycling process becomes uneconomic for all but scenario 2. Scenarios 1 and 3 both have cost-benefit ratio values greater than one, indicating that the process costs outweigh the revenues generated through recycling valuable materials.

For this final design concept, the revenue recovered from each of the end-of-life scenarios similar: the main variation lies in the costs of reprocessing. The high costs associated with scenario 1 are due to the labour intensive material separation steps, prior to precious metal recycling. For scenario 3 the high costs are associated with the precious metal recycling. In contrast to scenarios 1 and 2, no prior material separation is conducted, and so a large volume of material with low precious metal content is treated by the precious metal recycler. This incurs a high process cost, arising from a charge per kg of material received. When precious metal content is high, such as for design concept 1, this treatment cost is outweighed by the value of the recovered metal.

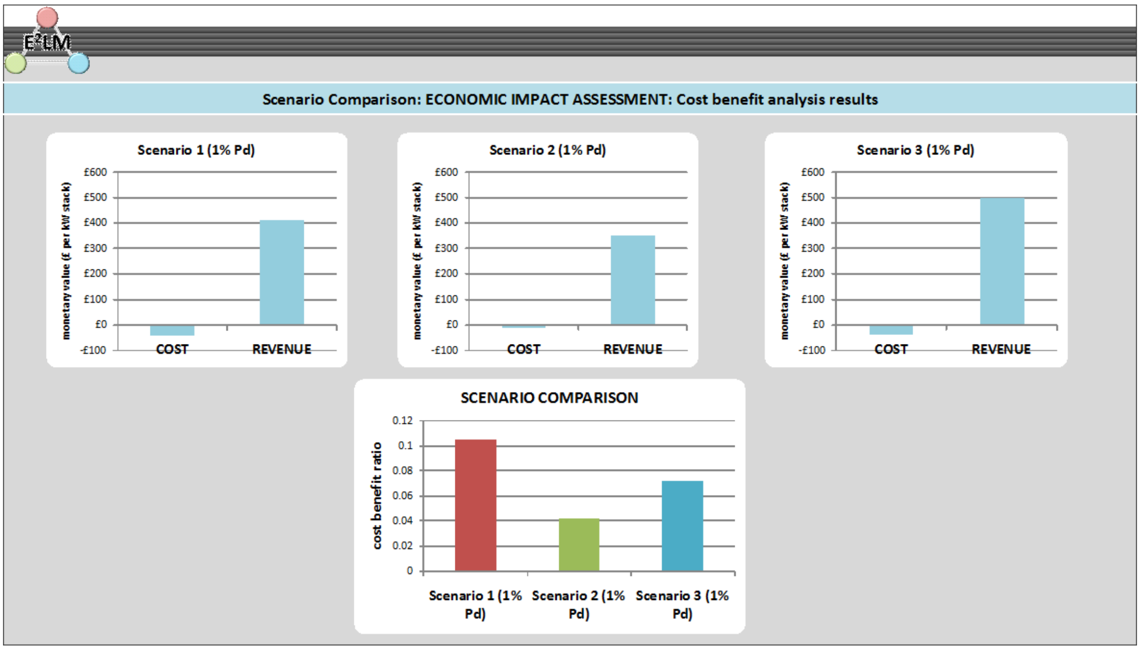


Figure 10.22: Single score results from the evaluation of economic impact arising from the end-of-life management of Design Concept 1 (1% Palladium) by three alternative scenarios.

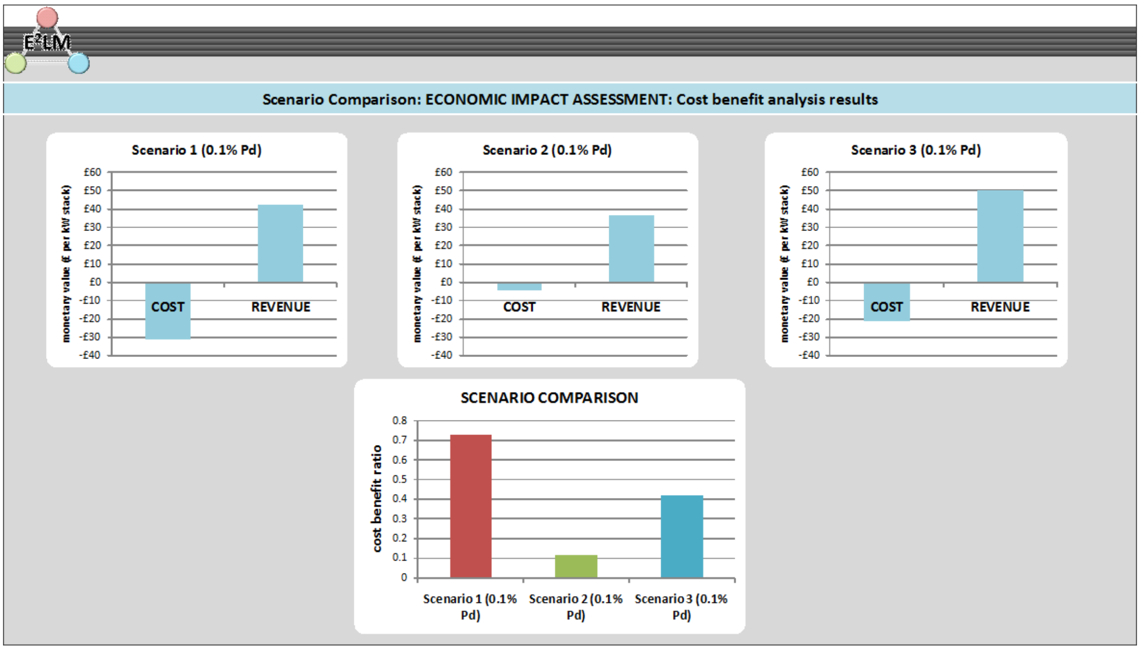


Figure 10.23: Single score results from the evaluation of economic impact arising from the end-of-life management of Design Concept 2 (0.1% Palladium) by three alternative scenarios.

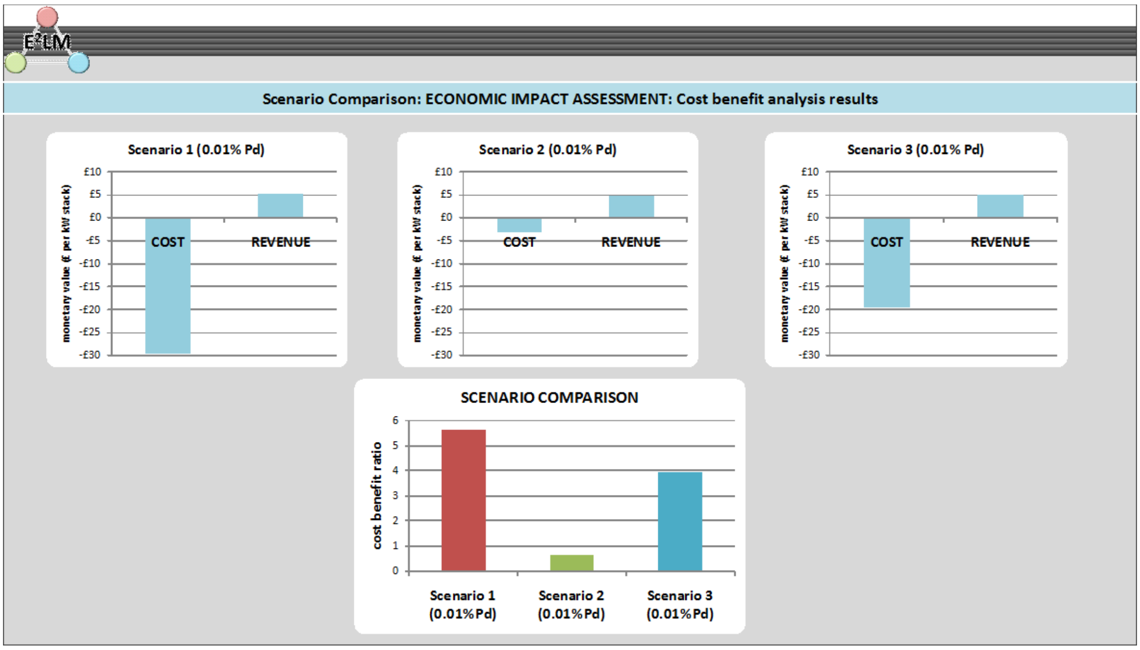


Figure 10.24: Single score results from the evaluation of economic impact arising from the end-of-life management of Design Concept 3 (0.01% Palladium) by three alternative scenarios.

These results indicate that as palladium content decreases, the adoption of a low-cost material separation process, prior to recovering the metal, becomes highly beneficial. Therefore this demonstrates that design parameters can be useful in directing the development of an economically viable end-of-life solution.

10.4.5.4 Multi-criteria decision making

Results from the application of the multi-criteria decision support tool are shown in Figures 10.25 – 10.27. Each figure shows a comparison of the performance of the three end-of-life scenarios, for Design Concept 1, 2 and 3 respectively. It can be seen from these results that although the magnitude of the results arising from the environmental and economic evaluation methods, presented in Sections 10.4.5.2 and 10.4.5.3 above, vary considerably for the different design concepts, the overall conclusion from the multi-criteria decision support tool remains unchanged: scenario 2 represents the lowest impact end-of-life scenario, relative to the other scenarios investigated in the case study. The difference in performance between the three scenarios becomes increasingly significant as the palladium metal is removed from the SOFC stack.

Despite there being no change in the scenario which would be recommended as the preferred end-of-life solution, changes in the triangular plots of the results are interesting. In Figure 10.25, the blue triangle (representing scenario 3) shows lowest environmental impact: by Figure 10.27 the contribution of environmental impact to the overall performance of scenario 3 has become more significant.

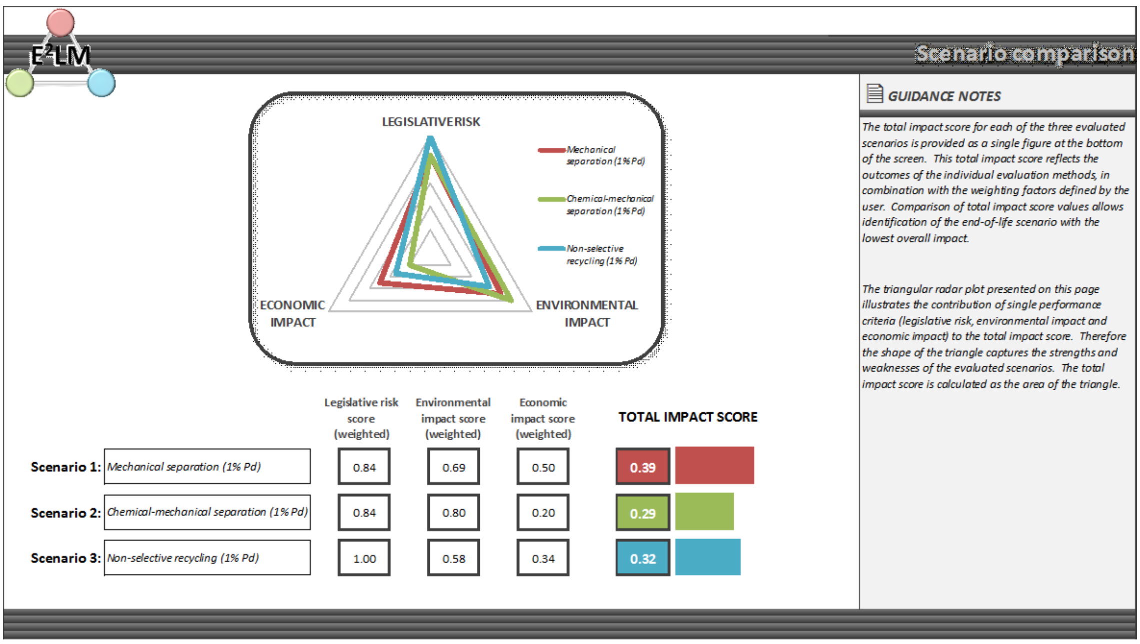


Figure 10.25: Final multi-criteria comparison of end-of-life scenarios for Design Concept 1 (1% Palladium)

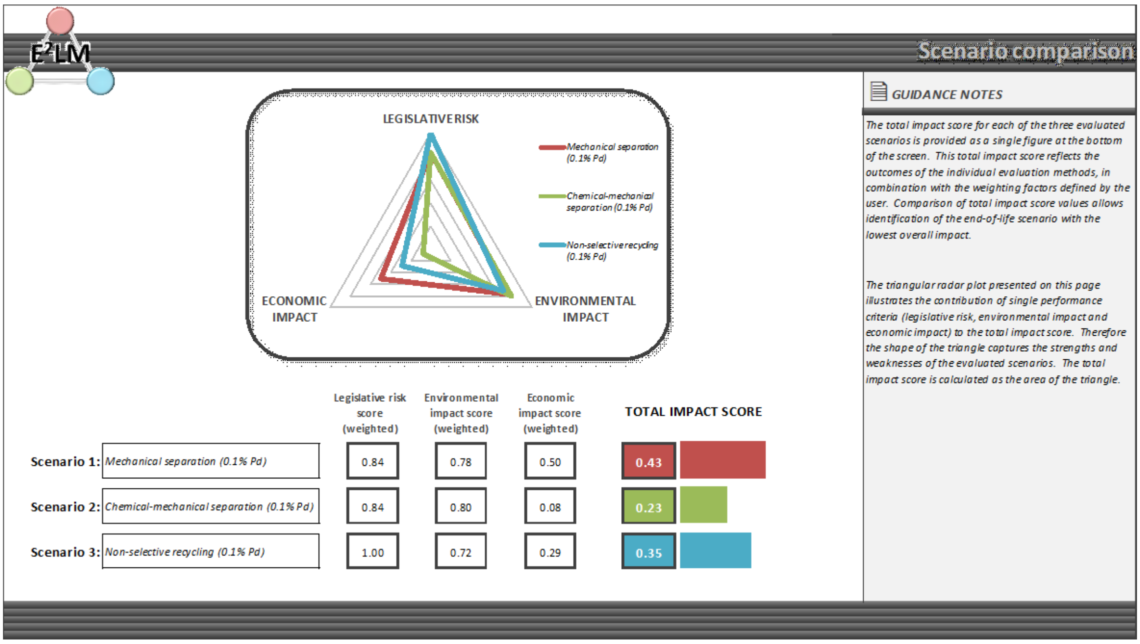


Figure 10.26: Final multi-criteria comparison of end-of-life scenarios for Design Concept 2 (0.1% Palladium)

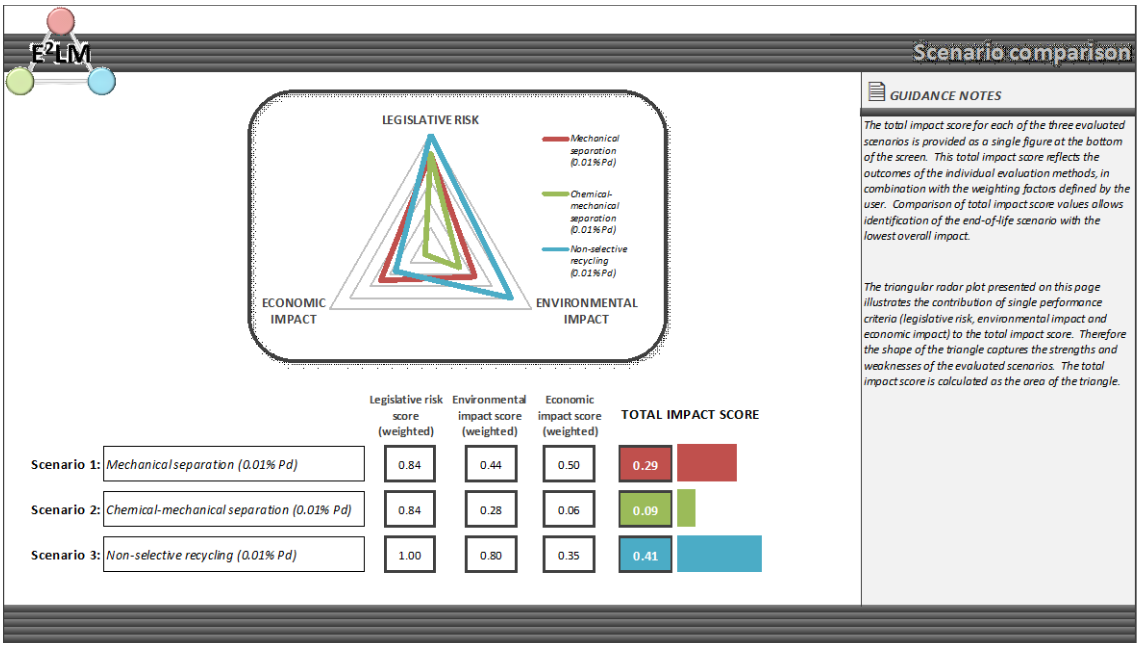


Figure 10.27: Final multi-criteria comparison of end-of-life scenarios for Design Concept 3 (0.01% Palladium)

10.4.6 Conclusions from case study 2

Case study 2 illustrates the application of the end-of-life management framework, developed in the thesis, to investigate the relationship between design modification and selection of an appropriate end-of-life scenario. The design modification investigated was concerned with the reduction of palladium within the SOFC stack. The results presented from this case study indicate the influence of the design modification on each of the three end-of-life performance parameters.

With regard to legislative compliance, no change was identified in association with a reduction in palladium content. The environmental impact of the end-of-life scenarios was found in case study 1 to be dominated by the recovery of palladium metal and ceramic material from the end-of-life process: this was shown to remain the case, even when the palladium content was reduced by an order of magnitude, as shown in the environmental impact results for the second design concept. However, when only trace amounts of palladium metal were available for recovery (i.e. design concept 3) the recycling of the bulk ceramic material became significant in scenarios 1 and 2. For this third design concept, the preferred end-of-life scenario, from an environmental perspective, changed from scenario 3 to scenario 2. In fact, whereas for the design concepts with 1% and 0.1% palladium content scenario 3 was found to offer the greatest environmental benefit, this scenario performed least well when applied to design concept 3 (0.01% palladium). In the economic impact evaluation, the removal of palladium metal from the SOFC stack has been shown to substantially increase the economic burden associated with the end-of-life phase of the product life cycle. When only a trace amount of palladium is present in the end-of-life waste stream (design concept 3), only scenario 2 is economically viable, with the other scenarios presenting a net cost. However, it is noted that this increase in cost associated with the end-of-life phase would presumably be counterbalanced with reduced production costs, assuming that palladium is replaced with a less expensive material. The adoption of a low-cost material separation step prior to precious metal recycling has been shown to have an economic benefit, which becomes more significant as the amount of precious metal in the SOFC stack is decreased. This finding from case study 2 is significant with respect to the development of an end-of-life management solution for future commercial SOFC products.

The application of a multi-criteria decision support tool to case study 2 leads to the conclusion that the preferred end-of-life scenario (scenario 2) remains unchanged when the three proposed design concepts are considered. However, it must be noted that the end-of-life scenarios developed for investigation in the case studies have been devised with priority given to precious metal recovery. In the absence of precious metals within the SOFC stack, it is necessary to investigate alternative end-of-life processes, which put more emphasis on recovery of the other materials contained within the SOFC stack.

Case study 2 illustrates how a simple design modification can be evaluated using the framework for end-of-life management defined in the thesis, in order to investigate the effect of the design change on legislative, environmental and economic performance at end-of-life. By using a simple example, the importance of the relationship between design and end-of-life management has been demonstrated. Although the results from the evaluation of design concept 1 (1% palladium) indicate a preference for the selection of end-of-life scenario 2, in terms of practical adoption of an end-of-life process only scenario 3 currently exists as a commercially available solution. Therefore, based on the strong environmental performance of scenario 3, as well as the large economic benefit achieved through recycling, it may be attractive for a SOFC developer to pursue non-selective recycling, despite the findings provided by the multi-criteria decision support tool. Although in the short term this pragmatic decision may avoid the need to invest in the development of the non-commercial process described in scenario 2, the results from case study 2 indicate that this decision may be short-sighted. Failure to develop an end-of-life solution which is economically viable when planned design changes (i.e. the removal of precious metals from the SOFC stack) are implemented could result in unnecessary costs being associated with the end-of-life phase of the commercial product life cycle.

10.5 Summary of findings from case studies

The case studies reported in this chapter apply the framework for end-of-life management, introduced in Chapter 6 of the thesis, to the question of end-of-life management of SOFCs. In the first case study, the framework is applied in a reactive approach: the design of the SOFC stack is fixed, and the framework supports the evaluation and comparison of three alternative end-of-life process routes. In the second case study, the framework is applied in a proactive approach: the relationship between end-of-life management and modification to the SOFC stack design is explored. Together, therefore, the case studies demonstrate the flexibility of the framework with regard to mode of application.

The first case study identifies the process defined as scenario 2 as being the preferred end-of-life solution, based on the application of the multi-criteria evaluation methodology developed within the research. This process utilises steam treatment in an autoclave to break down the ceramic stack components, followed by an automated sieving process to separate the active material fraction from the bulk ceramic material. This material separation step yields a highly concentrated fraction containing the palladium, which is sent for recycling at a smelter. In addition, the recovered ceramic is recycled. Although this process performs least favourably with respect to overall environmental impact, the low cost-benefit ratio and comparatively low risk of legislative non-compliance result in the overall impact score being superior to that of the other two end-of-life scenarios proposed.

The results from the first case study indicate that although scenario 2 provides the best overall performance, all three scenarios provide environmental and economic benefits. At present, the process described in scenario 3 (non-selective recycling) has been implemented within Rolls-Royce Fuel Cell Systems Limited in order to recover value from historic inventory of prototype components. This scenario provides the only process which is currently commercially available. The results from case study 1 suggest that greater benefits could be achieved by investing in further development of the process described in scenario 2; however they also indicate that nothing would be gained by investing further in the development of the process described in scenario 1.

Despite these interesting insights, it is acknowledged that the data utilised in the completion of case study 1 is of mixed quality, and as such the results provided by the application methodology should be considered with caution. In particular, the data used to define scenarios 1 and 2 have been based primarily on laboratory scale trials, supported with additional data from the literature. As such the accuracy of data, while believed to be representative of the processes described, has the potential to affect the final outcomes and therefore provide misleading direction. It is therefore important that the industrial application of the results produced in case study 1 would be subject to scrutiny, especially with regard to the details of the results generated using the environmental and economic evaluation methods.

The second case study identifies the preferred end-of-life solution for three different design concepts which reflect the fact that the SOFC stack adopted in future commercial products is not reliant on the use of precious metals. The results indicate that as the removal of palladium from the SOFC stack is implemented, the environmental and economic impacts of the end-of-life phase of the product life cycle are subject to significant change. Similar to case study 1, case study 2 also presents scenario 2 as the preferred end-of-life scenario, for all three of the proposed design modifications. However, more detailed examination of results provides some more interesting insights. Although, for the first design concept, all three scenarios provide environmental and economic benefits, for the final design concept where a minimal amount of palladium is utilised, only scenario 2 is economically viable. This result is specifically significant with respect to industrial application of the research, since it identifies a need to invest in the development of new end-of-life supply chains (such as that described in scenario 2) prior to the commercialisation of the SOFC product. While the benefits of the commercially available process described in scenario 3 may be useful as a short-term solution for the recovery of prototype components, the results from case study 2 indicate that a reliance on this available process route is not viable in the long term.

Case study 2 therefore illustrates the important link between product design and end-of-life management. SOFC developers are in an advantageous position, compared with other industrial sectors, in the fact that the designs for commercial products which will be produced at volume are in general not yet finalised. It is clear that the application of a framework for end-of-life management, such as that developed in this thesis, in a proactive manner could support the direction of end-of-life process development so as to maximise economic and environmental benefit arising at this stage of the product life cycle.

Although the results generated from both case studies are be influenced by the quality of the data available, the findings provide some interesting insights with regard to the quantification and comparison of alternative end-of-life scenarios. In addition, and perhaps of more value in the long term for the SOFC industry, the case studies illustrate the application of a systematic approach to end-of-life management which supports the development of a process which meets specified performance criteria. As the industry moves towards large scale commercialisation, the framework presented in this thesis and demonstrated through these case studies provides a useful tool to support the development of end-of-life management solutions which are environmentally and economically beneficial, and for which compliance with existing and future legislation has been considered.

CHAPTER 11 CONCLUDING DISCUSSION

11.1 Introduction

This chapter begins with a summary of the principal research contributions proposed in the thesis. The subsequent discussion follows the headings of the original research objectives and scope defined in Chapter 2, and aims to highlight the significant findings and knowledge gained from the research.

11.2 Research contributions

The research in this thesis has investigated the end-of-life management of SOFCs. The principal contributions from the research can be summarised as follows:

i. Identification of a need for the issues arising during the end-of-life phase of the SOFC life cycle to be addressed, prior to wide-scale commercialisation, in order to ensure that the environmental credentials of the technology are fully realised.

ii. Investigation of the challenges and opportunities presented by the end-of-life SOFCs based on a systematic analysis of design and material characteristics of the product within the wider context of extended producer responsibility legislation and other environmental product policies.

iii. Proposal of alternative practical solutions for the end-of-life management of SOFCs, based on a mixture of existing and novel waste management technologies and capability.

iv. Definition of a novel method for evaluating risks of non-compliance with existing and future legislative requirements in the development of end-of-life management solutions for products incorporating a new technology.

v. Demonstration of a novel multi-criteria evaluation methodology, which incorporates environmental, economic and legislative compliance performance criteria in order to support decision-making with respect to the development of an end-of-life management solution for SOFCs.

11.3 Concluding discussion

The following sections outline the results of the research under each of the headings defined within the original research objectives and scope.

11.3.1 Review of the current status of SOFC technology and relevant requirements and evaluation methods for end-of-life management

In order to establish the context for the research, it was necessary to complete a literature review. Two specific areas of literature were identified as being of particular relevance to the research: the review of SOFC technology is reported in Chapter 3 of the thesis, and a review of end-of-life requirements and evaluation methods is reported in Chapter 4.

Together, these review chapters identify that fuel cells are a technology in which significant investment continues to be made, with the view to developing a broad range of power generation products for both mobile and stationary applications. A substantial impetus for the technology lies in perceived environmental benefits resulting from high efficiencies during operation. These environmental claims have been substantiated by studies comparing the impacts of the technology during operation with impacts arising from other power generation technologies. Besides these environmental benefits, SOFC technology offers interesting opportunities for providing distributed power generation.

Based on this evidence it would appear that SOFC technology has a significant place in the future energy market, especially given growing demand for electricity in the developing world, and increasing concerns regarding the environmental impacts of conventional power generation. Widespread commercialisation of the technology will result in the eventual generation of a high-volume of end-of-life products and components, highlighting the need for consideration of various end-of-life management options, prior to market penetration. It was clear from the literature that end-of-life management of SOFC technology has not been considered with any rigour, and as such the literature review identified a gap in existing knowledge which the research presented in this thesis begins to address.

11.3.2 Development of a framework for end-of-life management of SOFC stacks

In the absence of an existing end-of-life management solution for SOFC technology there was a need within the research to explore various possible practical solutions. It was also identified that these potential solutions should be evaluated in terms of environmental performance, economic performance and compliance with existing and future legislation, in order to establish their viability. In order to ensure that this complex problem could be approached systematically, a framework was devised to support the research. This framework provides a step-wise approach to develop alternative end-of-life scenarios, based on a defined product design, and then to evaluate each of the performance criteria independently. The framework further supports decision making by, in its final stage, combining the three individual performance outcomes into a single performance measure.

This research therefore enables end-of-life management of SOFC technology to be considered in a holistic approach, using a framework which can be applied *prior* to design finalisation, in order to feed back into design refinement activity, and *after* design finalisation, in order to feed back into refinement of end-of-life management processes. Considering the lack of prior knowledge in this area, the framework provides a flexible, comprehensive approach to support the SOFC industry in addressing the need for an environmentally responsible and economically viable end-of-life solution which complies with relevant legislative requirements.

11.3.3 Definition of existing SOFC concepts in terms of design and material characteristics and development of alternative end-of-life scenarios for SOFC stacks

The initial review of SOFC technology identified the fact that various different stack design concepts have emerged during development by different commercial and academic bodies. Although these different concepts generally utilise common materials for the principal fuel cell components, the characteristics of different designs result in significant variation in the final material composition of the product. This therefore generates different priorities and challenges in the development of end-of-life management solutions, when environmental performance, economic performance and legislative compliance of the end-of-life processes are considered. These research findings, presented in Chapter 7 of the thesis, highlight the need for end-of-life management of SOFC stacks to be considered with focus given to a single design concept. While the research presents some broad findings of relevance to the end-of-life management of all SOFC stack concepts, a single SOFC stack design was selected for the subsequent stages of the research.

In defining the SOFC stack design, considered within the research as the future end-of-life product, various assumptions were made based on available data and knowledge. A significant assumption was made regarding the impact of the use phase on the SOFC stack. It was assumed that the material composition of the SOFC stack at end-of-life would be identical to the material composition of the as-manufactured product. In reality, issues such as contamination from fuel and oxidant gases and exposure to prolonged periods of high temperature and elevated pressure may impact the quality and chemical composition of the end-of-life product. While the author did not consider these impacts to be substantial, it is noted that further exploration of these issues would be beneficial in future research.

The development of alternative end-of-life scenarios was based on the assumption that the predicted size of the end-of-life waste stream did not warrant the development of bespoke process technologies, and as such existing infrastructure should be adopted where possible. This led to the development of three end-of-life scenarios, which the author identifies as being practically feasible, based on available waste processing capability. The research does not aim to present an optimised end-of-life management process, but rather uses these scenarios as a vehicle for developing and validating the evaluation methodology. Generation of additional end-of-life scenarios, based on real-life process development activities, would add value to the research.

11.3.4 Development of a methodology to evaluate risk of non-compliance with current and future legislation

One of the primary drivers for effective end-of-life management is legislation. Environmental policy increasingly adopts a life cycle approach, identified in policies such as IPP and the growing body of extended producer responsibility legislation in the European Union. Manufacturers therefore face the challenge of needing to design products to a wide range of legislative requirements.

This challenge, although significant for all product types, presents a particular issue for manufacturers developing novel technologies for commercialisation in the medium to long term. From the review of legislation conducted in this research, few existing legislative requirements were identified as being of direct relevance to the end-of-life management of SOFC stacks; however, any end-of-life management solution must anticipate future legislative requirements, especially regarding the development of the EPR principle.

The research therefore presents a novel methodology to support manufacturers in identifying potential future requirements, and evaluating the significance of these requirements in terms of risk. High risk of future non-compliance indicates that a proposed end-of-life solution is likely only to be viable for a short period, and therefore will need further investment and improvement following its implementation. Low risk of future non-compliance indicates that a proposed end-of-life process has anticipated legislative developments and is likely to be viable as a long-term solution. This methodology has been developed on the basis of legislation in force today, and will need periodic revision to ensure that the assumptions continue to be based on the most up-to-date legislative requirements.

11.3.5 Application of life cycle assessment and cost-benefit analysis methodologies to the evaluation of alternative end-of-life scenarios for SOFC stacks

LCA and CBA are commonly applied to the evaluation of end-of-life management options and have proved to be useful tools for the evaluation of environmental and economic impacts, respectively. While both tools adopt a recognised methodology for generating an evaluation result, the limitations are widely recognised in that results are heavily influenced by the scope of the models used in the evaluation process and the quality and completeness of the input data. Given the novel area of the research, and commercial sensitivities regarding the development of fuel cell technology, data availability was one of the greatest challenges encountered during the completion of the thesis. Opportunities for development of the LCA and CBA models will arise as this area is explored in more detail by the SOFC industry, and as more comprehensive, high quality data become available.

An interesting feature of the research arose from the selection of a SOFC stack concept for which the current design incorporates an amount of precious metal. This precious metal flow was found to have associated with it both high environmental impact in its production (and hence high impact avoidance through recovery and recycling operations), and high economic impact, especially with regard to offering an attractive revenue from end-of-life recovery processes. The requirement for commercial products to reach tight cost targets is driving reduction and/or elimination of such materials from the product design. This research highlights the requirement to consider cost reduction activities within the context of the complete product life cycle. While reduction of these high impact materials is likely to be beneficial, elimination may detrimentally affect the end-of-life waste stream by removing a financial incentive for pursuing resource-efficient processes. The results obtained from the LCA and CBA presented in the thesis are valid in relation to the current product design definition. The impact of design change on the outcome of these evaluation methods is illustrated in the second case study, and highlights the need for updating of the LCA and CBA models as the product design evolves towards the final commercial solution.

11.3.6 Development of a method for evaluating the outputs from compliance, environmental and economic assessments using a single performance parameter

While existing evaluation tools, such as LCA and CBA, are valuable for assessing individual performance characteristics, it became apparent during the course of the research that the value of the output from these tools was limited, for a number of reasons. Firstly, the results can be difficult to interpret in a meaningful manner, especially when data are presented to a non-expert, such as an industrial manager. Secondly, the individual evaluation of three performance parameters (environmental impact, economic impact and legislative compliance) results in three disparate results which may conflict in their evaluation of alternative end-of-life options, leading to a decision-making challenge.

The potential benefits of a methodology for amalgamating the three individual assessment results were identified, in supporting decision-making in a user-friendly manner. The evaluation methodology presented in Chapter 9 provides a flexible and customisable decision support tool, which provides clear and simple results with transparency. This tool was demonstrated in the case studies reported in Chapter 10, and provides a powerful approach for further development and optimisation of end-of-life management solutions for SOFCs. The author is of the opinion that with minimal effort this tool could find application across a broad range of multi-criteria decision making applications.

11.3.7 Demonstration and of the framework through case studies

Two case studies were carried out to demonstrate the framework for end-of-life management of SOFC stacks, and the evaluation methodology developed in the research. The primary objective of the case studies was to implement the framework for end-of-life management of SOFCs, as defined in Chapter 6 of the thesis, in a systematic manner in order to support decision making regarding the selection of the most appropriate end-of-life solution. The case studies were specifically selected to demonstrate application of the evaluation methodology in a reactive approach (case study 1) and in a proactive approach (case study 2). In the first case study, the evaluation methodology was simply required to support selection of an end-of-life solution which provided best performance when environmental impact, economic impact and legislative compliance were considered together. The second case study explored the relationship between design and end-of-life management by evaluating end-of-life management of design concepts containing varying levels of precious metals.

11.4 End-of-life management of SOFCs

The principal research assertion, presented at the beginning of this thesis is that prior to commercialisation of SOFC technology, the challenges and opportunities arising at the end-of-life phase must be identified and addressed. This assertion has been supported by a comprehensive review of the literature, which identifies end-of-life management as a challenge to product designers and manufacturers, driven by legislation and environmental concerns. The exploration of end-of-life management of SOFC technology, as reported in the thesis, extends an existing body of knowledge by applying proven approaches and principles to a novel power generation technology still in the development stage, but likely to play an important role in future energy scenarios.

The challenges and opportunities arising during the end-of-life management of products can be categorised as falling into three categories. Environmental challenges exist in ensuring that wastes arising from end-of-life products are processed in a way which presents least environmental burden, while opportunities for recovering and reusing resources can be exploited to offset the impacts of virgin material production.

As evidenced by other product waste streams (i.e. packaging, WEEE and ELV), economic challenges and opportunities are, in reality, of greater significance, especially when developing end-of-life solutions viable for commercial application. The recovery of revenue from recycled material streams can play an important role in offsetting end-of-life management costs and, where valuable materials are concerned, can also offset original manufacturing costs.

Finally, increasing legislative control on end-of-life management presents a challenge to designers and manufacturers in ensuring products demonstrate compliance across the complete product life cycle. This legislation, however challenging, also provides opportunities to explore and implement more sustainable approaches to end-of-life management.

The requirement to be able to evaluate all three performance criteria and to weigh the relative significance of one against the other is necessary to support decision-making, whether end-of-life management is considered in a reactive or proactive approach. The research therefore allows the challenges and opportunities in end-of-life management of SOFC stacks to be addressed by providing a comprehensive evaluation methodology which systematically assesses the environmental impact, economic impact and legislative compliance of alternative solutions, providing the final evaluation output in a single score format to allow effective decision making.

End-of-life management has historically been based on a reactive approach, in which the end-of-life product is regarded as a waste problem which must be managed in an appropriate manner. However, environmental policy is increasingly prompting a proactive approach to end-of-life management, with end-of-life considerations being taken into account during product design. In the development of a new technology, such as SOFCs, designers are faced with many challenges; notably those concerned with technical functionality and cost. These aspects of a new product are fundamental to commercialisation, and have a tendency to dominate design priorities.

The framework presented in the research has been constructed in such a way as to acknowledge this aspect of new product development. The framework assumes the existence of a product concept which has been developed with technical functionality and other critical aspects in mind. This concept is the subject of the end-of-life scenario definition and subsequent evaluation steps. The output from the framework supports the selection of a preferred end-of-life scenario; however, the knowledge gained during the process of applying the framework supports a deepening understanding of the issues associated with the end-of-life management of the product concept, and the impact the design has on environmental impact, economic impact and cost. Thus, where the framework is applied in a reactive manner to an early product concept, this knowledge can inform future design iterations, prior to the finalisation of a commercial product.

Therefore, the research not only draws some preliminary conclusions regarding the viability of some proposed practical solutions for end-of-life management of SOFCs, but also provides a flexible and transparent evaluation methodology which can be adopted to support further optimisation of the life cycle impacts of this emerging power generation technology.

11.5 Constraints and limitations to the research

While the previous discussion indicates that the research has been successful in addressing the original aim and objective, several weaknesses are acknowledged.

The principal weakness in the research stems from the very nature of the product under consideration. SOFC technology is still, in general, in the pre-commercial phase of development, which presents a number of challenges with regard to the application of data-driven evaluation methods. The main challenge arises from ambiguity surrounding various aspects of the product, including those related to design and market behaviour. These two factors have been shown to be closely linked with the impacts associated with the end-of-life phase of the product life cycle, such that uncertainties regarding the exact nature of the commercial product result in uncertainties regarding end-of-life management. Therefore, much of the research presented in the thesis is based on assumptions and synthesised data. The lack of real data, with which to rigorously challenge and validate the theories presented in the thesis, is a weakness.

This lack of data has further been fuelled by the confidentiality requirements attached to the development of a product in its pre-commercial phase. While part of the research was conducted during a Knowledge Transfer Collaboration project, allowing access to data owned by the sponsoring company, sensitivity regarding the use and publication of company data has hindered reporting and wider dissemination of research findings. In addition, concerns regarding the loss of intellectual property through the distribution of prototype SOFC components to third parties have significantly restricted the amount of practical work which has been able to be conducted, in particular with respect to conducting trials of alternative commercially available recycling routes.

Based on this experience, the absence of literature specifically addressing the end-of-life management of SOFC products raises some questions. While this is undoubtedly a novel area in which to be conducting research, it is possible that some other preliminary research in this area has been completed by individual SOFC developers, but not disseminated. While the need to preserve commercial advantage is acknowledged to be a necessity for SOFC businesses, the inability to share and build on knowledge gained from similar studies restricts the development of ideas and practical solutions.

Aside from limitations resulting from the nature of the SOFC product, it is acknowledged that the evaluation methodology, and in particular the cost-benefit analysis model, could be further developed to provide a more robust evaluation of economic impacts at end-of-life. While a limited amount of sensitivity analysis has been conducted as part of the validation of the multi-criteria evaluation tool, more systematic and extensive sensitivity analyses of different aspects of the complete evaluation methodology would provide a higher level of confidence in and understanding of the results generated. Also, while it has been attempted to develop a user-friendly interface to facilitate the application of the evaluation methodology by a non-expert user, it is acknowledged that the development of software lies outside the author’s primary skill-set. As such, it is clear that a more sophisticated and automated tool could be developed, based on the principles outlined in the thesis.

CHAPTER 12 CONCLUSIONS AND FURTHER WORK

12.1 Introduction

This chapter summarises the principal research conclusions proposed by the thesis and identifies some interesting opportunities for extension of the work.

12.2 Research conclusions

SOFC technology offers the potential to contribute to generation of electrical power within a future energy market characterised by decentralised power generation and improved sustainability with regard to fuel consumption and emissions. This potential is highly attractive given the ever-increasing demands for electricity arising in particular from industrialising nations alongside a developing awareness of the link between conventional power generation technologies and their detrimental impacts on the planet.

The research presented in the thesis leads to the following conclusions:

i. The immaturity of SOFC technology, especially with respect to the development of commercial products, leaves various uncertainties regarding the complete product life cycle. In particular, widespread uptake of the technology will result in the generation of high volumes of end-of-life waste products and components: significantly the SOFC stack, which will require replacement several times throughout the operational life of a SOFC power generation system. The published literature suggests that little consideration has been given to the management of the end-of-life SOFC stack. It is clear that a failure to address the issues arising at end-of-life represents a risk to SOFC developers in terms of the technology failing to live up to its environmental credentials and failing to comply with legislative requirements.

ii. Legislation relating to end-of-life management, incorporating principles such as IPP and EPR, has been adopted in the European Union and continues to develop globally. As such, the development of new products must increasingly consider how compliance with existing and future legislation can be achieved. While much of the current legislation in this area is not directly relevant to SOFCs today, the identification of potential future conflicts, as both the legislation and the technology develop, may allow early mitigation of risks of non-compliance through design modifications and/or the implementation of management plans and controls. In light of this, the research has proposed a risk assessment approach as means of drawing early attention to potential legislative conflicts.

iii. The practical challenges regarding the processing of end-of-life SOFC stacks can in part be met by existing waste management infrastructure, however, optimisation with regard to material separation and recycling processes would provide opportunities for improving overall environmental and economic performance. In particular, as the drive to commercialisation continues, changes in material selection and design are likely to increase the challenges associated with end-of-life management, particularly as expensive, yet highly recyclable, materials are "designed out" of commercial products. It would be beneficial for SOFC developers to consider such design improvements in the light of the complete product life cycle, including in their considerations the capabilities and limitations of existing recycling technologies. Investment in recycling technologies for less mainstream materials may be necessary to ensure ongoing compliance and to conserve valuable resources.

iv. End-of-life management is influenced significantly not only by technical aspects, but also by the business model adopted for the commercialisation of the product. With respect to SOFC technology, a Product Service Systems model presents an attractive option, especially with regard to stationary power generation applications. The ability of the SOFC manufacturer to maintain control of the product throughout its life time allows optimised end-of-life management solutions to be applied. In such a model, the commercial feasibility of SOFC technology depends on the life cycle costs rather than being primarily dependent on production costs. The emphasis for cost reduction initiatives must therefore focus on processes (including manufacturing and recycling) with less dependence on material costs. This may be significant where the use of expensive materials allow for improved durability or performance

v. The consideration of legislative compliance, environmental impact and cost is essential in deciding between alternative end-of-life routes, however, it is unlikely that a single solution will demonstrate superior performance across all three criteria. Therefore, the complex issues involved in developing an end-of-life management solution require a systematic approach to be adopted when tackling this problem. This research therefore provides a framework within which alternative end-of-life scenarios can be defined and evaluated based on existing product concepts. In particular, the definition of a bespoke multi-criteria evaluation methodology which incorporates LCA, CBA and a novel legislative risk assessment method, and supports decision making by combining the results from these individual evaluation methods into a single performance parameter. This methodology maintains a degree of rigour, in terms of dealing with the complex issues associated with end-of-life management, while presenting the final results in a simple, user friendly format.

vi. The results from the case studies emphasise the fact that all evaluation methods are limited by the availability and quality of relevant data. In particular, the challenge of developing an end-of-life process for a product which incorporates novel technology and has not yet reached commercial maturity has been emphasised. Uncertainties regarding final product design and market behaviour lead to uncertainties in the development of end-of-life scenarios, and the absence of high quality data from repeated process trials results in the requirement for economic and environmental impact evaluations to be based on assumptions rather than facts. However, the benefits of the research are believed by the author to outweigh these shortcomings, since the conceptualisation of future challenges paves the way for proactive measures to be taken before SOFC technology reaches full-blown commercialisation and opportunities for influencing and improving the environmental and economic impacts of the product life cycle become substantially reduced.

vii. The challenge of end-of-life management of SOFCs is significant, but it is the author’s view that the end-of-life phase of the life cycle should be viewed as an opportunity to ensure that the benefits of the technology are fully maximised, rather than viewing the requirements imposed by developing legislation as a burden. SOFC developers should view the end-of-life stack as a resource-rich asset which, if managed effectively, offers the potential for contributing to reductions in the environmental impact and cost of the technology across its life cycle. In contrast to many product manufacturers, the fact that most SOFC products are still within the pre-commercial stage offers SOFC developers a unique opportunity to embrace end-of-life considerations in the finalisation of their product designs, rather than being lumbered with mature products which are awkward to manage at end-of-life and expensive to modify.

12.3 Further work

The research documented in this thesis could be further developed in various directions. Aspects of particular interest to the author are described below.

12.3.1 Further practical work to explore alternative end-of-life processes for SOFC stacks

The objective of this research has not been to develop an optimised end-of-life solution for SOFC stacks, but rather to provide a framework by which such an end-of-life solution could be realised. As such, practical trials of end-of-life processes were limited to some small-scale laboratory trials of novel processes, and large-scale commercial trials using existing waste management infrastructure. However, the research has identified that the SOFC stack presents some interesting challenges with respect to material separation and recycling at end-of-life. In particular, processes for recovering and recycling rare earth oxides and ceramic materials are not widely available, and further development of this capability would be beneficial to the end-of-life management of SOFC stacks in general, and the IP-SOFC stack concept in particular. Further practical research into alternative end-of-life processes for the SOFC stack would not only support the development of optimised process routes, but would also act as a source of data to support further understanding the environmental and economic impacts associated with the end-of-life phase of the technology.

12.3.2 Integration of end-of-life considerations in a complete SOFC life cycle study

This research has deliberately focused on the end-of-life phase of the product life cycle, based on an identified knowledge gap. However, the author acknowledges the importance of a complete life cycle approach in the development of products and processes. As such, it is important to be able to place the environmental and economic impacts arising during end-of-life management in the context of the environmental and economic impacts arising during the manufacture and use phases. In particular, it would be interesting to complete a comparative study of alternative power generation technologies (including conventional and renewable energy technologies) which incorporates in a detailed manner the end-of-life management of power generating components and products. This comprehensive study could be compared with existing studies of alternative power generation technologies in order to identify the influence that end-of-life management might have on technology selection.

12.3.3 Consideration of additional performance parameters at end-of-life and integration of factors into the multi-criteria evaluation methodology

The research reported in this thesis has identified legislative risk, environmental impact and economic impact as the three principal performance parameters associated with the end-of-life management of SOFC stacks. However, it is acknowledged that additional performance parameters may grow in significance over time. In particular, concerns regarding material security have become an issue at the national and international level in recent time. While economic factors, such as material cost, are likely to be affected by specific material security concerns, it is unclear as to whether the issue would be adequately incorporated into the economic impact evaluation method defined in the current research. Additional considerations, including global political stability and international relations are likely to play a substantial role in defining materials whose long-term supply poses substantial concern. The author believes that these issues may become increasingly significant in directing end-of-life management priorities, as material recycling becomes not just an economic and environmental issue, but also one of resource retention, reducing the need for material imports. Therefore it is suggested that the consideration of these issues, and how they might be incorporated into end-of-life decision making, may be essential to ensure end-of-life management priorities continue to be relevant in future climates.

12.3.4 Further development of the framework for end-of-life management and decision support tool

The issues addressed in this research with regard to end-of-life management are not unique to SOFCs. It is believed that the framework for end-of-life management provides a systematic approach for exploring and evaluating these issues, and could be applied to other technologies. In particular, other alternative energy technologies, such as photovoltaic cells, wind turbines and wave power, face similar challenges to fuel cells as they aim to penetrate the energy market. As well as the general framework for end-of-life management, it is believed that the multi-criteria evaluation methodology could further be developed to support end-of-life decision with wider industrial application.

REFERENCES

ABB (2011). *Environmental Product Declarations* [online]. Available from: http://www.abb.com/cawp/abbzh258/3d76091aeb235c70c12569ee002b47f4.aspx [accessed: 4th May 2011].

Ackermann T., Andersson G. and Soder L. (2001). Distributed generation: a definition, *Electric Power Systems Research*, **57**, 195-204.

Acumentrics (2011). *Trusted Power Innovations – Solid Oxide Fuel Cells* [online]. Available from: http://www.acumentrics.com/about-us-company-history.htm [accessed 24th April 2011].

Adamson, K. (2008). *2008 Large Stationary Survey* [online]. Fuel Cell Today, UK. Available from: http://www.fuelcelltoday.com/media/pdf/surveys/2008-LS-Free.pdf [accessed: 3rd May 2011].

Agnew G.D., Collins R.D., Jorger M.B., Pyke S.H. and Travis R. (2007). The Components of a Rolls-Royce 1 MW SOFC System, *ECS Transactions*, **7**, 105-111.

Agnew G.D., Moritz R.R., Berns C., Spangler A., Tarnowski O. and Bozzolo M. (2003). A Unique Solution to Low Cost SOFC Hybrid Power Plant. In: *ASME Conference Proceedings GT2003, Volume 2: Turbo Expo 2003.*

alibaba.com (2011a). *Nickel oxide* [online]. Available from: http://www.alibaba.com/showroom/nickel-oxide-price.html [accessed 19th April 2011].

alibaba.com (2011b). *Yttria-stabilized zirconia* [online]. Available from: http://www.alibaba.com/showroom/yttria-stabilized-zirconia.html [accessed 19th April 2011].

alibaba.com (2011c). *Lanthanum Oxide* [online]. Available from: http://www.alibaba.com/product-gs/409168268/Supply_Lanthanum_Oxide_High_Quality.html [accessed 19th April 2011].

alibaba.com (2011d). *Strontium Oxide* [online]. Available from: http://www.alibaba.com/product-gs/313923905/STRONTIUM_OXIDE.html [accessed 19th April 2011].

alibaba.com (2011e). *Manganese Dioxide* [online]. Available from: http://www.alibaba.com/product-gs/306159734/manganese_dioxide.html [accessed 19th April 2011].

alibaba.com (2011f). *Fused Magnesium Spinel* [online]. Available from: http://www.alibaba.com/product-gs/306159734/manganese_dioxide.html [accessed 19th April 2011].

Ashby M.F. (2009). *Materials and the Environment. Eco-informed Material Choice.* Elsevier: Oxford.

Autoclaves Group (2010). *Autoclaves Group's Key Role in Waste Recycling Project* [online]. Available from: http://www.autoclavesgroup.com/autoclaves-group%E2%80%99s-key-role-in-waste-recycling-project/ [accessed 24th April 2011].

Azapagic A. (1999). Life cycle assessment and its application to process selection, design and optimisation, *Chemical Engineering Journal*, **73**, 1-21.

Azzopardi B. and Mutale J. (2010). Life cycle analysis for future photovoltaic systems using hybrid solar cells, *Renewable and Sustainable Energy Reviews*, **14** (3), 1130-1134.

Babcock International Group Plc (2011). *Autoclave* [online]. Available from: http://www.vtplc.com/pages/services/template.aspx?pageId=414 [accessed 4th May 2011].

Baratto F. and Diwekar U.M. (2005). Life cycle assessment of fuel cell-based APUs, *Journal of Power Sources*, **139** (1-2), 188-196.

Baratto F., Diwekar U.M. and Manca D. (2005). Impacts assessment and tradeoffs of fuel cell based auxiliary power units, Part II. Environmental and health impacts, LCA and multi-objective optimization, *Journal of Power Sources*, **139** (102), 214-222.

Bare J.C., Norris G.A., Pennington D.W. and McKone T. (2003). TRACI - The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Journal of Industrial Ecology*, **6** (3-4), 49-78.

Basel Convention Secretariat (2011). *Origins of the Basel Convention* [online]. Available from: http://www.basel.int/convention/basics.html [accessed 28th April 2011].

Battisti R. and Corrado A. (2005). Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology, *Energy*, **30** (7), 952-967.

Bauen A. and Hart D. (2000). Assessment of the environmental benefits of transport and stationary fuel cells, *Journal of Power Sources*, **86**, 482-492.

Baumann H. and Tillman A-M. (2004). *The Hitch Hiker's Guide to LCA*. Studentlitteratur: Lund, Sweden.

Baur E. and Preis H. (1937). Uber Brennstoff-Ketten Mit Festleitern, *Z. Elektrochem.*, **43**, 727-732. Cited in Minh N.Q. (2003). Ceramic Fuel Cells, *Journal of the American Ceramics Society*, **76** (3), 563-588.

Tay B.Y., Jun W., Lan N.F., Wiria F.E., Goh C.W., Lee M.W., and Qiujun H. (2008). *End-of-life management of SOFC components.* Unpublished project work, completed at the Singapore Institute of Manufacturing Technology for Rolls-Royce Fuel Cell Systems Ltd., UK.

Belton V. and Stewart T.J. (2002). *Multiple criteria decision analysis: an integrated approach.* Kluwer Academic Publishers.

Berger W., Simon F.G., Weimann K. and Alsema E.A. (2010). A novel approach for the recycling of thin film photovoltaic modules, *Resources, Conservation and Recycling*, **54** (10), 711-718.

Bloom Energy (2010a). *Products* [online]. Available from: http://www.bloomenergy.com/products/ [accessed 24th April 2011].

Bloom Energy (2010b). *Customers* [online]. Available from: http://www.bloomenergy.com/customers/ [accessed 3rd May 2011].

Bozza F., Polini R. and Traversa E. (2009). High performance anode-supported intermediate temperature solid oxide fuel cells (IT-SOFCs) with $La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.2}O_{3-\delta}$ electrolyte films prepared by electrophoretic deposition, *Electrochemistry Communications,* **11** (8), 1680-1683.

Brundtland G., ed. (1987). *Our Common Future: The World Commission on Environment and Development*. Oxford University Press: Oxford.

Burgess A.A. and Brennan D.J. (2001). Application of life cycle assessment to chemical processes, *Chemical Engineering Science*, **56** (8), 2589-2604.

Castell A., Clift R. and France C. (2006). Extended Producer Responsibility in the European Union – A horse or a camel?, *Journal of Industrial Ecology*, **8** (1-2), 4-7.

Ceramics Fuel Cells Limited (2011). *Clean power for your home. Products* [online]. Available from: http://www.cfcl.com.au/products/ [accessed 24th April 2011].

Ceres Power (2008). *Ceres Power and British Gas enter development, supply and distribution agreement for UK residential CHP* [online]. Press Release, Ceres Power Holdings plc, UK. Available from: http://www.cerespower.com/store/files/12-BG%20development%20supply%20 and%20distribution%20agreement.pdf [accessed 3rd May 2011].

Ceres Power (2011). *Company overview* [online]. Available from: http://www.cerespower.com/AboutUs/CompanyOverview/ [accessed 24th April 2011].

Chong, J., Mason, L., Pillora, S., Giurco, D. (2009). Briefing Paper – Product stewardship schemes in Asia: China and Taiwan, Japan, South Korea. Paper prepared for Department for the Environment, Water, Heritage and the Arts, by the Institute for Sustainable Futures, UTS: Sydney.

Clauzade C., Osset P., Hugrel C., Chappert A., Durande M. and Palluau M. (2010). Life cycle assessment of nine recovery methods for end-of-life tyres, *International Journal of Life Cycle Assessment*, **15**, 883-892.

Clift R. and France C. (2006). Extended Producer Responsibility in the EU – A visible march of folly, *Journal of Industrial Ecology*, **10**, (4), 5-7.

Contreras A., Posso F. and Guervos E. (2010). Modelling and simulation of the utilization of a PEM fuel cell in the rural sector of Venezuela, *Applied Energy*, **87** (4), 1376-1385.

Cooper J.S. (2004). Design analysis of PEFC bipolar plates considering stack manufacturing and environmental impact, *Journal of Power Sources*, **129**, 152-169.

Crawley G. (2007). *Solid Oxide Fuel Cells (SOFC)* [online]. Fuel Cell Today, UK. Available from: http://www.fuelcelltoday.com/media/pdf/surveys/2007-SOFC-Survey.pdf [accessed 3rd May 2011].

Crotty J. and Smith M. (2006). Strategic Responses to Environmental Regulation in the UK Automotive Sector, *Journal of Industrial Ecology*, **10** (4), 95-111.

Cummins Power Generation (2011). *Fuel Cell Research and Development* [online]. Available from: http://cumminspower.com/en/about/environmental/fuelcells/ [accessed 24th April 2011].

Curran M.A. and Notten P. (2006). *Summary of Global Life Cycle Inventory Databases* [online]. Prepared for UNEP/SETAC Life Cycle Initiative. Available from: http://www.epa.gov/nrmrl/lcaccess/pdfs/summary_of_global_lci_data_resources.pdf [accessed 24th April 2011].

Darney A. and Nuss G. (1971). *Environmental impacts of Coca-Cola beverage containers – Executive Summary Volume I* [online]. Prepared for Coca-Cola USA by Midwest Research Institute, USA. Available from: http://www.lcacenter.org/history.aspx [accessed 12th April 2011].

Davis G.A., Wilt C.A. and Barkenbus J.N. (1997). Extended Product Responsibility: A Tool for a Sustainable Economy, *Environment: Science and Policy for Sustainable Development*, **39** (7), 10-38.

Department of Energy and Climate Change (2011). *Quarterly Energy Prices March 2011* [online]. National Statistics publication. Available from: http://www.decc.gov.uk/assets/decc/Statistics/publications/prices/1492-qepmar11.pdf [accessed 24th April 2011].

Design Associates (2010). *China RoHS answers to Frequently Asked Questions* [online]. Available from: http://www.chinarohs.com/faq.html [accessed 24th April 2011].

Diesel & Gas Turbine Worldwide (2008). 32nd Power Generation Order Survey, *Diesel & Gas Turbine Worldwide*, October 2008.

Diesel & Gas Turbine Worldwide (2009). 33rd Power Generation Order Survey, *Diesel & Gas Turbine Worldwide,* October 2009.

Diesel & Gas Turbine Worldwide (2010). 34th Power Generation Order Survey", Diesel & Gas Turbine Worldwide, October 2010.

Doeleman J.A. (1985). Historical perspective and environmental cost-benefit analysis, *Futures*, **17** (2), 149-163.

Doublet G. and Jungbluth N. (2011). Environmental product information (EPI) and LCA, *International Journal of Life Cycle Assessment*, **16**, 90-94.

Dreyer L.C., Niemann A.L. and Hauschild M.Z. (2003). Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-Indicator 99. Does it matter which one you choose?, *International Journal of Life Cycle Assessment,* **8** (4), 191-200.

Ecobalance Inc. (2000). *Life cycle assessment of nickel products – final report* [online]. Prepared for the Nickel Industry LCA Group. Available from: http://www.nickelinstitute.org/index.cfm/ci_id/10663/la_id/1/document/1/re_id/0 [accessed 4th May 2011].

Ecoinvent Centre (2007). *Ecoinvent data v2.0*. Ecoinvent reports No.1-25, Swiss Centre for Life Cycle Inventories, Dübendorf, 2007.

EG&G Technical Services Inc. (2004). *Fuel Cell Handbook Seventh Edition* [online]. U.S. Department of Energy, National Energy Technology Laboratory. Available from: http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/pubs/FCHandbook7.pdf [accessed 4th May 2011].

Energy Information Administration (2010). *International Energy Outlook 2010 – Electricity* [online]. Available from: http://www.eia.doe.gov/oiaf/ieo/electricity.html [accessed 3rd May 2011].

Environment Agency (2008). *What is a Hazardous Waste? A guide to the Hazardous Waste Regulations and the List of Waste Regulations in England and Wales* [online]. Available from: http://www.environment-agency.gov.uk/static/documents/GEHO0506BKTR-e-e.pdf [accessed 22nd April 2011]

European Commission (2001). *Green Paper on Integrated Product Policy*, COM(2001) 68 final, Brussels, 7th February 2001.

European Commission (2003a). *Communication from the Commission Towards a thematic strategy on the prevention and recycling of waste.* COM(2003) 301 final, Brussels, 27th May 2003.

European Commission (2003b). *Communication from the Commission to the Council and the European Parliament, Integrated Product Policy – Building on life-cycle thinking*, COM(2003) 302 final, Brussels, 18th June 2003.

European Commission (2005). *Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste*, COM(2005) 666 final, Brussels, 21st December 2005.

European Commission (2008). *Environment: Commission welcomes EP vote on revision of waste directive* [online]. Press release, Brussels/Strasbourg 17th June 2008. Available from:

http://europa.eu/rapid/pressReleasesAction.do?reference=IP/08/950&format=HTML&aged=0&language=EN&guiLanguage=en [accessed 4th May 2011].

European Commission (2010a). *Integrated Product Policy (IPP)* [online]. Available from: http://ec.europa.eu/environment/ipp/ [accessed 24th April 2011].

European Commission (2010b). *ELCD core database version II* [online]. European Commission Joint Research Centre, Life Cycle Thinking and Assessment, Institute for the Environment and Sustainability. Available from: http://lct.jrc.ec.europa.eu/assessment/data [accessed 4th May 2011].

European Commission (2011a). *LARGE-SOFC – Towards a large SOFC power plant* [online]. Cordis, Sixth Framework Programme, Project Fact Sheet. Available from: http://cordis.europa.eu/fetch?CALLER=FP6_PROJ&ACTION=D&DOC=1&CAT=PROJ&RCN=81194 [accessed 3rd May 2011].

European Commission (2011b). *REAL-SOFC – Realising Reliable, Durable, Energy Efficient and Cost Effective SOFC Systems* [online]. Cordis, Sixth Framework Programme, Project Fact Sheet. Available from: http://cordis.europa.eu/fetch?CALLER=FP6_PROJ&ACTION=D&DOC=1&CAT=PROJ&RCN=73960 [accessed 3rd May 2011].

European Commission (2011c). *Waste* [online]. European Commission, Environment. Available from: http://ec.europa.eu/environment/waste/index.htm [accessed 5th May 2011].

European Commission (2011d). *Sustainable and responsible business legislation* [online]. Available from: http://ec.europa.eu/enterprise/policies/sustainable-business/documents/eco-design/legislation/index_en.htm [accessed 5th May 2011].

European Council (1991). Directive 91/689/EEC of 12 December 1991 on hazardous waste, *Official Journal of the European Union,* **L 377**, 20-27, 31st December 1991.

European Council (1993). Council Regulation (EEC) No 259/93 of 1 February 1993 on the supervision and control of shipments of waste within, into and out of the European Community, *Official Journal of the European Union*, **L 030**, 1-28, 6th February 1993.

European Council (1999). Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste, *Official Journal of the European Union*, **L 182**, 1-19, 16th July 1999.

European Parliament and Council (1994). Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, *Official Journal of the European Union,* **L 365**, 10-23, 31st December 1994.

European Parliament and Council (2000). Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles, *Official Journal of the European Union,* **L 269**, 34-43, 21st October 2000.

European Parliament and Council (2003a). Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE), *Official Journal of the European Union*, **L 37**, 24-39, 13th February 2003.

European Parliament and Council (2003b). Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, *Official Journal of the European Union*, **L 37**, 19-23, 13th February 2003.

European Parliament and Council (2005). Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products, *Official Journal of the European Union*, **L 191**, 29-58, 22nd July 2005.

European Parliament and Council (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, *Official Journal of the European Union*, **L 312**, 3-30, 22nd November 2008.

European Parliament and Council (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-using products, *Official Journal of the European Union*, **L 285**, 10-35, 31st October 2009.

Fishburn P.C. (1967). Additive utilities with incomplete product set: Applications to priorities and assignments. *Operations Research*, **15** (3), 537-542.

Flowwaterjet.com (2011). *Abrasive water jet cutting* [online]. Available from: http://www.flowwaterjet.com/en/waterjet-technology/abrasive-waterjet.aspx [accessed 3rd May 2011].

Franklin Associates (2008). *Life Cycle Inventory (LCI) summary for four half-gallon milk containers* [online]. Available from: http://www.fal.com/projects.html [accessed 4th May 2011].

Friends of the Earth (2008). *Briefing Autoclaving* [online]. Available from: http://www.foe.co.uk/resource/briefings/autoclaving.pdf [accessed 24th April 2011].

Fuentes R.O. and Baker R.T. (2008). Synthesis and properties of Gadolinium-doped ceria solid solutions for IT-SOFC electrolytes*, International Journal of Hydrogen Energy*, **33** (13), 3480-3484.

García-Valverde R., Miguel C., Martinez-Bejar R. and Urbina A. (2009). Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system, *Solar Energy*, **83**, 1434-1445.

Gardner F.J., Day M.J., Brandon N.P., Pashley M.N and Cassidy M. (2000). SOFC technology development at Rolls-Royce, *Journal of Power Sources*, **86**, 122-129.

Gehin A., Zwolinski P. and Brissaud D. (2009). Integrated design of product lifecycles – The fridge study, *CIRP Journal of Manufacturing Science and Technology*, **1**, 214-220.

General Electric Company (2007). *SOFC Research & Development* [online]. Available from: http://www.gepower.com/research/seca/sofc_research.htm [accessed 24th April 2011].

Gengo T., Kobayashi Y., Hisatome N., Kabata T., Ando Y. and Kosaka K. (2007). Progressing steadily, Development of high-efficiency SOFC combined cycle system, *Mitsubishi Heavy Industries Ltd., Technical Review*, **44** (1), 1-5.

Gerrard J. and Kandlikar M. (2007). Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on 'green' innovation and vehicle recovery, *Journal of Cleaner Production*, **15** (1), 17-27.

Ghoniem A.F. (2011). Needs, resources and climate change: Clean and efficient conversion technologies, *Progress in Energy and Combustion Science*, **37**, 15-51.

Goedkoop M. and Spriensma R. (2000). *The Eco-indicator 99: A Damage Oriented Method for Life Cycle Assessment, Methodology Report*. 2nd ed. Pré Consultants: Amersfoort, Netherlands.

Goedkoop M.J., Heijungs R., Huijbregts M., de Schryver A., Struijs J. and van Zelm R. (2009). *ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation* [online]. National Institute for Public Health and the Environment (RIVM), the Netherlands; Institute of Environmental Sciences (CML), University of Leiden; Pre Consultants; Radboud University Nijmegen; CE Delft. Available from: http://www.lcia-recipe.net [accessed 3rd May 2011].

Google Maps (2011). Available from: http://maps.google.co.uk/ [accessed 24th April 2011].

Gottberg A., Morris J., Pollard S., Mark-Herbert C. and Cook M. (2006). Producer responsibility, waste minimisation and the WEEE Directive: Case studies in eco-design from the European lighting sector, *Science of the Total Environment*, **359**, 38-56.

Graedel T.E. and Allenby B.R. (1995). *Industrial Ecology.* 1st ed. Prentice Hall: New Jersey.

Greenfield T., ed. (1996). *Research Methods – Guidance for Postgraduates*. Arnold: London.

Grot S., Grot W., Anderson A. and Tyler R. (2005). *Platinum Recycling Technology Development* [online]. DOE Hydrogen Program FY 2005 Progress Report. Available from: http://www.hydrogen.energy.gov/pdfs/progress05/vii_e_1_grot.pdf [accessed 24th April 2011].

Grot S., Grot W., Nguyen H. and Pinto J. (2005). *Fuel Cell Operation Using Components Manufactured with Recycled End-of-life Membrane Electrode Assemblies*. Presentation given at the 2005 Fuel Cell Seminar, 17th November 2005.

Grove W.R. (1839). On Voltaic Series and the Combination of Gases by Platinum, *Philosophical Magazine*, **14**, 127-130.

Guinée J.B., Gorrée M., Heijungs R., Huppes G., Kleijn R., de Koning A., van Oers L., Wegener Sleeswijk A., Suh S., Udo de Haes H.A., de Bruijn H. , van Duin R. and Huijbregts M.A.J.

(2002). *Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background,* Kluwer Academic Publishers: Dordrecht.

Guinée J.B., Udo de Haes H.A. and Huppes G. (1992). Quantitative life cycle assessment of products – 1: Goal definition and inventory, *Journal of Cleaner Production,* **1** (1), 3-14.

Haile S.M. (2003). Fuel cell materials and components, *Acta Materialia*, **51** (19), 5981-6000.

Hallett M. (2009). Distributed power in Afghanistan: The Padisaw micro-hydro project, *Renewable Energy*, **34** (12), 2847-2851.

Handley C., Brandon N.P. and van der Vorst R. (2002). Impact of the European Union waste directive on end-of-life options for polymer electrolyte fuel cells, *Journal of Power Sources*, **106**, 344-352.

Hanley N. and Spash C.L. (1993). *Cost-Benefit Analysis and the Environment.* Edward Elgar: Cheltenham, UK.

Harjula T., Rapoza B., Knight W.A. and Boothroyd G. (1996). Design for Disassembly and the Environment, *CIRP Annals - Manufacturing Technology*, **45** (1), 109-114.

Harper E. and Graedel T.E. (2004). Industrial ecology: a teenager's progress, *Technology in Society*, **26** (2-3), 433-445.

Hart N., Brandon N.P. and Shemilt J. (1999). The Environmental impact of solid oxide fuel cell manufacturing, *Fuel Cells Bulletin*, **2** (15), 4-7.

Hart D. and Hörmandinger G. (1998). Environmental benefits of transport and stationary fuel cells, *Journal of Power Sources*, **71** (1-2), 348-353.

Hauschild M. and Potting J. (2004). *Spatial differentiation in life cycle impact assessment – the EDIP2003 methodology* [online]. Guidelines from the Danish Environmental Protection Agency, Copenhagen. Available from: http://www2.mst.dk/udgiv/publications/2005/87-7614-579-4/pdf/87-7614-580-8.pdf [accessed 3rd May 2011].

Hauschild M. and Wenzel H. (1998). *Environmental Assessment of Products. Volume II – Scientific background,* 1st ed. Chapman & Hall: London.

Hawkes A.D., Aguiar P., Hernandez-Aramburo C.A., Leach M.A., Brandon N.P., Green T.C. and Adjiman C.S. (2006), Techno-economic modelling of a solid oxide fuel cell stack for micro combined heat and power, *Journal of Power Sources*, **156**, 321-333.

H.M. Revenue and Customs (2010). *Landfill Tax Bulletin, Bulletin for: October 2010* [online]. Available from: https://www.uktradeinfo.com/index.cfm?task=bulllandfill&hasFlashPlayer=true [accessed 12th April 2011].

Hicks D. (2006). *Conflicting Interpretations of Sustainable Development*. Presentation given at Environmental Legislation – today and tomorrow, IChemE, Birmingham, 28th September 2006.

Hischier R., Weidema B., Althaus H.-J., Bauer C. Doka G. Dones R., Frischknecht R., Hellweg S., Humbert S., Jungbluth N., Kollner T., Loerincik Y., Margni M. and Nemecek T. (2010). *Implementation of Life Cycle Impact Assessment Methods.* Ecoinvent report no. 3, v2.2. Swiss Centre for Life Cycle Inventories: Dubendorf.

Hoff T.E., Wenger H.J. and Farmer B.K. (1996). Distributed generation. An alternative to electric utility investments capacity, Energy Policy, 24 (2), 137-147.

Houston Advanced Research Centre (2006). *Fuel Cell Industry Assessment 2005* [online]. Available from: http://files.harc.edu/Projects/FuelCell/Reports/IAR/2005FuelCellIndustryAssessment.pdf [accessed 3rd May, 2011].

Huijsmans J.P.P., van Berkel F.P.F. and Christie, G.M. (1998). Intermediate temperature SOFC – a promise for the 21st century, *Journal of Power Sources*, **71** (1-2), 107-110.

Hunt R.G., Franklin W.E. and Hunt R.G. (1996). LCA – How it came about – Personal reflections on the origin and development of LCA in the USA, *International Journal of Life Cycle Assessment*, **1** (1), 4-7.

Ijomah W.L., McMahon C.A., Hammond G.P and Newman S.T. (2007). Development of design for remanufacturing guidelines to support sustainable manufacturing, *Robotics and Computer-Integrated Manufacturing*, **23** (6), 712-719.

Intergovernmental Panel on Climate Change (2007). *Climate Change 2007. IPCC Fourth Assessment Report. The Physical Science Basis* [online]. Available from: http://www.ipcc.ch/ipccreports/ar4-wg1.htm [accessed 3rd May 2011].

International Energy Agency (2010). *2010 Key World Energy Statistics* [online]. Available from: http://www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf [accessed 3rd May 2011].

ISO (2006a). *ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework*, International Standards Organisation: Switzerland.

ISO (2006b). *ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines,* International Standards Organisation: Switzerland.

Ishii K., Eubanks C.F. and Di Marco P. (1994). Design for product retirement and material life-cycle, *Materials & Design*, **15** (4), 225-233.

Ito T. (2011). *3R Initiative and Japan's International Cooperation towards Zero Waste* [online]. Presentation given by Director-General, Department of Waste Management and Recycling, Ministry of the Environment, Japan, 17 February 2011. Available from: http://www.uncrd.or.jp/env/spc/docs/Keynote%20MOE%20japan.pdf [accessed 24th April 2011].

Johnson Matthey (2011). *Platinum Today: Current and Historical Prices* [online]. Available from: http://www.platinum.matthey.com/cgi-bin/dynamic.pl?template=historical [accessed 19th April, 2011].

Jovane F., Alting L., Armillotta A., Eversheim W., Feldmann K., Seliger G., and Roth N. (1993). A Key Issue in Product Life Cycle: Disassembly, *CIRP Annals - Manufacturing Technology*, **42** (2), 651-658.

Kannan R., Leong K.C., Osman R., Ho H.K. and Tso C.P. (2006). Life cycle assessment study of solar PV systems: An example of a 2.7 kW_p distributed solar PV system in Singapore, *Solar Energy*, **80** (5), 555-563.

Karakoussis V., Brandon N.P., Leach M. and van der Vorst R. (2001). The environmental impact of manufacturing planar and tubular solid oxide fuel cells, *Journal of Power Sources*, **101**, 10-26.

Karakoussis V., Leach M., van der Vorst R., Hart D., Lane J., Pearson P. and Kilner J. (2000). *Environmental emissions of SOFC and SPFC system manufacture and disposal* [online]. Prepared for the Energy Technology Support Unit, on behalf of the Department for Trade and Industry, UK. Available from: http://www.berr.gov.uk/files/file15216.pdf [accessed 4th May 2011].

Kaundinya D.P., Balachandra P. and Ravindranath N.H. (2009). Grid-connected versus stand-alone energy systems for decentralized power – A review of literature, *Renewable and Sustainable Energy Reviews*, **13**, 2041-2050.

Kerr W. and Ryan C. (2001). Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia, *Journal of Cleaner Production*, **9** (1), 75-81.

Ketlogetswe C. and Mothudi T.H. (2009). Solar home systems in Botswana – Opportunities and constraints, *Renewable and Sustainable Energy Reviews*, **13**, 1675-1678.

Kalpakjian S. and Schmid S.R. (2008). *Manufacturing Processes for Engineering Materials*. 5th ed. Prentice Hall: Singapore.

Kluppel H.J. (1998). Environmental management – Life cycle assessment – Goal and scope definition – Inventory analysis, *International Journal of Life Cycle Assessment*, **3** (6), 301.

Knight W.A. and Sodhi M. (2000). Design for Bulk Recycling: Analysis of Materials Separation, *CIRP Annals - Manufacturing Technology*, **49** (1), 83-86.

Kozac G. (2003). *Printed Scholarly Books and E-book Reading Devices: A Comparative Life Cycle Assessment of Two Book Options.* Thesis (Masters), School of Natural Resources and Environment, University of Michigan.

Kriwet A., Zussman E. and Seliger G. (1995). Systematic integration of design-for-recycling into product design, *International Journal of Production Economics*, **38** (1), 15-22.

Krozer J. and Doelman P. (2003). Policy incentives for waste prevention. An economic approach to design for recycling, *The Journal of Sustainable Product Design*, **3**, 3-17.

Kumar R. (2005). *Research Methodology: A step-by-step guide for beginners.* 2nd ed. Sage: London

Kyocera (2011). *Environmental Products* [online].
Available from: http://global.kyocera.com/company/csr/environment/ [accessed 24th April 2011].

Lattin, W.C., and Utgikar V.P. (2007). Transition to hydrogen economy in the United States: A 2006 status report, *International Journal of Hydrogen Energy*, **32** (15), 3230-3237.

LCA Food (2007). *LCA Food Database* [online]. Available from: http://www.lcafood.dk/ [accessed 24th April 2011].

Le Borgne R. and Feillard P. (2001). End-of-life of a Polypropylene Bumper Skin. Some Key Elements for a Pragmatic Environmental Management, *International Journal of LCA*, **6** (3), 167-176.

Lhendup T. (2008). Rural electrification in Bhutan and a methodology for evaluation of distributed generation system as an alternative option for rural electrification, *Energy for Sustainable Development*, **12** (3), 13-24.

Lindhqvist T. (2000). *Extended Producer Responsibility in Cleaner Production. Policy Principle to Promote Environmental Improvements of Product Systems.* Thesis (Doctoral), The International Institute for Industrial Environmental Economics, Lund University.

Lisbona P., Corradetti A., Bove R. and Lunghi P. (2007). Analysis of a solid oxide fuel cell system for combined heat and power applications under non-nominal conditions, *Electrochimica Acta*, **53** (4), 1920-1930.

Mabee D.G., Bommer M. and Keat W.D. (1999). Design charts for remanufacturing assessment, *Journal of Manufacturing Systems*, **18** (5), 358-366.

Macauley M., Palmer K. and Shih J. (2003). Dealing with electronic waste: modelling the costs and environmental benefits of computer monitor disposal, *Journal of Environmental Management*, **68**, 13–22.

Marsmann M. (2000). The ISO 14040 Family, *International Journal of Life Cycle Assessment*, **5** (6), 317–318.

Materials KTN (2011). *A study of the recycling and recovery infrastructure for materials critical to the UK* [online]. Materials Knowledge Transfer Network and Materials UK, draft report. Available from:
http://www.matuk.co.uk/docs/UK_Critical_Materials_Recycling_Infrastructure.pdf
[accessed 14th May 2011].

Maxwell and van der Vorst (2003). Developing sustainable products and services, *Journal of Cleaner Production*, **11** (8), 883-895.

Mayer C.K., France C.M. and Cowell S.J. (2005). Extended Producer responsibility for Waste Electronics – an example of printer recycling in the United Kingdom, *Journal of Industrial Ecology*, **9** (3), 169-189.

Minh N.Q. (2003). Ceramic Fuel Cells, *Journal of the American Ceramics Society*, **76** (3), 563-588.

Minh N.Q. (2004). Solid oxide fuel cell technology—features and applications, *Solid State Ionics*, **174**, 271–277.

Minh N.Q., Singhal S.C. and Williams M.C. (2008). Solid Oxide Fuel Cells: Development Activities, Trends and Technological Challenges", *ECS Transactions*, **17** (1), 211-219.

Ministry of Economy, Trade and Industry (2010). *Towards a 3R-Oriented, Sustainable Society: Legislation and Trends 2010* [online]. Available from: http://www.meti.go.jp/policy/recycle/main/data/pamphlet/pdf/handbook2010-eng.pdf [acccessed 24th April 2011].

Mitsubishi Heavy Industries Ltd (2011). *Development Status of SOFC* [online]. Available from: https://www.mhi.co.jp/en/power/technology/sofc/development_situation.html [accessed 24th April 2011].

Morris J.R., Phillips P.S and Read A.D. (1998). UK landfill tax: an analysis of its contribution to sustainable waste management, *Resources, Conservation and Recycling*, **23**, 259-270.

Mortimer N.D., Evans A.K.F., Ashley A., Hatto C., Shaw V.L., Whittaker C. and Hunter A.J. (2010), Life cycle assessment workbooks for a selection of major renewable chemicals [online]. Project report completed by North Energy for National Non-food Crops Centre, UK. Available from: http://www.nnfcc.co.uk/tools/lca-workbooks-for-a-selection-of-major-renewable-chemicals-nnfcc-09-018 [accessed 24th April 2011].

Mott MacDonald Group Limited (2011). *Waste treatment world better* [online]. Available from: http://www.mottmac.com/newsandpublications/leadingedge/?id=79261 [accessed 4th May 2011].

Narita N., Nakahara Y., Morimoto M., Aoki R. and Suda S. (2004). Current LCA database development in Japan - results of the LCA project, *International Journal of Life Cycle Assessment*, **9** (6), 355-359.

National Energy Technology Laboratory (2011a). *Solid State Energy Conversion Alliance (SECA)* [online]. Available from: http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/index.html [accessed 3rd May 2011].

National Energy Technology Laboratory (2011b). *Solid State Energy Conversion Alliance (SECA) Industry Teams* [online]. Available from: http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/industry.html [accessed 3rd May 2011].

National Renewable Energy Laboratory (2010). *U.S. Life cycle inventory database* [online]. Available from: http://www.nrel.gov/lci/ [accessed 24th April 2011].

Nicoletti G.M., Notarnicola B. and Tassielli G. (2002). Comparative life cycle assessment of flooring materials: ceramic versus marble tiles, *Journal of Cleaner Production*, **10** (3), 283-296.

Nilsson K., Flysjo A., Davis J., Sim S., Unger N. and Bell S. (2010). Comparative life cycle assessment of margarine and butter consumed in the UK, Germany and France", *International Journal of Life Cycle Assessment*, **15**, 916-926.

Nishimura A., Hayashi Y., Tanaka K., Hirota M., Kato S., Ito M., Araki K. and Hu E.J. (2010). Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system, *Applied Energy*, **87** (9), 2797-2807.

Nordson Corporation (1999). *Nordson® 110 Vac Rotary Sieve* [online]. Customer Product Manual. Available from: http://emanuals.nordson.com/finishing/files/Powder/108167E.pdf [accessed 4th May 2011]

NSI Equipments Ltd (2011). *Ball mills* [online]. Available from: http://www.nsiequipments.com/gifs/ball-mills-2.jpg [accessed 24th April 2011].

Nuij R. (2001). Eco-innovation: Helped or hindered by Integrated Product Policy, *The Journal of Sustainable Product Design*, **1**, 49-51.

Ofgem (2003). *Electricity distribution losses – A consultation document* [online]. Available from: http://www.ofgem.gov.uk/NETWORKS/ELECDIST/POLICY/DISTCHRGS/Documents1/1362-03distlosses.pdf [accessed 3rd May 2011].

Osman A. and Reis R. (2007). Life cycle assessment of electrical and thermal energy systems for commercial buildings, *International Journal of Life Cycle Assessment*, **12** (5), 308-316.

PE International GmbH (2007). GaBi 4: Software and data base for Life Cycle Engineering.

Pehnt M. (2000). Life-cycle assessments of fuel cells and relevant fuel chains, *Proceedings of the International Hydrogen Energy Forum*, 11th-15th September 2000, Munich.

Pehnt M. (2001). Life-cycle assessment of fuel cell stacks*, International Journal of Hydrogen Energy*, **26**, 91-101.

Pehnt M. (2003a). Assessing future energy and transport systems: The case of fuel cells - Part 1: Methodological Aspects, *International Journal of Life Cycle Assessment*, **8** (5) 283-289.

Pehnt M. (2003b). Assessing future energy and transport systems: The case of fuel cells - Part 2: Environmental Performance, *International Journal of Life Cycle Assessment*, **8** (6) 365-378.

Pehnt M. (2003c). Life cycle analysis of fuel cell components. In: Vielstich W., Lamm A. and Gasteiger H.A. (eds.) *Handbook of Fuel Cells – Fundamentals, Technology and Applications*. John Wiley & Sons Ltd.: Chichester, UK. pp 1293-1317.

Pehnt M. (2008). Environmental impacts of distributed energy systems – the case of micro cogeneration, *Environmental Science and Policy*, **11** (1), 25-37.

Pehnt M. and Rahmesol S. (2003). *Fuel cells for distributed power: benefits, barriers and perspectives* [online]. Commissioned by WWF in co-operation with Fuel Cell Europe. Available from: http://wwf.panda.org/what_we_do/footprint/climate_carbon_energy/climate_change/publications/?7364/Fuel-cells-for-distributed-power-benefits-barriers-and-perspectives-Full-report [accessed 4th May 2011].

Pennington D.W., Potting J., Finnveden G., Lindeijer E., Jolliet O., Rydberg T. and Rebitzer G. (2004). Life cycle assessment: Part 2: Current impact assessment practice, *Environment International*, **30**, 721-739.

Pepermans G., Driesen J., Haeseldonck D., Belmans R. and D'haeseleer W. (2005). Distributed generation: definition, benefits and issues, *Energy Policy*, **33**, 787-798.

Pigosso D.C.A., Zanette E.T., Filho A.G., Ometto A.R. and Rozenfeld H. (2010). Ecodesign methods focusing on remanufacturing, *Journal of Cleaner Production*, **18** (1), 21-31.

PlasticsEurope (2011). *Eco-profiles and Environmental Declarations* [online]. Version 2.0, April 2011. Available from: http://www.plasticseurope.org/documents/document/20110421141821-plasticseurope_eco-profile_methodology_version2-0_2011-04.pdf [accessed 3rd May 2011].

Pré Consultants (2006). SimaPro7: Life Cycle Assessment Software.

Rahimifard S., Coates G., Staikos T., Edwards C. and Abu-Bakar M. (2009). Barriers, drivers and challenges for sustainable product recovery and recycling, *International Journal of Sustainable Engineering*, **2** (2), 80-90.

Raugei M., Bargigli S. and Ulgiati S. (2005). A multi-criteria life cycle assessment of molten carbonate fuel cells (MCFC) – a comparison to natural gas turbines, *International Journal of Hydrogen Energy*, **30**, 123-130.

Raugei M., Bargigli S. and Ulgiati S. (2007). Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si, *Energy*, **32** (8), 1310-1318.

Rebitzer G., Ekvall T., Frischnecht R., Hunkeler D., Norris G., Rydberg T., Schmidt W.P., Suh S., Weidema B.P. and Pennington D.W. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications, *Environment International*, **30**, 701-720.

Renckens S. (2008). Yes, We Will! Voluntarism in US E-Waste Governance, *Review of European Community & International Environmental Law*, **17** (3), 284-297

Riva A., D'Angelosante S. and Trebeschi C. (2006). Natural gas and the environmental results of life cycle assessment, *Energy*, **31**, 138–148.

Rolls-Royce Fuel Cell Systems (2008). *SOFC stack composition*. Unpublished data.

Rolls-Royce plc (2007). *Solid-Oxide Fuel Cell System for megawatt scale stationary power generation* [online]. Fact Sheet. Available from: http://www.rolls-royce.com/energy/tech/fuelcell.pdf [accessed 12th November 2007].

Rolls-Royce plc (2011a). *Fuel cells* [online]. Available from: http://www.rolls-royce.com/energy/energy_products/fuel_cells/index.jsp [accessed 24th April 2011].

Rolls-Royce plc (2011b). *TotalCare* [online]. Available from: http://www.rolls-royce.com/civil/services/totalcare/ [Accessed 3rd May 2011].

Rubik F. (2001). Environmental sound product innovation and Integrated Product Policy, *The Journal of Sustainable Product Design*, **1**, 219-232.

Ruhland A. Striegel G. and Kreisel G. (2000). Functional equivalence of industrial metal cleaning processes ` of metal cleaning processes within LCA, *International Journal of Life Cycle Assessment*, **5** (3), 127-133.

Ryan A., O'Donoghue L. and Lewis H. (2011). Characterising components of liquid crystal displays to facilitate disassembly, *Journal of Cleaner Production*, **19** (9-10), 1066-1071.

Scharnhorst W., Althaus H-J, Classen M., Jolliet O. and Hilty L.M (2005). The end of life treatment of second generation mobile phone networks: Strategies to reduce the environmental impact, *Environmental Impact Assessment Review*, **25** (5), 540-566.

Seip K.L., Thorstensen B. and Wang H. (1991). Environmental impacts of energy facilities: fuel cell technology compared with coal and conventional gas technology, *Journal of Power Sources*, **35**, 37-58.

Seppala J., Basson L. and Norris G.A. (2002). Decision Analysis Frameworks for Life-Cycle Impact Assessment, *Journal of Industrial Ecology*, **5** (4), 45-68.

Sheehan B., and Spiegelman H. (2005). Extended Producer Responsibility Policies in the United States and Canada: History and Status. In: Scheer D. & Rubik F., eds. *Governance and Sustainability: The Case of Integrated Product Policy*. Greenleaf Publishing: Sheffield, UK.

Siemens AG (2010a). *SOFC / Gas Turbine Hybrid* [online]. Available from: http://www.energy.siemens.com/us/en/power-generation/fuel-cells/sofc-gt-hybrid.htm [accessed 3rd May 2011].

Siemens AG (2010b). *The principle behind the technology* [online]. Available from: http://www.energy.siemens.com/us/en/power-generation/fuel-cells/principle-behind-technology.htm [accessed 5th May 2011].

Singhal S.C. (2002). Solid oxide fuel cells for stationary, mobile and military applications, *Solid State Ionics,* **152-153**, 405-410.

Singhal S.C. and Kendall K., eds. (2003). *High Temperature Solid Oxide Fuel Cells: Fundamentals, design and applications.* Elsevier: Oxford, UK.

Staffell I., Green R. and Kendall K. (2008). Cost targets for domestic fuel cell CHP, *Journal of Power Sources*, **181** (2), 339-349.

Staikos T. (2007). *The realisation of end-of-life recovery to support a zero-waste to landfill approach in footwear industry*. Thesis (PhD). Loughborough University.

Stambouli A. B. and Traversa E. (2002). Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy, *Renewable and Sustainable Energy Reviews*, **6** (5), 433-455.

Steele B.C.H (1999). Running on natural gas, *Nature*, **400**, 619-621.

Steele B.C.H. (2000). Materials for IT-SOFC stacks – 35 years R&D: the inevitability of gradualness?, *Solid State Ionics*, **134**, 3–20.

Sterecycle (2011). *Process overview* [online]. Available from: http://www.sterecycle.com/process.htm [accessed 4th May 2011].

Strazza C., Del Borghi A., Costamagna P., Traverso A. and Santin M. (2010). Comparative LCA of methanol-fuelled SOFCs as auxillary power systems on-board ships, *Applied Energy*, **87** (5), 1670-1678.

Terazono A. (2009). *Utilization of Material Flow Analysis in 3R Policy in Japan* [online]. Research Center for Material Cycles and Waste Management, National Institute for Environmental Studies. Available from: http://www.eria.org/pdf/research/y2009/no10/Ch10_3R.pdf [accessed 24th April 2011].

Tesko Laser Division (2005). *Standard metal cutting processes: laser cutting vs. water jet cutting* [online]. Available from: http://www.teskolaser.com/waterjet_cutting.html [accessed 3rd May 2011].

Thierry M., Salomon M., Van Nunen J. and Van Wassenhove L. (1995). Strategic Issues in Product Recovery Management. *California Management Review*, **37** (2), 114-135.

Thijssen J. (2010). *Market Impacts of Rare Earth Element Use in Solid Oxide Fuel Cells* [online]. Prepared for the National Energy Technology Laboratory. Available from: http://www.netl.doe.gov/technologies/coalpower/fuelcells/publications/Rare%20Earth%20Markets%20and%20Solid%20Oxide%20Fuel%20Cells%20101018.pdf [accessed 3rd May 2011].

Triantaphyllou E. (2000*). Multi-Criteria Decision Making Methods: A Comparative Study.* Kluwer Academic Publishers: Dordrecht.

Tukker A. (2006). Identifying Priorities for Environmental Product Policy, *Journal of Industrial Ecology*, **10** (3), 1-4.

United Nations Environment Programme (1972). *Stockholm 1972: Report on Conference on the Human Environment* [online]. Available from: http://www.unep.org/Documents.Multilingual/Default.asp?documentID=97 [accessed 4th May 2011].

United States Environmental Protection Agency (2008). *Introduction to the Resource Conservation and Recovery Act, Chapter I, Orientation Manual 2008: Resource Conservation and Recovery Act* [online]. Available from: http://www.epa.gov/osw/inforesources/pubs/orientat/rom1.pdf [accessed 3rd May 2011].

United States Environmental Protection Agency (2010). *Resource Conservation Challenge update – Materials Matter* [online]. Available from: http://www.epa.gov/waste/rcc/resources/rcc-rpt5.pdf [accessed 25th April 2011].

van Hemel C. and Cramer J. (2002). Barriers and stimuli for ecodesign in SMEs, *Journal of Cleaner Production*, **10**, 439-453.

Verda V. and Quaglia M.C. (2008). Solid oxide fuel cell systems for distributed power generation and cogeneration, *Journal of Hydrogen Energy*, **33**, 2087-2096.

Versa Power Systems (2011). *Products* [online]. Available from: http://www.versa-power.com/products.htm [accessed 24th April 2011].

Volkswagen AG (2010). *The Golf. Environmental Commendation Background Report* [online]. Available from: http://www.volkswagen.com/etc/medialib/vwcms/virtualmaster/de/Unternehmen/mobilitaet_und_nachhaltigkeit/downloads/umweltpraedikate.Par.0064.File.pdf/101129_vw_hb_golf.pdf [accessed 4th May 2011].

Wang J-J., Jing Y-Y., Zha ng C-F. and Zhao J-H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making, *Renewable and Sustainable Energy Reviews*, **13**, 2263–2278.

Williams M.C., Strakey J.P., Surdoval W.A. and Wilson L.C. (2006). Solid oxide fuel cell technology development in the U.S., *Solid State Ionics*, **177**, 2039-2044.

Wincewicz K.C. and Cooper J.S. (2005). Taxonomies of SOFC material and manufacturing alternatives, *Journal of Power Sources*, **140**, 280-296.

World Steel Association (2010). *About the worldsteel Life Cycle Inventory* [online]. Available from: http://www.worldsteel.org/?action=storypages&id=320 [accessed 24th April 2011].

WRAP (2010). *Gate Fees Report 2010. Comparing the cost of alternative waste treatment options* [online]. Available from: http://www.wrap.org.uk/downloads/2010_Gate_Fees_Report.e8614870.9523.pdf [accessed 5th May 2011].

Wright E., Azapagic A., Stevens G., Mellor W. and Clift R. (2005). Improving recyclability by design: a case study of fibre optic cable, *Resources, Conservation and Recycling*, **44** (1), 37-50.

Wright E.I., Rahimifard S. and Clegg A.J. (2009). Impacts of environmental product legislation on solid oxide fuel cells, *Journal of Power Sources,* **190** (2), 362-371.

Yu J., Hills P. and Welford R. (2007). Extended Producer Responsibility and Eco-Design Changes: Perspectives from China, *Corporate Social Responsibility and Environmental Management,* **15**, 111-124.

Zapp P. (1996). Environmental analysis of solid oxide fuel cells, *Journal of Power Sources*, **61**, 259-262.

Zeleny M. (1982). *Multiple criteria decision making.* McGraw-Hill: New York

Zhang X., Chan S.H., Li G., Ho H.K, Li J. and Feng Z. (2010). A review of integration strategies for solid oxide fuel cells, *Journal of Power Sources*, **195** (3), 685-702.

Zhong Z.W., Song B. and Loh P.E. (2011). LCAs of a polycrystalline photovoltaic module and a wind turbine, *Renewable Energy,* **36** (8), 2227-2237.

APPENDIX A

ENVIRONMENTAL LEGISLATION AND ITS IMPLICATIONS ACROSS THE LIFE-CYCLE OF STATIONARY SOLID OXIDE FUEL CELL SYSTEMS IN EUROPE

This paper was presented at the 5rd International Conference of Design and Manufacture for Sustainable Development in Loughborough, 10th – 11th July 2007.

Environmental legislation and its implications across the life-cycle of stationary solid oxide fuel cell systems in Europe

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ABSTRACT

Solid oxide fuel cell (SOFC) systems offer an alternative technology for stationary power generation and their development has been driven primarily by environmental benefits during operation. SOFC systems offer the potential for reduced emissions of green-house gases and other pollutant species when compared with conventional combustion technologies. At present SOFC systems are not yet generally commercially available and the technology is being developed from the prototype stage towards the first generation of product.

Given the green credentials of SOFC technology, it is important that the emerging concept of sustainable product design is integrated into ongoing development activities. Environmental policy places an increasing emphasis on the life-cycle impacts of products, as demonstrated by the implementation of various recent legislative measures. Assuming that compliance with environmental legislation is one of the fundamental steps in the development of a sustainable product, this paper presents a review of new and recent legislation perceived to be of direct relevance to the life-cycle of stationary SOFC systems. Specific European Directives and Regulations have been identified and mapped against a matrix constructed from defined product sub-assemblies and individual life-cycle stages. A discussion regarding the specific implications of each piece of legislation is presented.

The findings presented in this paper will provide input to further studies regarding the implementation of sustainability principles in the development of commercial SOFC systems for stationary power generation applications.

1 INTRODUCTION

1.1 Solid oxide fuel cells for stationary power generation

Solid oxide fuel cells (SOFCs) offer an alternative technology for electrical power generation. The ceramic electrolytes used in SOFCs require an operating temperature of between 600 °C and 950 °C to be employed to maximise efficiencies. The technology is well suited to applications in stationary power generation and internal reforming capability allows cost-efficient operation on a range of readily available hydrocarbon fuels. In addition, the operating temperature results in the production of high-quality waste heat, making the technology suitable for combined heat and power generation and for incorporation into a

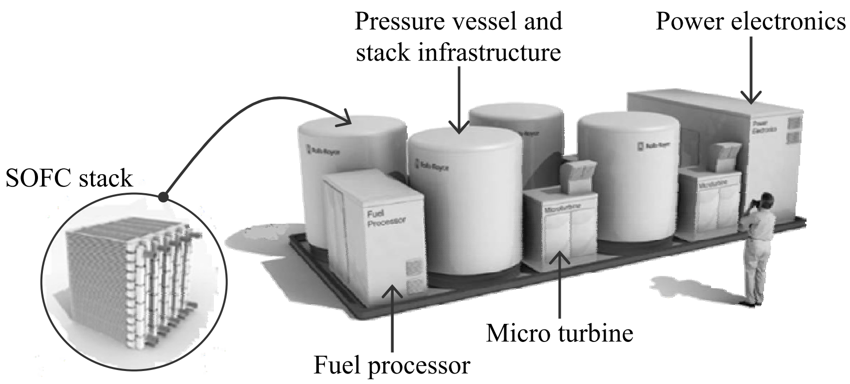

Figure 1, Schematic of the 1 MW SOFC system being developed by Rolls-Royce Fuel Cell Systems Limited (adapted from Rolls-Royce plc. 2006). This is a hybrid system where a small gas turbine is used to provide the pressurised conditions under which the fuel cell stack operates.

hybrid system with conventional gas turbine technology. An example of the type of product currently under development is shown in Figure 1.

Stationary power generation systems based on SOFC technology are characterised by efficient fuel utilisation, reduced emissions of carbon dioxide and other greenhouse gases, and virtual elimination of other polluting emissions, such as oxides of nitrogen and sulphur. These advantageous characteristics stem from the electrochemical nature of the devices, which eliminates both the energy losses associated with intermediate thermal and mechanical conversion steps and the formation of undesirable combustion products common to most conventional power generation technologies.

These benefits are widely accepted and continue to drive the development of commercially viable products. Several detailed reviews of the technology are available (for example, Minh 1993, Stambouli and Traversa 2002). Published environmental assessments of the operation of SOFC systems and comparisons with conventional power generation systems can also be read (for example, Bauen and Hart 2000).

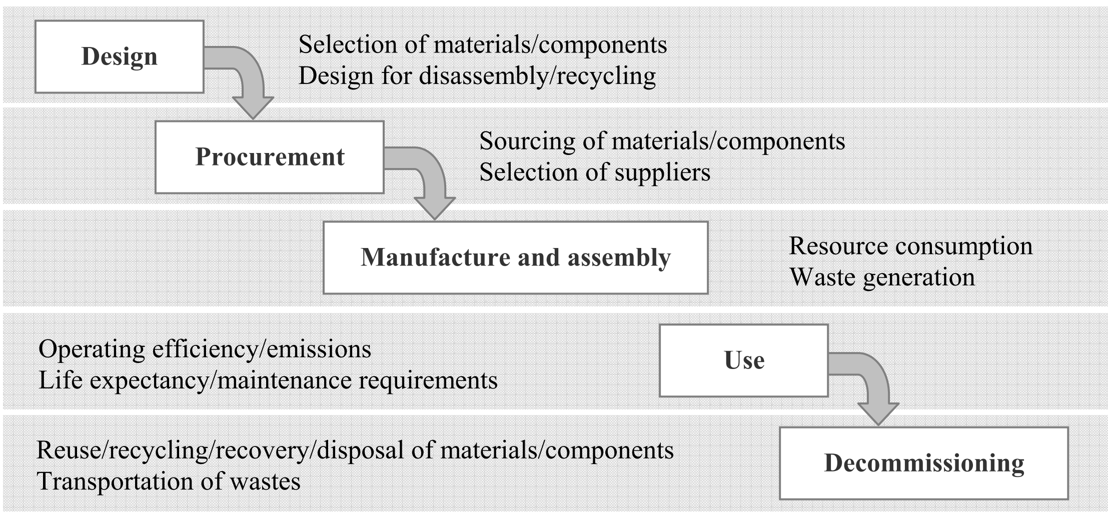

Figure 2, A simple product life-cycle showing some examples of common activities associated with each life-cycle stage which may influence the total environmental impact of the product.

1.2 Trends in environmental policy and legislation

During the second half of the twentieth century the focus of environmental policy shifted. Around the time of the First International Conference on the Human Environment in Stockholm, environmental policy was shaped by responding to environmental crises; in the 1980s the emphasis moved to target point sources of pollution and control emissions; by the end of the 20th century and in response to growing consumerism, products became the focus of environmental policy (Tukker 2006).

The environmental policy of the 1990s is reflected in the legislation of today. In Europe, recent developments in legislation have brought many aspects of the product life-cycle outlined in Figure 2 under legislative control. For example, the Waste Electrical and Electronic Equipment Directive (Directive 2002/96/EC) has introduced recycling/recovery targets for a specific product sector; the new REACH chemicals legislation (Regulation (EC) No 1907/2006) will impact aspects of materials selection and procurement; the Energy using Products Directive (Directive 2005/32/EC) provides a framework for regulating eco-design activities.

Although legislation will not in itself lead to optimised environmental performance of products it surely provides a minimum standard to which all producers are obligated. In addition, forward-looking businesses will strive to keep ahead of legislative developments in order to ensure that future requirements do not compromise their products and activities. Environmental excellence will only be achieved when businesses are committed to minimising all environmental impacts, even when self-imposed standards surpass the requirements laid down by law.

1.3 The implications of environmental legislation for the life-cycle of solid oxide fuel cell systems for stationary power generation

It could be argued that, given the green credentials of SOFC power generation systems during operation, customers and other stakeholders are likely to be more demanding of environmental excellence across all aspects of the product life-cycle. In order to achieve this, it is important that a thorough understanding of the environmental legislation relevant to the life-cycle of the product is in place as a foundation during product development. Only when compliance is ensured can opportunities for improvement be determined and pursued and sustainable product design practiced successfully.

2 METHODOLOGY

Figure 3 illustrates the methodology adopted in identifying environmental legislation relevant across the SOFC system product life-cycle. A systematic approach was required, given both the complexity of the product system, as illustrated by Figure 1, and the wide range of issues addressed by environmental legislation.

In order to simplify the product system, discrete sub-assemblies were defined, each characterised by distinct component-types and materials employment. The field of environmental legislation is very broad and spans the complete life-cycle of the product. To maintain clarity and focus in identifying relevant legislation, individual life-cycle phases were defined into which environmental legislation could be categorised.

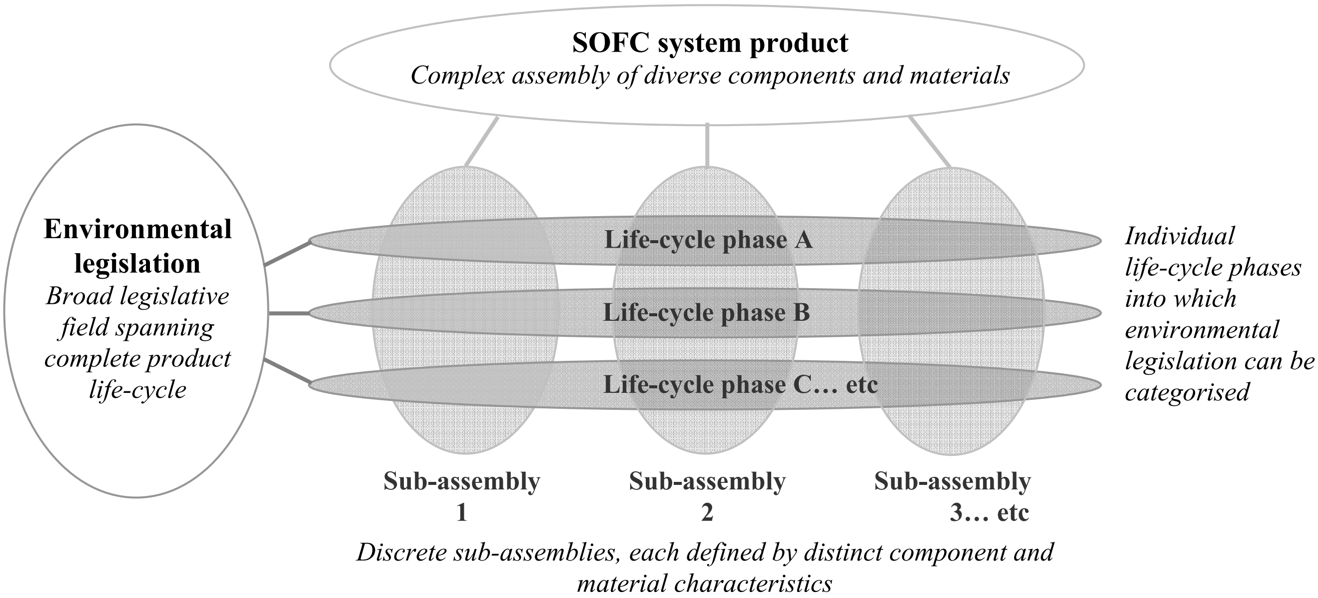

Figure 3, Pictorial description of the methodology applied to the mapping of environmental legislation relevant to the SOFC system product life-cycle. Legislation was identified in each of the overlap areas, i.e. for each life-cycle phase of the pre-defined sub-assemblies.

Following the definition of these two sets of categories a two-dimensional matrix was developed against which legislation could be reviewed, evaluated and the relevant legislation mapped. The product system, based on understanding gained from general information published by SOFC developers, was then assessed against the relevant legislation to identify any potential compliance issues. The legislation identified was not fully comprehensive, but focused on recent legislative developments which could be regarded as promoting sustainable product design.

3 RESULTS

3.1 Definition of sub-assemblies

The definition of discrete sub-assemblies within the SOFC system product is shown in Table 1. Three principal sub-assemblies were defined, namely the SOFC Stack, the SOFC System and the Power & Controls. This expands on previous studies where the SOFC System and the Power & Controls are grouped together as the “Balance of Plant” (e.g. Karakoussis *et al.* 2001). For the purposes of the current work this distinction was made to allow the relevance of legislation specifically targeted at electrical and electronic equipment to be clearly evaluated.

Although a variety of SOFC Stack designs exist the general characteristics are similar (Minh 2004). The fuel cell consists of a multi-layer assembly of functional materials, supported on a substrate. The substrate is fabricated from one of the functional materials, from a conducting interconnect material (i.e. a suitable high temperature alloy (Bance *et al.* 2004)) or from ceramic (Costamagna *et al.* 2004). In addition to the substrate material, the SOFC Stack sub-assembly is comprised principally of functional ceramics and other metal/rare-earth oxides (Haile 2003).

The SOFC System sub-assembly incorporates fuel processing assemblies, piping and insulation infrastructure required for supply of fuel and air to the SOFC Stack, heat

Table 1, Definition of sub-assemblies

SOFC system	
Sub-assembly	***Characteristics***
SOFC Stack	Constructed from multi-layer assemblies of active materials on single substrates. *Principal active materials:* Yttria-stabilised zirconia, Nickel oxide, Strontium-doped lanthanum manganite, doped lanthanum chromite *Substrate materials:* Any active material (as above), high temperature alloys, inert ceramics
SOFC System	Plant infrastructure including fuel processor, vessel and pipe-work. *Principal material groups:* Low-temperature alloys, High-temperature alloys, Insulation materials
Power & Controls	Conventional electrical/electronic components

exchangers and all external casing. In addition this sub-assembly will incorporate pressure vessels required for pressurised systems and gas turbine machinery utilised in a hybrid system. Operating environments range from room temperature to the operating conditions experienced by the SOFC Stack. Components can be regarded as employing conventional technology used in other power generation systems. The principal material groups will be insulation materials and alloys (ranging from standard steels to specialised high-temperature alloys).

The Power & Controls sub-assembly contains all the electrical and electronic assemblies required to convert the DC signal produced in the SOFC Stack to AC electricity suitable for grid-connection. Control and safety systems are also included in this sub-assembly. Components can be regarded as employing conventional electrical/electronic technology and materials.

3.2 Definition of life-cycle stages

Table 2 shows the life-cycle stages identified and used for the categorisation of environmental legislation. At the Design stage, components and assemblies are conceptualized, and appropriate materials are selected and specified. The Procurement stage encompasses the sourcing of materials and components according to specification. This is a significant stage of the life-cycle for ensuring compliance with legislation, since it acts as a gate through which every material or component must pass before being incorporated into the product.

To date the work has focused on product-related legislation; therefore the environmental legislation regulating the Manufacturing stage is not reported in this paper. Some aspects of manufacturing will be similar to activities in other stages of the life-cycle, such as the selection of process materials (see materials selection, Design) and waste management (see Decommissioning).

For the purposes of this study it was assumed that emissions and fuel utilisation efficiencies for a SOFC system in operation would fall well within the limits of current legislation relevant to conventional power generation facilities. Future work will explore this area in greater detail, but the Use stage was excluded from the scope of this paper.

Table 2, Definition of life-cycle stages

Life-cycle stages	
Life-cycle stage	***Comments***
Design	Design of components and assemblies; materials selection
Procurement	Sourcing of specified components and materials
Manufacture	Outside scope of current work
Use	Outside scope of current work
Decommissioning	Disassembly; waste management (reuse, recycling, recovery and disposal)

The final stage of the life-cycle, namely Decommissioning, concerns all aspects of the management of products after they reach the end of their useful life. This includes any disassembly activities and waste management. A good understanding of the legislative requirements for the Decommissioning stage can be used to influence future design iterations.

3.3 Identification and mapping of legislation

From these definitions a matrix was developed and populated with relevant environmental legislation. The result of this mapping process is shown in Table 3. The focus of the mapping exercise was restricted to the most recent developments in environmental legislation. In total seven distinct legislative measures were identified as being of greatest relevance; these are listed below.

EuP Directive: The Directive establishing a framework for setting requirements for the Ecodesign of Energy using Products imposes no regulatory requirements, but indicates that eco-design as a practice is likely to be brought under legislative control (Directive 2005/32/EC).

REACH Regulation: REACH stands for the Registration, Evaluation, Authorisation and Restriction of Chemicals and is a new regulation, of which the final text was agreed in December 2006. The regulation will be phased in over a period of approximately 10 years and requires all chemical substances manufactured in or imported to Europe to be registered and evaluated (Regulation (EC) No 1907/2006)

WEEE Directive: The Waste Electrical and Electronic Equipment Directive specifies recycling and recovery targets for defined product categories. The Directive is closely linked with the RoHS Directive (Directive 2002/96/EC).

RoHS Directive: Under the Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment, the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and polybrominated biphenyl ethers is restricted (Directive 2002/95/EC).

Landfill Directive: The Landfill Directive controls the operation of landfill sites. The Directive specifies requirements for disposal of hazardous, non-hazardous and inert wastes to separate sites and has introduced increased levels of administration and monitoring of sites (Directive 1999/31/EC).

Hazardous Waste Directive: The amended Waste Directive (Directive 75/442/EEC) applies to hazardous waste as well as general waste types; however supplementary provision for the control of hazardous waste requiring special treatment is contained in the Hazardous Waste Directive (Directive 91/689/EEC). The Directive, together with the European list of wastes

Table 3, Matrix showing results of legislation mapping exercise

	SOFC Stack	SOFC System	Power & Controls
Design	**EuP Directive**	**EuP Directive**	
	REACH Regulations	**REACH Regulations**	
Procurement	**REACH Regulations**	**REACH Regulations**	
			RoHS Directive
			WEEE Directive
Manufacture		***Outside scope***	
Use		***Outside scope***	
Decommissioning	**Landfill Directive**	**Landfill Directive**	**Landfill Directive**
	Hazardous Waste Directive	**Hazardous Waste Directive**	
	Shipments of Waste	**Shipments of Waste**	**Shipments of Waste**
			WEEE Directive

(Decision 2000/532/EC) provides guidance for categorising waste as hazardous or non-hazardous. Under this legislation, producers are responsible for ensuring wastes are properly stored, packaged, labelled, transported and treated.

Shipments of Waste Legislation: The regulation on waste shipments (Regulation (EC) No 1013/2006) controls the shipment of waste into, out of and through the European Community. In particular the regulation is intended to protect developing countries from being used as a disposal ground for hazardous or difficult waste streams.

4 DISCUSSION

4.1 The implications of environmental legislation for the Design phase

The EuP Directive specifies its scope as being limited to "…a product which, once placed on the market and/or put into service, is dependent on energy input (electricity, fossil fuels and renewable energy sources) to work as intended, or a product for the generation, transfer and measurement of such energy…"(Directive 2005/32/EC). On the basis of this definition the Directive would be directly applicable to SOFC system products, however the Directive emphasises its focus on consumer goods with a high market volume (over 200,000 units per year). With respect to the content of the Directive, the framework for establishing cross-sector metrics by which the environmental profile of a product could be communicated to consumers is a useful tool which SOFC developers could utilise to their advantage. Assuming an environmentally-aware customer base, it is likely that the availability of this type of information would be advantageous, and that an ability to demonstrate a life-cycle approach to product design would provide a competitive edge in the initial period of commercialisation.

Materials selection is part of the Design activity and the implications of REACH are significant. It will be advantageous to select low-risk materials, which are not subject to Authorisation or Restriction under the regulations. In particular, substances of very high concern (SVHC) should be avoided, since these will effectively become black-listed. Nickel oxide is commonly used in the fuel electrodes of the SOFC stack and is classified as a category 1 carcinogen. It is probable that there will be pressure to substitute this material for a safer alternative, and SOFC developers should be able to demonstrate technical justification for their continued use of this material, as well as considering the provisions under REACH for authorisation of substances based on a socio-economic argument (Regulation (EC) No 1907/2006).

The Power & Controls sub-assembly is likely to be built from commercially available components; therefore the implications of the above legislation will principally be the concern of individual suppliers.

4.2 The implications of environmental legislation for the Procurement phase

The Procurement phase of the life-cycle acts as a gate through which all components and materials must pass before being incorporated into a product through manufacturing and assembly activities. This is therefore a stage where measures can be taken to ensure that each material or component purchased meets the necessary compliance standards. The Procurement phase will also be affected by legislation introduced further up the supply chain.

REACH (Regulation (EC) No 1907/2006), as well as providing some direction for materials selection, poses significant implications for the manufacturers and importers of chemical substances into Europe. Fuel cell developers will in most cases be classified as downstream users of substances, in which case their primary responsibility will be to communicate with their supply chain to ensure that all substances, and the way in which those substances are being used, have been registered. It is possible that some manufacturers or importers will choose to discontinue the supply of a specific substance, especially where the economic benefit of them keeping it in their portfolio does not outweigh the administrative effort of registration. It is therefore possible that some substances will become unavailable. This is a potential cause of concern for SOFC developers who are reliant on specialty chemicals to provide the functionality of their product. This is especially relevant to the SOFC Stack sub-assembly, where some unusual metal oxides are employed, and also in the SOFC System where specialised high-temperature alloys or insulating materials may be required.

REACH also poses economic implications; where a supplier is an SME with limited resources, it may be necessary for the SOFC developer to contribute to the costs of substance registration in order to ensure continued supply. The administrative burden of REACH is almost certain to be reflected in increased material prices.

With regard to the Power & Controls sub-assembly, SOFC developers should be aware of the impact of RoHS (Directive 2002/95/EC) on the supply chain. Although the SOFC system as a product is outside the scope of the Directive and therefore is not required to use compliant components, manufacturers will move towards production of compliant components as standard. This may involve increased costs, or substitution of materials resulting in unknown technical reliability. In order to promote a “green” image, SOFC developers may choose to source only components which are compliant with the RoHS restrictions.

As with RoHS, the SOFC system product falls outside the scope of the WEEE Directive (Directive 2002/96/EC). However, it is reasonable to expect that at the end of a product’s life, the manufacturer will face some responsibility for management of the waste produced. This should be considered during the Procurement phase and, where appropriate, division of responsibility agreed between the SOFC manufacturer and the suppliers of electrical and electronic components.

4.3 The implications of environmental legislation for the Decommissioning phase

Little information regarding the strategy for end-of-life management of stationary SOFC systems has been published (Karakoussis *et al.)*. However, this phase of the life-cycle has become the focus of environmental legislation in several different product sectors.

Most general waste legislation requires the classification of waste as hazardous or non-hazardous, and the results of this classification define the regulatory controls to which the waste is then subject during storage, packaging, transportation, treatment and disposal. Hazardous waste is understandably subject to tighter controls than non-hazardous waste, and therefore its management is a more costly process; from both environmental and economic perspectives it is in the interests of SOFC developers to minimise the volume of hazardous waste produced during the decommissioning of end-of-life products.

Waste is categorised depending on the presence of hazardous substances and their composition with respect to bulk material. Most of the materials employed in the SOFC stack are non-hazardous; however, nickel oxide is commonly used in the fuel electrodes (Haile, 2003). As a category 1 carcinogen, the concentration threshold for a waste stream containing this substance is only 0.1 % by weight, over which it is classified as hazardous (Decision 2000/532/EC). SOFC developers may want to consider the minimisation or substitution of this material in order to ensure that waste streams generated after Decommissioning fall below this threshold.

Legislation such as the Landfill Directive (Directive 1999/31/EC) has been implemented with the aim of reducing the amount of waste sent for disposal, while sector-specific legislation sets mandatory recycling targets. SOFC developers should therefore anticipate economic penalties for disposal to landfill, and increasing pressure to demonstrate recyclability of their products. Even before this becomes a legislative requirement, the elevated profile of resource efficiency and waste management issues will undoubtedly provoke consumer expectation. While, for the Power & Controls sub-assembly, some of this pressure may be shared with the supply chain, the SOFC Stack and the SOFC System sub-assemblies will possibly require more sophisticated and novel solutions for end-of-life management.

Since the development of bespoke end-of-life treatments for SOFC Stack or SOFC System sub-assemblies may spur the development of centralised processing plants, the legislation controlling shipments of waste into, out of, and within Europe holds implications where a global market is anticipated. In considering the viability of such a scenario, SOFC manufacturers should take into account the administrative and financial burden of obtaining the correct permits and consents. The viability of waste shipment operations will also be related to the classification of waste streams, since different restrictions apply for hazardous and non-hazardous wastes (Regulation (EC) No 1013/2006).

These implications of environmental legislation at the Decommissioning phase of the life-cycle should influence future Design activities as first and second generation commercial SOFC products are developed.

4 CONCLUSIONS

Environmental legislation is a broad-ranging area impacting SOFC systems across their life-cycle and its significance should be appreciated as products are developed towards commercialisation. Although the impact of a new regulation such as REACH cannot be fully appreciated until it is put into practice, awareness and anticipation of its potential implications will provide an advantage.

For companies developing SOFC systems for stationary power generation, the environmental benefits of the technology are a significant selling-point. A conscientious approach to the additional requirements imposed by environmental legislation should be sufficient to ensure compliance is achieved as a fundamental principle, underpinning further commitment to minimising the total environmental burden of products across their life-cycle.

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REFERENCES

Bance P., Brandon N.P., Girvan B., Holbeche P., O'Dea S. and Steele B.C.H., Spinning-out a fuel cell company from a UK University – 2 years of progress at Ceres Power, *Journal of Power Sources*, 2004, **131** (1-2), 86-90

Bauen A., Hart D., Assessment of the environmental benefits of transport and stationary fuel cells, *Journal of Power Sources*, 2000, **86** (1-2), 482-494

Costamagna P., Selimovic A., del Borghi M., Agnew G., Electrochemical model of the integrated planar solid oxide fuel cell (IP-SOFC), *Chemical Engineering Journal*, 2004, **102**, 61-69

Decision 2000/532/EC of 3 May 2000 establishing a list of wastes pursuant to Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Council Directive 91/689/EEC on hazardous waste, *Official Journal of the European Communities*, 2000, **L 226**, 3-24

Directive 75/442/EEC of 15 July 1975 on waste, *Official Journal*, 1975, **L 194**, 39-41

Directive 91/689/EEC of 12 December 1991 on hazardous waste, *Official Journal of the European Communities,* 1991, **L 377**, 20-27

Directive 1999/31/EC of 26 April 1999 on the landfill of waste, *Official Journal of the European Communities*, 1999, **L 182**, 1-19

Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE), *Official Journal of the European Union*, 2003, **L 37**, 24-39

Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, *Official Journal of the European Union*, 2003, **L 37**, 19-23

Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council", *Official Journal of the European Union*, 2005, **191**, 29-58

Haile S.M., Fuel cell materials and components, *Acta Materialia*, 2003, **51**, 5981-6000

Karakoussis V., Brandon N.P., Leach A., Leach M., van der Vorst R., The environmental impact of manufacturing planar and tubular solid oxide fuel cells, *Journal of Power Sources*, 2001, **101** (1), 10-26

Minh N.Q., Ceramic fuel-cells, *Journal of the American Ceramic Society*, 1993, **76** (3), 563-588

Minh N.Q., Solid oxide fuel cell technology - features and applications, *Solid State Ionics*, 2004, **174** (1-4), 271-277

Quadakkers W.J., Jülich develops new SOFC material, *Fuel Cells Bulletin*, December 2003

Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste, *Official Journal of the European Union*, 2006, **L 190**, 1-98

Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC, *Official Journal of the European Union*, 2006, **L 396** (49), 1-849

Rolls-Royce plc., Fuel cells fact sheet, 2006
Available online at: www.rolls-royce.com/energy/tech/fuelcells.jsp (accessed 9th March 2007)

Stambouli A.B. and Traversa E., Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy, *Renewable and Sustainable Energy Reviews*, 2002, **6**, 433-455

Tukker A., Identifying Priorities for Environmental Product Policy, *Journal of Industrial Ecology*, 2006, **10** (3), 1-4

APPENDIX B

AN INVESTIGATION INTO END-OF-LIFE MANAGEMENT OF SOLID OXIDE FUEL CELLS

This paper was presented at the 3rd International Conference on Life Cycle Management (LCM2007) in Zurich, 27th – 29th August 2007.

An investigation into end-of-life management of solid oxide fuel cells

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ABSTRACT

Solid oxide fuel cell (SOFC) systems offer an alternative technology for power generation in stationary plants. The environmental benefits of this technology in the use phase are well understood and stem from improved fuel efficiencies when compared with combustion-based systems. These benefits have driven technology development towards commercialisation. Recent trends in environmental policy have highlighted the need to manage products responsibly throughout their entire life-cycle, including the end-of-life (EoL) phase. At present EoL management of SOFC stacks is not well understood and requires consideration prior to market entry. Using the waste management hierarchy as a framework for the development of an EoL strategy a methodology is proposed to move from a reactive approach to a proactive approach. This paper presents results from the initial steps of this methodology. Analysis of existing SOFC stack design has provided an initial definition of the EoL problem. By drawing parallels with EoL problems faced by other more mature product streams and existing waste management solutions, a body of knowledge is built. This knowledge will support the development of a reactive short-term solution to EoL management of SOFC stacks, and will provide input to the longer-term development of a proactive approach to minimising the environmental burden of this future waste stream.

Introduction

Solid oxide fuel cell (SOFC) systems offer an alternative technology for power generation in stationary plants. Systems currently under development range from small domestic units providing power to a single home, to larger units offering power outputs of several Megawatts [1]. The environmental benefits of SOFC technology have driven its development, especially in recent decades when a reliance on fossil-fuels and combustion-based technologies has been recognized as unsustainable and detrimental to the local and global environment. Indeed, SOFC systems have the potential to offer a highly efficient means of converting hydrogen-rich fuels into electricity, with a reduction in carbon dioxide emissions and virtual elimination of the release of other pollutants, including oxides of nitrogen and sulphur and particulate matter [2].

The commercialisation of SOFC systems is being pursued by several companies in Europe, North America and Asia [3]. However, prior to the release of a significant volume of products into the market-place, a solution for the end-of-life (EoL) is required. This requirement is driven by:

i) Legislative developments

Environmental legislation is increasingly concerned with EoL management of products. The automotive and electrical/electronics sectors have been set mandatory recovery and recycling targets by recent European legislation [4, 5]. Although no legislation currently applies directly to EoL management of SOFC systems, development of this observed trend to encompass a wider range of product-types should be anticipated. In addition, a lack of provision for EoL management may preclude the incorporation of SOFC technology as a power source in products which themselves are subject to legislated recycling requirements. For example, SOFC-based auxiliary power units are being developed for automotive applications [6]. If these are not readily recyclable then their adoption by car manufacturers may conflict with the requirements imposed by legislation such as the European End-of-Life Vehicles Directive [4, 7].

ii) Customer expectations

Although SOFC technology offers increased efficiency and reduced emissions during operation, the environmental impacts of all life-cycle stages must be taken into account when evaluating the benefits of the technology. Previous authors have identified a lack of information regarding EoL management of the technology as a barrier to understanding the total life-cycle impacts [6, 8, 9]. Since SOFC systems are promoted as a "green" source of power generation, it would be highly damaging to their commercialisation if any aspect of the life-cycle were to be exposed as presenting an unreasonable environmental burden.

For the purposes of the current work it is assumed that sub-assemblies within the SOFC system which are based on conventional technologies will follow established EoL routes exploiting existing waste management capability. These sub-assemblies include pipe work for fuel and air supplies, vessels and containers, electrical and electronic systems and fuel processing equipment. Therefore the scope of the current study is limited to the SOFC stack, which is the term for an assembly of individual fuel cells.

Methodological considerations

It is proposed that the waste management hierarchy be used as the foundation for the development of an EoL management strategy for SOFC stacks. This hierarchy defines a preferred route to waste minimisation, and has been adopted at an international level [10]. The hierarchy identifies the reduction of waste at source as the preferred approach to waste management, followed by reuse, recycling and, only as a last resort, disposal to landfill. Where the waste management hierarchy is applied specifically to wastes arising from EoL products, it can be considered to be a hierarchy for EoL management.

Figure 1 shows a schematic of the waste management hierarchy and outlines the means by which compliance with the principle can be approached within EoL management. Reduction of waste volume and toxicity by addressing the primary source (namely the product design) can be considered to be a proactive approach. This requires early consideration of how design and materials selection define the waste streams arising from EoL products. Similarly opportunities for reuse of components will be significantly improved if disassembly considerations are incorporated at the design stage.

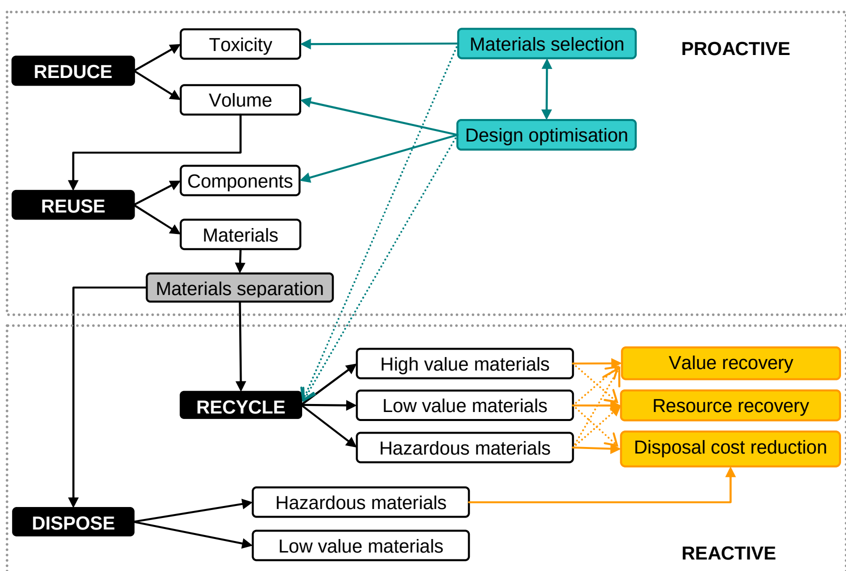

Figure 1: Hierarchical approach to end-of-life management

Reducing waste by recycling the materials contained within EoL products requires an additional level of processing. Segregation and purification of different material-types are required in order to produce useful inputs to downstream processes, whether in closed-loop or open-loop scenarios.

Although incorporating recyclability into design by careful materials selection is a proactive approach to EoL management, recycling can also be applied in a reactive approach. Although product design may limit the technical and/or economic feasibility of pursuing recycling as a viable EoL strategy, most EoL products offer opportunities for the recovery of useful materials. As a last resort, disposal may be considered for any non-recyclable fraction. The separation of hazardous materials from a non-hazardous bulk waste stream prior to disposal may have benefits from both environmental and economic perspectives.

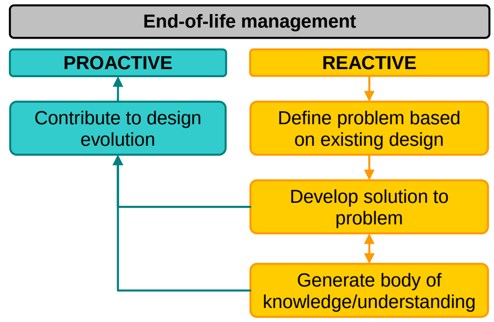

Figure 2: Methodology applied to the development of a proactive end-of-life strategy

Although a proactive approach to end-of-life management supports the preferred routes of reducing waste at source and reusing components, there may be barriers to applying this approach to novel products which are based on immature technologies. During early product or technology development, the focus of the design process is likely to be heavily dominated by technical requirements, reliability and cost. Therefore the initial solution to EoL management must be developed in reaction to an initial product (or prototype) design. During the development of this solution, a body-of- knowledge will be generated. This body-of-knowledge should determine the limitations of existing waste management capability in coping with the requirements posed by the novel product. Where limitations exist these may be eliminated either by modification of the design in future product development, or, if this is not possible, by the development of new waste management processes. It is anticipated that most product manufacturers will not wish to invest in a bespoke waste treatment capability, therefore using the body-of-knowledge to influence design development will be the preferred option. The EoL management strategy therefore begins with a reactive approach and develops into a proactive approach (Figure 2).

This methodology is being applied to the development of an EoL strategy for SOFC stacks in the ongoing project work. This paper presents the initial part of the work including:

i) The definition of the EoL management problem based on analysis of existing SOFC stack design;
ii) Preliminary steps towards the compilation of a body-of-knowledge based on existing EoL management solutions from other product sectors.

Given the status of SOFC-based products with regard to commercialisation it is hoped that a proactive EoL management strategy can be implemented prior to large-volume manufacture.

Results and discussion

Definition of existing problem

The existing EoL management problem is characterised primarily by the material composition of the waste stream. During SOFC development, a common set of materials has emerged which satisfy the requirements of electrochemical performance and stability. Although improved performance is pursued through ongoing materials development it is likely that the first commercial products will utilise the materials shown in Table 1 [11]. The contribution of each material to the composition of the EoL waste stream is defined by the cell and stack design. The dominating material will come from the layer providing structural support.

Table 1: Common SOFC materials

Component	Material	Material classification*	Hazardous waste threshold**	Material value
Electrolyte	Yttria-stabilized zirconia	Non-hazardous	N/A	Med
Anode* **	Nickel oxide Nickel	Cat. 1 carcinogen Cat. 3 carcinogen	> 0.1 wt% > 1 wt%	Med
Cathode	Strontium-doped lanthanum manganite	Irritant	> 20 wt%	Med
Interconnect	Doped lanthanum chromate	Irritant, harmful	> 20 wt%	Med
	Inert metals/alloys	Non-hazardous	N/A	High
Sealant	Glass/Glass-ceramic	Non-hazardous	N/A	Low
Substrate	Ceramic	Non-hazardous	N/A	Low

* As defined on Material Safety Data Sheets provided by material suppliers.
** As defined by the European Waste Catalogue. If materials are present in compositions greater than this threshold value, the entire waste stream is classified as hazardous.
*** Under controlled shut-down conditions all nickel in the anode will be present in metallic form. Nickel oxide would therefore only be present in end-of-life stack experiencing abnormal shut-down conditions or in end-of-life stack which had never been exposed to a fuel environment.

This can be any functional layer (electrolyte, anode, cathode or interconnect) or an external substrate [1].

The Integrated-Planar SOFC stack design under development at Rolls-Royce Fuel Cell Systems Limited utilises an external substrate as a support for the functional fuel cell layers. The substrate material is a low-cost ceramic which minimises the use of high-value fuel cell materials [12]. The waste stream will consist mainly of inert ceramic, highly integrated with a small amount of hazardous and valuable materials. It is assumed that common SOFC materials are used for each of the active layers.

As a reactive approach to the management of waste from this existing design, the strategy shown in Figure 3 is proposed. High-value and hazardous materials will be recovered from the low-value ceramic waste. It is anticipated that the high-value materials will be readily recycled in a high-value application. Recovery of hazardous materials from the bulk waste stream should be carried out primarily to minimise the volume of hazardous waste produced. Following the recovery process the hazardous content may be available for recycling and, depending on purity, may be suited to high or low-value applications. Recycling of the material in a low-value application would be preferable to disposal. Following the recovery of the high-value and hazardous materials the bulk waste stream, which consists of low-value ceramic material, is available for recycling. Disposal of the low-value ceramic waste should be avoided; however, if no suitable recycling application can be found then the previous extraction of hazardous and high-value materials will have minimised the negative impacts of disposal.

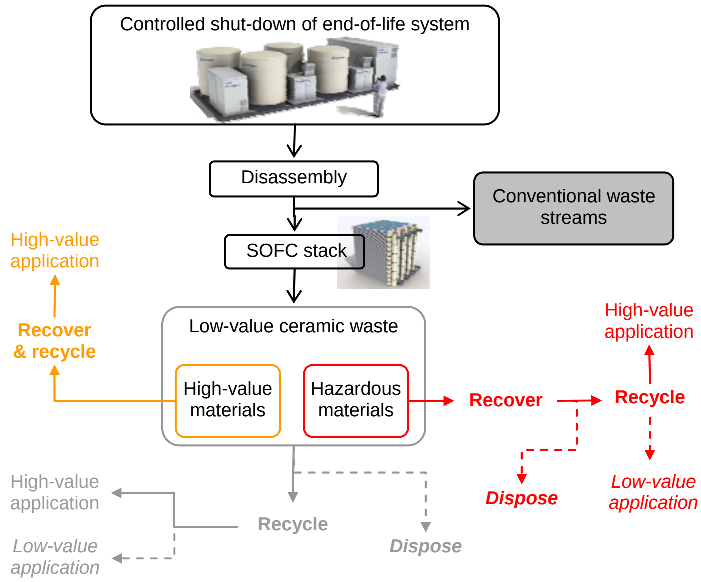

Figure 3: Proposed strategy for end-of-life management of SOFC system. Dashed lines and italic text indicate the least-preferred route.

The feasibility of pursuing this approach has been explored by investigating existing waste-management capability from other product sectors.

Recovery of hazardous and valuable metals from end-of-life catalysts

Ceramic-supported catalysts are used in a range of applications and present an end-of-life waste stream with similarities to that arising from EoL SOFC stacks. Of particular interest with respect to the current work are catalysts which incorporate valuable metals or nickel/nickel oxide as the active material. These find application in the automotive and petrochemical industries [13-16]. The environmental implications of disposing of nickel oxide catalysts to landfill have prompted the development of a recovery process for nickel oxide [13]. The process is based on the reaction of nickel oxide with sulphuric acid to form nickel sulphate. A maximum recovery rate of 99% was achieved under optimised conditions. Nickel sulphate is a useful feedstock for the electroplating industry, providing an opportunity for recycling in a high-value application.

The recovery of valuable metals from EoL catalyst waste is driven by economic return and increasing demand for raw materials [15-17]. Recovery is often carried out using traditional metallurgical routes similar to the smelting process required for extraction of virgin metals from ore. Recent research has investigated alternatives to the recovery of valuable metals, including chemical leaching followed by ion-exchange and pyrolysis [15] and the use of microbiological processes [16].

Metal extraction from electrical and electronic equipment

Recovery of metals from electrical and electronic equipment is an area of growth, especially given recent legislative developments setting mandatory recycling targets for the industry [5]. In addition to traditional thermal and metallurgical methods, initial materials separation is carried out by mechanical means. EoL waste is shredded: from the residue ferrous metals are recovered using magnetic separation, and eddy current separation is used to recover non-ferrous metals. These techniques are dependent on discrete particles containing high concentrations of metals and eddy current separation methods do not work when non-separable materials encase separable materials [18].

Recycling of ceramics

The high energy requirements associated with ceramic processing and the inherent low material value do not encourage recycling of this waste stream. Some success has been reported in closed-loop recycling of refractory ceramics [19] in response to the environmental concerns of resource depletion and disposal to landfill. With regard to the recycling of the bulk ceramic waste stream from end-of-life SOFC stacks it is unlikely that a closed-loop solution would be easily developed. The high temperature environments required during cell fabrication promote the migration of chemical species and the presence of contaminants, even in trace amounts, will lead to performance degradation [20]. It is likely that the economic and environmental costs of obtaining a high-purity recycled material would outweigh any benefits gained in waste management. Recycling ceramics in down-graded applications removes the requirements for extensive processing. The construction industry is a potential user of recovered ceramic waste and the use of fired pottery ware in brick manufacture has been reported [21]. Ceramic is also a potential replacement for aggregate in the manufacture of concrete. One study reports the successful use of waste from the electrical insulator industry in this application [22].

Conclusions and further work

A methodology has been presented for the development of a proactive approach to the development of an EoL management strategy for products based on novel technologies. It has been proposed that the initial approach must be reactive in response to early product/prototype design. The reactive approach attempts to provide a suitable EoL management solution by exploiting existing capability from the waste management of other product types. The body-of-knowledge generated through the development of this reactive solution provides direction for future design improvement activities.

This methodology is being applied to the development of an EoL strategy for SOFC stacks. The EoL problem based on early SOFC stack design has been identified and some of the materials-related issues have been related to existing EoL product streams including catalysts, electrical and electronic equipment and ceramics. Many techniques exist for the recovery of hazardous and valuable materials from existing EoL wastes. These need to be explored in further depth and their application to SOFC stacks investigated. Some experimental work is required to evaluate the efficiency of material recovery when these processes are applied to a novel product-type. With regard to the recycling of the bulk ceramic waste stream, it is unlikely that a closed-loop solution would be easily developed; therefore the reuse of this material in lower-grade applications should be explored. Further investigative activity should explore the recovery of the more unusual medium-value SOFC materials, including those used in the cathode and current collectors.

These initial findings provide direction for future research, which should include more detailed analysis of how existing materials separation processes might be applied to existing SOFC stack designs. This analysis will lead to an appreciation of the limitations of existing waste management capability in processing this novel waste stream. An understanding of the limitations and challenges will direct the development of a proactive approach to EoL management of SOFC stacks.

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References

[1] Minh N. Q., "Solid oxide fuel cell technology – features and applications", *Solid State Ionics*, **174**, 271-277, 2004

[2] Bauen A. and Hart D., "Assessment of the environmental benefits of transport and stationary fuel cells", *Journal of Power Sources*, **86**, 482-492, 2000

[3] Crawley G., "Solid oxide fuel cells – Technology article", *Fuel Cell Today*, January 2007, accessed online at http://www.fuelcelltoday.com on 13th April 2007

[4] European Parliament and Council, "Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles", *Official Journal of the European Union*, **269** (34), 21st October 2000

[5] European Parliament and Council, "Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE)", *Official Journal of the European Union*, **37** (24), 13th February 2003

[6] Baratto F., Diwekar U. M. and Manca D., "Impacts assessment and trade-offs of fuel cell-based auxiliary power units. Part II: Environmental and health impacts, LCA, and multi-objective optimization", *Journal of Power Sources*, **139**, 214-222, 2005

[7] Handley C., Brandon N. P. and van der Vorst R., "Impact of the European Union vehicle waste directive on end-of-life options for polymer electrolyte fuel cells", *Journal of Power Sources*, **106**, 344-352, 2002

[8] Zapp P., "Environmental analysis of solid oxide fuel cells", *Journal of Power Sources*, **61**, 259-262, 1996

[9] Karakoussis V., Brandon N. P., Leach M. and van der Vorst R., "The environmental impact of manufacturing tubular and planar solid oxide fuel cells", *Journal of Power Sources*, **101**, 10-26, 2001

[10] United Nations Conference on Environment and Development, Agenda 21, Chapter 21, Rio de Janeiro, Brazil, June 3-14, 1992

[11] Kendall K., "Progress in solid oxide fuel cell materials", *International Materials Reviews*, **50** (5), 257-264, 2005

[12] Agnew G., Moritz R., Berns C., Spangler A., Tarnowski O. and Bozzolo M., "A unique solution to low cost SOFC hybrid power plant", *Proceedings of ASME Turbo Expo 2003 Power for Land, Sea, and Air*, GT2003-38944, Atlanta, Georgia, USA, June 16-19, 2003

[13] Al-Mansi N.M. and Abdel Monem N.M., "Recovery of nickel oxide from spent catalyst", *Waste Management*, **22**, 85-90, 2002

[14] Furimsky E., "Spent refinery catalysts: environment, safety and utilization", *Catalysis Today*, **30**, 223-286, 1996

[15] Shams K. and Goodarzi F., "Improved and selective platinum recovery from spent α-alumina supported catalysts using pretreated anionic exchange resin", *Journal of Hazardous Materials*, **B131**, 229-237, 2006

[16] Chassary P., Vincent T., Marcano J.S., Macaskie L.E. and Guibal E., "Palladium and platinum recovery from bicomponent mixtures using chitosan derivatives", *Hydrometallurgy*, **76**, 131-147, 2005

[17] Hageluken C., "Platinum Group Metals, the power to improve lives", *The Newsletter of the International Platinum Association*, May 2005, 1-3, 2005

[18] Kang H.Y. and Schoenung J.M., "Electronic waste recycling: A review of U.S. infrastructure and technology options", *Resources, Conservation and Recycling*, **45**, 368-400, 2005

[19] Othman A.G.M. and Nour W.M.N., "Recycling of spent magnesite and ZAS bricks for the production of new basic refractories", *Ceramics International*, **31**, 1053-1059, 2005

[20] Mogensen M., Jensen K.V., Jørgensen M.J. and Primdahl S., "Progress in understanding SOFC electrodes", *Solid State Ionics*, **150**, 123-129, 2002

[21] Smith A.S., "Waste/secondary raw material usage opportunities in the UK brick industry", CERAM Building Technology, 2005

[22] Senthamarai R.M. and Devadas Manoharan P., "Concrete with ceramic waste aggregate", *Cement & Concrete Composites*, **27**, 910-913, 2005

APPENDIX C

IMPACTS OF ENVIRONMENTAL PRODUCT LEGISLATION ON SOLID OXIDE FUEL CELLS

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Impacts of environmental product legislation on solid oxide fuel cells

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ABSTRACT

Ongoing development of solid oxide fuel cell (SOFC) technology coincides with a rapid increase in legislation aiming to control the environmental impacts of products across their life cycle. A risk-based method is used to explore the potential future impacts of this body of legislation on the technology. Legislation controlling the use of hazardous materials is one area of significance. Under the new European REACH Regulation some nickel compounds, used widely throughout general industry but also in the fabrication of anode structures, may fall under the classification of a substance of very high concern (SVHC) in future, which presents a risk of restrictions being placed on their continued use. This risk must drive the development of alternative anode materials, or requires the SOFC industry to identify a socio-economic argument justifying exemption from any future restrictions. A legislative trend establishing recycling requirements for end-of-life products is also identified as having a potential future impact on the technology. Recycling strategies for SOFC products must be considered, prior to commercialisation. It is proposed that failure to meet these future environmental requirements may be detrimental to the perception of SOFC technology, the demand for which is substantially driven by the environmental benefits offered over incumbent power generation technologies. The consideration of these issues in the design of commercial products will mitigate this risk.

1. Introduction

The past decade has seen the rapid increase of legislation addressing the environmental impacts of products. In Europe, the Integrated Product Policy identifies the opportunities for reducing human impact on the environment through direct targeting of product life cycles [1]. At the early stages of the product life cycle, manufacturers are increasingly constrained in their selection of materials by legislation aiming to reduce the use of substances which have potential to detrimentally impact the health of humans and/or the wider environment [2,3]. At the other end of the product life cycle the concept of Extended Producer Responsibility attempts to extend the responsibility of the manufacturer beyond the factory to include the management of wastes arising from end-of-life products [4,5].

Against this background, the development of fuel cell technology continues. Fuel cells have long been hailed as a clean and efficient means of electricity generation; however, general availability of the technology in a commercial market has yet to be realised. In particular, the development of solid oxide fuel cell (SOFC) technology for application in stationary power generation is being pursued towards commercialisation by a number of global players [6–8]. While the environmental benefits of the technology during operation are particularly attractive with current climate change concerns, it must be expected that these will lead future customers to scrutinise and demand environmental excellence across all aspects of the technology life cycle. An ability to demonstrate compliance, as a minimum standard, is essential for successful market entry. In order to ensure that compliance is achieved, current and future legislative requirements must be considered within the design process.

The principal aim of this research is to develop an awareness of some of the issues which SOFC developers are likely to face as this area of legislation continues to evolve, and thus to highlight opportunities for addressing these issues during continuing design development, prior to commercialisation. Sections 2 and 3 of the paper provide information regarding the two main subject areas behind the research; namely SOFC technology and environmental legislation. In Section 2, the SOFC stack, the SOFC system and the power and controls system are defined as representing the three principal technologies employed in stationary power generation systems, while in Section 3 specific developments in environmental legislation are described. In Section 4 the risk-based method used to evaluate the impacts of legislation on the technology is presented, and this method is applied and the findings discussed

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in Section 5. The principal conclusions drawn from this discussion are summarised in the final section of the paper.

2. Solid oxide fuel cells for stationary power generation

Solid oxide fuel cell technology offers an alternative means of electricity generation. The ceramic electrolytes used in SOFCs require an operating temperature of between 600 °C and 950 °C to maximise efficiencies. The technology is well suited to applications in stationary power generation, and offers opportunities for cost-effective internal reforming over a range of readily available hydrocarbon fuels. In addition, the operating temperature results in the production of high-quality waste heat, making the technology suitable for combined heat and power generation and for incorporation into a hybrid system with conventional gas turbine technology. Examples of commercial developments are described by Rolls-Royce [6], Siemens-Westinghouse [7] and Mitsubishi Heavy Industries [8].

2.1. Definition of sub-assemblies

SOFC products under development for stationary power generation applications are complex systems incorporating several technology types. Given that different technology types are impacted differently by environmental legislation, the principal components within a stationary SOFC plant have been classified into three high-level sub-assemblies. These sub-assemblies are the SOFC stack, the SOFC system and the power and controls system. This expands on previous studies where the SOFC system and the power and controls system are grouped together as the "Balance of Plant" [9]. For the purposes of the current work this distinction was made to allow the relevance of legislation specifically targeted at electrical and electronic equipment to be clearly evaluated. Each of the sub-assemblies is defined in the following sections.

2.1.1. SOFC stack

The SOFC stack is the heart of any SOFC plant, and consists of an assembly of individual fuel cells, in which a hydrogen-rich gas undergoes electrochemical reaction with oxygen to yield electrical power. Although a variety of SOFC stack designs exist [10], the general characteristics are similar. The fuel cell consists of a multilayer assembly of functional materials, supported on a substrate. The substrate is fabricated from one of the functional materials, from an electrically conducting interconnect material [11] or from ceramic [12]. In addition to the substrate material, the SOFC stack is comprised principally of functional ceramics and other metal/rare-earth oxides [13,14]. An overview of the most commonly used SOFC stack materials is provided in Table 1.

2.1.2. SOFC system

The SOFC system incorporates the fuel processing assemblies and pipe-work infrastructure required for supply of fuel and air to the SOFC stack, as well as heat exchangers, insulation and external casing. In addition this sub-assembly incorporates pressure vessels required for pressurised systems and gas turbine machinery utilised in hybrid systems. Operating environments range from room temperature (for external components) to the high temperatures required for good SOFC stack performance. Components can be regarded in general as employing conventional technology used in other power generation systems. The principal material groups are ceramics (silica- or alumina-based insulating materials) and metal alloys (ranging from standard steels to specialised high-temperature alloys) [9].

Table 1
Common SOFC materials.

Component	Material	Hazardous waste threshold*
Electrolyte	Yttria-stabilized zirconia	N/A
Anode	Nickel	>1 wt%
	Nickel oxide**	>0.1 wt%
Cathode	Strontium-doped lanthanum manganite	>20 wt%
Interconnect	Doped lanthanum chromate	>20 wt%
	Inert metals/alloys	N/A
Sealant	Glass/glass-ceramic	N/A
Substrate	Ceramic	N/A

* As defined by the European Waste Catalogue. If materials are present in compositions greater than this threshold value, the entire waste stream is classified as hazardous.

** Under operating conditions, all nickel in the anode will be present in metallic form. Nickel oxide will be present only during the initial fabrication of the anode, until exposed to a fuel environment. A controlled shut-down of end-of-life systems will prevent the oxide re-forming.

2.1.3. Power and controls system

The power and controls system contains all the electrical and electronic assemblies required to convert the electrical output from the fuel cell stack into a suitable input for local or national grid connection. Control and safety systems are also included in this sub-assembly. Components can be regarded as employing conventional electrical and electronic technology and materials.

2.2. Environmental characteristics of SOFC technology

Stationary power generation systems based on SOFC technology are characterised by efficient fuel utilisation, reduced emissions of carbon dioxide and other greenhouse gases, and virtual elimination of other polluting emissions, such as oxides of nitrogen and sulphur. These advantageous characteristics stem from the electrochemical nature of the devices, which eliminates both the energy losses associated with intermediate thermal and mechanical energy conversion steps and the formation of undesirable combustion products common to many conventional power generation technologies.

These benefits are widely accepted and continue to drive the development of commercially viable products. Several detailed reviews of the technology are available [10,13,15,16]. Published environmental assessments of the operation of SOFC systems and comparisons with conventional power generation can also be read [9,17,18].

3. Developments in environmental legislation

Tukker [19] describes an observable shift in the emphasis of environmental legislation across the second half of the twentieth century. Historically the emphasis was directed towards controlling the impacts of high profile, large-scale processes and point-sources of pollution. More recently, and in reaction to increased consumerism, the emphasis of legislation has moved to control the less obvious and dispersed environmental impacts of products.

Every manufactured item contributes to detrimental human impact on the environment. In a typical product life cycle (Fig. 1), impacts arise at each stage; for examples, depletion of natural resources during materials production; waste generation during the manufacturing process; energy or fuel consumption during operation; and, leaching of hazardous substances after disposal. In 2001 the European Commission published a Green Paper on Integrated Product Policy (IPP) [1], recognising that environmental impacts from products are dispersed across the product life cycle, and cannot be effectively addressed by focusing regulatory

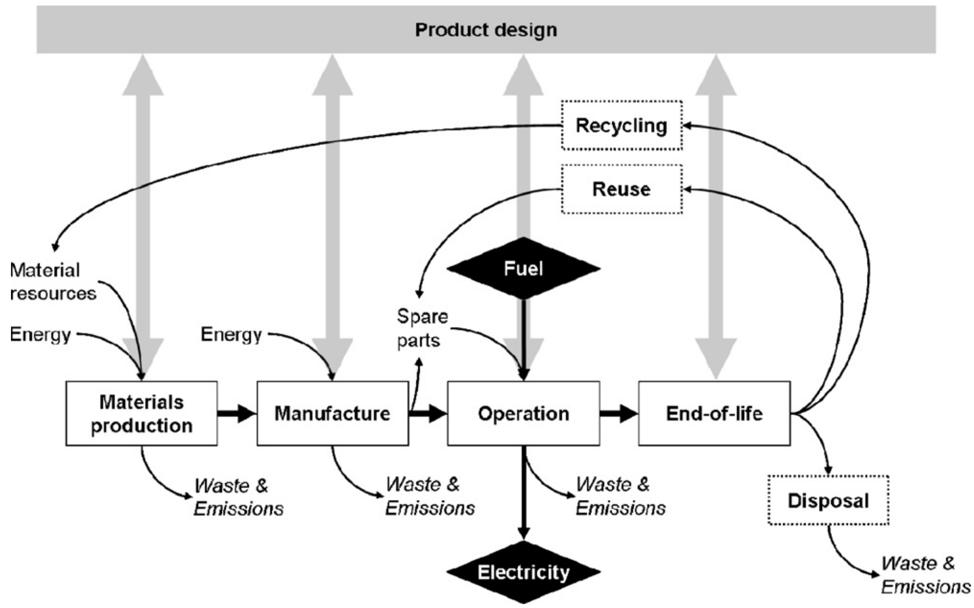

Fig. 1. A generic product life cycle for an electricity-generating product. All stages of the product life cycle are influenced by and can influence product design.

requirements on processes alone. Although IPP identifies a need for a multi-pronged approach towards tackling life cycle issues, including voluntary market-driven schemes such as environmental product declarations, mandatory measures in the form of legislation also form part of the strategy for implementation. Much of the legislation explored in the current research has its roots in the IPP concept.

3.1. Geographical considerations

The power generation market, and hence the future market for SOFC power generation systems, is global in nature. Efforts to develop the technology are ongoing in Europe, North America and Asia. When developing a product with global market opportunities, it is important to recognise the different legislative standards required in different regions. Unless a clear strategy exists in which the product is to be sold only into a specific market, then it is prudent to design products which match the most stringent global requirements. This approach reduces the risk of products being excluded from certain markets on the grounds of non-compliance, and also pre-empts inevitable legislative "catch-up", where regions with slower or less innovative legislative processes follow the routes determined by more pro-active regions. Efforts to comply with the most advanced legislative requirements also demonstrate a commitment to best practice.

Following a brief survey of trends in global product-centred environmental legislation it was decided to narrow the scope of the current research to European legislation only. This decision was made on the basis that Europe appears to be the global leader in the development of this body of legislation, when compared to Asia and North America.

Japan was identified as being the major legislative influence in Asia, and has long-embraced concepts such as waste reduction and sustainable use of resources [20]. However, these concepts were found to be emphasised in policy documents but not translated clearly into regulatory requirements. No evidence was found that the legislation controlling the life cycle impacts of products was further advanced than in Europe. In addition, European legislation such as the Restriction of Hazardous Substances Directive [3] has prompted the development of similar regulations in China and other Asian countries [21,22].

The USA was perceived as leading the development of legislation on the American continent, with California pioneering environmental legislation at state level. However, with respect to product-focused legislation, few developments appear to have emerged at federal level [23]. At state level no evidence was found to indicate that this type of legislation was more advanced than in Europe, with initiatives from business appearing to be at least as significant as any regulatory controls [24].

3.2. Developments in environmental legislation in Europe

In Europe, recent developments in legislation have brought many aspects of the product life cycle under legislative control. Various aspects of the use phase of stationary SOFC systems are expected to be regulated by specific legislation controlling emissions, noise and interaction with existing fuel and electricity infrastructures. These legislative aspects have not been explored in the current research: it is assumed that they are so fundamental to the product performance that known requirements will already form the basis for design targets in SOFC development. It is also expected that any new developments in legislation specifically targeting the installation and operation of SOFC technology will be developed with direct consultation with SOFC developers. The current research identifies legislation relevant to the wider life cycle, the relevance of which may not have been widely recognised within the SOFC sector. In this research legislation has been classified as targeting materials selection and design of products, and end-of-life or waste management. Specific pieces of legislation identified as being most relevant to the current research are described below. A web-based reference has been provided for each, which can be followed for further information and to review the most recent developments.

3.2.1. Legislation targeting materials selection and design

Two principal legislative developments were identified as being of relevance to the early part of the product life cycle, since they control the selection of materials from which products are manufactured. These are the REACH Regulation [2], which deals with the Registration, Evaluation and Authorisation of Chemicals and the Restriction of Hazardous Substances Directive [3], which applies specifically to electrical and electronic equipment. In addition the Eco-design of Energy using Products Directive [25] was identified as being more generally relevant to product design.

3.2.1.1. REACH Regulation. The REACH Regulation was adopted in December 2006 and entered into force in June 2007. The principal requirements are that all chemical substances manufactured or imported in Europe must be registered with a central European Chemicals Bureau. Registered substances are evaluated based on hazards to human health and the environment, and in the case of those posing a significant risk the continued use of that substance may be prohibited, or limited to authorised applications. Implementation of the regulation is being phased in from June 2007 to May 2018, with priority given to the registration of substances with existing hazard classifications and high market volumes. Further details and updates with regard to implementation can be found at the European Commission's website [26].

3.2.1.2. Restriction of Hazardous Substances Directive. The Restriction of Hazardous Substances (RoHS) Directive identifies specific high risk substances and, from July 2006 has restricted their use in defined categories of electrical and electronic equipment. The scope of the RoHS Directive is closely linked with the Waste Electrical and Electronic Equipment (WEEE) Directive [4], and together these two legislative measures aim to reduce the hazards of a specific end-of-life waste stream through pro-active (materials selection) and reactive (waste management) measures. Further details and updates with regard to implementation can be found at the European Commission's website [27].

3.2.1.3. Eco-design of Energy using Products Directive. The Eco-design of Energy using Products (EuP) Directive was adopted in July 2005 and establishes a framework for implementing eco-design principles, with particular respect to products which consume energy during their operation. The Directive establishes no direct requirements, but identifies aspects which may be required to be communicated to customers and other stakeholders relating to a product's environmental performance across its entire life cycle. The Directive places emphasis on high volume consumer products. Further details and updates with regard to implementation can be found at the European Commission's website [28].

3.2.2. Legislation targeting the end-of-life management of products

The end-of-life management of products is targeted specifically by legislation encompassing the principle of Extended Producer Responsibility (EPR), and also by more conventional waste management legislation. The Waste Electrical and Electronic Equipment (WEEE) Directive [4] was identified as being the most relevant piece of legislation encompassing the EPR principle, although other legislative measures with less direct relevance were also considered. The conventional field of waste management legislation is extensive [29] covering all aspects from storage and transportation of waste to the operation of treatment facilities. The current research considers waste management legislation with specific relevance to the end-of-life phase of the SOFC product life cycle. As such, the Landfill Directive [30] and the Hazardous Waste Directive [31] were identified as being most significant.

3.2.2.1. Waste Electrical and Electronic Equipment Directive. The WEEE Directive establishes mandatory recycling and recovery targets for specific categories of domestic and industrial electrical and electronic equipment, and places the responsibility on equipment manufacturers to demonstrate compliance. The targets established by the Directive range from 50% to 80% recycling of components and materials by weight, and from 70% to 80% recovery, which includes material burnt for energy generation purposes. These requirements have been in force since December 2006. Further details and updates with regard to implementation can be found at the European Commission's website [27].

3.2.2.2. Other Extended Producer Responsibility legislation. Other end-of-life waste streams subject to legislation implementing the EPR concept include cars, batteries and packaging. Similar to the WEEE Directive, the End-of-life Vehicles Directive [5,32] establishes a requirement to recycle 80% by weight of the material in a scrapped car. The Batteries and Accumulators Directive [33,34] defines appropriate disposal routes for different types of batteries, again placing a significant emphasis on recycling targets. Packaging is another waste stream which has been targeted under Extended Producer Responsibility legislation [35,36].

3.2.2.3. Landfill Directive. The Landfill Directive entered into force in July 1999 and has established restrictions and controls over waste disposal to landfill since July 2001. The emphasis of the legislation is on reducing the volumes of waste disposed of, with no recovery of material or energy resources, and on reducing the hazards likely to result from landfill sites, such as leaching of hazardous materials into the local environment. Further details and updates with regard to implementation can be found at the European Commission's website [37].

3.2.2.4. Hazardous Waste Directive. The Hazardous Waste Directive, with other supporting legislation, identifies wastes which are perceived as having hazardous properties, which include those which are likely to harm human health and/or the environment. The Directive establishes additional requirements on the management of such wastes, controlling storage, labelling, transportation and treatment. Further details and updates with regard to implementation can be found at the European Commission's website [38].

4. A risk-based method for evaluating future legislative impacts

SOFC technology has not yet reached commercial maturity and therefore is not yet the target of specific legislation in the same way that other product-types, such as vehicles and electrical consumer goods, have become. In addition, much of the legislation considered in the current research encompasses relatively new concepts, such as Extended Producer Responsibility. These new concepts are likely to be rolled out across other product sectors in time, if the current legislation proves to be a successful approach.

Therefore the evaluation of the impacts of the legislation on SOFC technology must consider a future scenario where both the legislative and the technological landscapes have evolved beyond today's situation. For this reason, a risk-based method was identified as the most appropriate means of evaluating future impacts.

4.1. Impact evaluation in four steps

The risk-based method employed in the current research is shown in Fig. 2. The method follows four steps, in line with a conventional risk assessment methodology.

The first step requires identification of potential impacts (i). This requires knowledge of both the SOFC product and the body of legislation. Impacts are likely to be indicated by conflicts between current SOFC design parameters and specific requirements within the legislation.

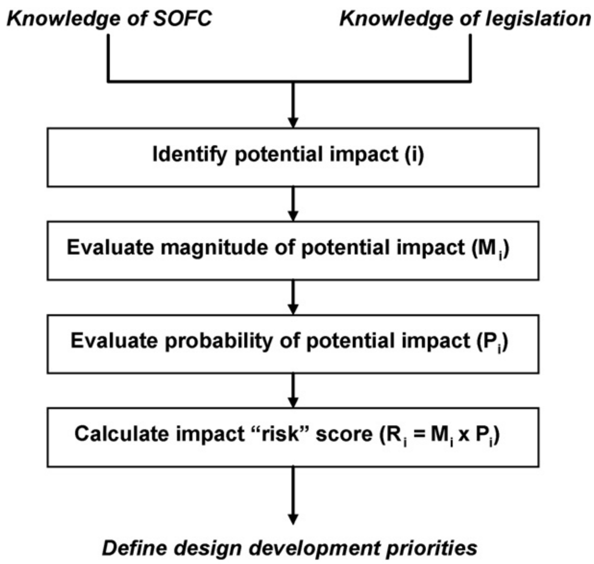

Fig. 2. The risk-based method developed to evaluate future impacts of legislation on SOFC technology. Required inputs to the process are knowledge of the SOFC product and knowledge of the relevant legislation. The process results in output which can be used to define design priorities.

Table 2
Definition of scoring system for impact magnitude.

Score	Magnitude (M_i)
1	Will have minimal impact on SOFC technology. Solutions are already available for implementation or can be developed with no significant impact on technology adoption.
2	Will impact on SOFC technology. May result in setback for technology adoption, but a feasible solution should be achievable with some development effort.
3	Will have severe impact on SOFC technology requiring significant development efforts of unknown feasibility. May result in serious setbacks for widespread technology adoption.

The second step requires the magnitude of the impact (M_i) to be evaluated. In this case, the magnitude is related to technology adoption, and Table 2 provides definitions for each available score.

In the third step, the probability of the impact occurring (P_i) is evaluated. This is related to how the technology and the legislation are expected to develop with time. The score definition used for this parameter is presented in Table 3.

Finally, the overall impact score (R_i) is calculated as a product of M_i and P_i. This parameter would be the risk score in a traditional risk assessment process. A high impact score indicates that the impact poses a significant risk to the success of SOFC technology. All impacts identified using this method should be considered during ongoing design development prior to commercialisation. Quantification of scores for each impact allows priority to be given to high risk areas, thus directing design efforts.

Table 3
Definition of scoring system for impact probability.

Score	Probability (P_i)
1	Low probability—general trend suggests potential future impact in >25 years.
2	Moderate probability—current or developing legislation is likely to impact within 5–25 years.
3	High probability—legislation currently impacts or is expected to impact in <5 years.

4.2. Application of the risk-based method to evaluate future impacts of legislation

The risk-based method was used to evaluate future impacts of product-centred legislation on SOFC technology. A systematic approach was followed, evaluating the impact of each piece of legislation, outlined in Section 3.2, against each sub-assembly, defined in Section 2.1. Fig. 3 provides an overview of the evaluation matrix. Shaded areas indicate that the legislation was perceived to impact the sub-assembly. All legislation impacting an individual sub-assembly impacts the SOFC product by default. Only the Energy using Products Directive was identified as impacting the overall product assembly with no additional specific impacts associated with individual sub-assemblies.

The results from the application of the risk-based evaluation method are presented in Tables 4–7. Results are presented separately for each sub-assembly of a SOFC-based stationary power generator unit; namely the SOFC stack, the SOFC system and the SOFC power and controls; and for the complete stationary SOFC system package, respectively. Results are presented as risk scores for each piece of relevant legislation. The magnitude of the impact presented by the legislation has been evaluated, and awarded a numerical score as defined in Table 2. A short justification for this score is provided in the table of results. Similarly, the probability of each impact arising has been evaluated according to the scale presented in Table 3, and justified. The magnitude and probability scores have been used to calculate the overall risk score.

The results presented in Tables 4–7 are discussed in Sections 4.2.1–4.2.4.

4.2.1. Impacts of environmental legislation on the SOFC stack

Table 4 summarises the impacts identified for the SOFC stack arising from REACH and waste legislation.

4.2.1.1. REACH Regulation. REACH is a complex and broad-ranging piece of legislation, impacting many areas of the manufacture, supply and use of all chemical substances. The first area of risk identified for the SOFC stack is future restriction on the use of hazardous materials. Under REACH the continued use of all substances is subject to the approval of the European Chemicals Agency, following a registration stage. Substances which pose significant hazards to human health and/or the environment will be subject to authorisation. This means that the ongoing use of these substances may be restricted to specific applications, and, in the worst cases, prohibited. Nickel oxide which is typically used in the fabrication of anode structures, has been classified under REACH as a substance of high concern (SVHC), with the potential that it may be subject to authorisation and, in the worst instance its use may be prohibited.

The inability to use nickel oxide could have a potentially significant effect on the SOFC industry. Although several other materials suitable for application in the SOFC anode are under development no single alternative has been adopted by the industry. While future anode materials may provide optimised performance, the timeframe for commercial availability could be considerable. Nickel oxide has the advantage of being a readily available material, used in a number of high volume industries. Thus the supply chain is well established.

The probability of restrictions being implemented on nickel oxide is uncertain. REACH is in its very early stages and, as a substantial and controversial piece of legislation, its implementation is very much uncertain. In any case, the impacts of the legislation are not likely to be felt by industry for a number of years. REACH has made provision for substances which, although hazardous in themselves, provide over-riding benefits in their application. Socio-economic analysis can be used as evidence to persuade regulators to authorise continued use of a substance. It is likely that, given the

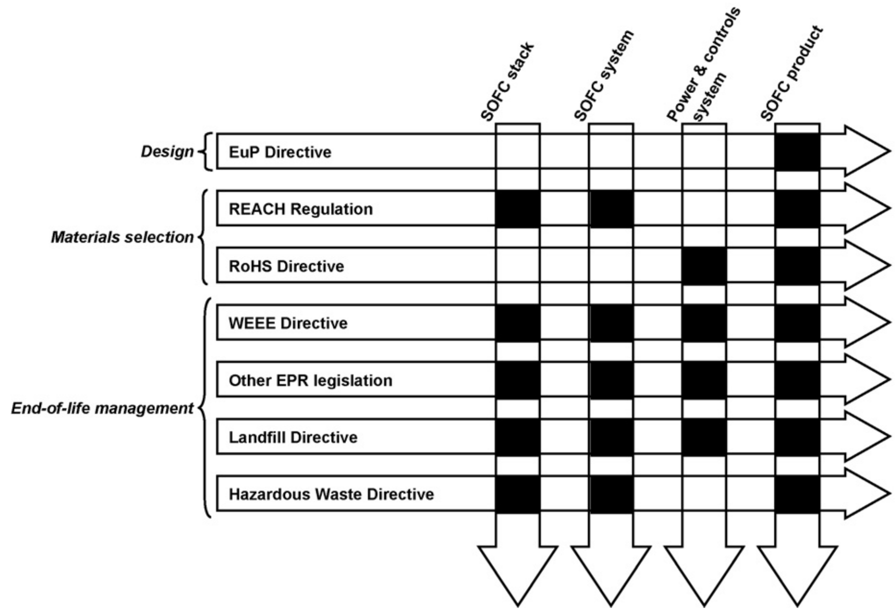

Fig. 3. A summary matrix indicating the scope of the research. Shading indicates that a specific legislative measure was found to impact upon a specific sub-assembly of the SOFC product.

potential benefits offered by SOFC technology, justification for the continued use of nickel oxide could be established.

The second way in which REACH may impact the SOFC stack is by adversely affecting the supply chain. REACH introduces an additional administrative burden on the supply chain, where registration of all manufactured and important chemical substances is required. The costs of registration are to be met by the payment of fees by the manufacturer or importer. This risk is associated most closely with materials utilised exclusively in SOFC applications. Examples would be the perovskite materials commonly used in cathode components. It is anticipated that where these are supplied by SMEs, the financial burden may be prohibitive for continued supply. In SMEs and larger companies, product portfolios are likely to be stream-lined to minimise costs of registration. Given that SOFC technology is not currently a significant market sector with large demand and reward, these SOFC-specific materials may be candidates for portfolio exclusion.

Although the magnitude of the impact of discontinued materials supply was identified as being high, the probability of the situation was determined to be low. Suppliers of specialised materials tend to have close relationships with their customers, since mutual dependence is generally clear to both parties. In situations where the company developing SOFC technology has substantially greater economic power than the material supplier, it would be in its interest to support the financial requirements imposed by REACH. Smaller SOFC developers are less likely to be able to support the supply chain, however, providing that several major players remain in the field the small SOFC developers will be able to reap the benefits of their intervention.

The final aspect of REACH which has potential to impact the development of SOFC stack technology is the increased administrative burden being transferred into material costs. Cost reduction is one of the significant challenges faced by SOFC developers, and therefore any unexpected increase in raw material costs will increase the extent of the challenge. It is, however, recognised that increased material costs of this origin are unlikely to be significant compared with the overall requirements for cost reduction. Real breakthroughs in cost reduction require manufacturing solutions, especially for high volume production, and may potentially involve the substitution of high value materials with cheaper alternatives. Various cost breakdown studies for SOFC stacks explore the relationship between material and manufacturing costs and show the relative contribution to unit cost as being dependent on specific aspects of stack design and production assumptions [39].

4.2.1.2. Waste legislation. Waste legislation was the second area identified as having specific relevance to the SOFC stack assemblies. Management of end-of-life stack assemblies is a challenge yet to be encountered at any great scale in the SOFC industry. Although components manufactured for research and development purposes have been produced for several decades, the volumes involved are comparatively low and most components will be retained for future analysis or other scientific purposes. To date, the disposal of stack components has therefore not been a high priority issue for SOFC developers.

On the other hand, measures for responsible management of waste must be in place before SOFC technology becomes widely adopted in the commercial energy market. Legislation has been identified as being relevant in two principal areas: in the first instance in the classification of hazardous waste, and in the second instance in controlling how waste is treated.

Waste arising from the SOFC stack has the potential to be classified as hazardous. Waste classifications arise from the content of hazardous substances present in a given waste stream. The state-of-the-art anode material for SOFCs is nickel. Nickel metal is permitted in waste in concentrations up to 1 wt% before the entire stream is classified as hazardous. SOFC anodes are typically fabricated from nickel oxide, exposure to fuel gas results in reduction to nickel metal. Nickel oxide, if entering a waste stream, has the potential for classifying it as hazardous in concentrations of 0.1 wt% or greater. The classification of waste arising from SOFC stack assemblies is therefore heavily dependent on the stack design, which defines the content of anode material, as well as the environmental history. Alternative anode materials may also possess hazardous properties, although the current work has not fully explored these alternatives. With regard to the other state-of-the-art SOFC stack materials (Table 1), the hazard classifications do not present a significant risk of this waste stream being classified as hazardous.

Table 4
Impacts of legislation on the SOFC stack, evaluated using a risk-based method.

Legislation	Identified impact (i)	Magnitude (M_i)		Probability (P_i)		Risk (R_i)
REACH Regulation	Use of hazardous substances is prevented.	2	NiO is the state-of-the-art anode material, and classified under REACH as SVHC*. Activity to develop alternative materials is ongoing but the technology would be significantly impacted by prevented use of NiO.	2	REACH is already in force, but is a complex regulation, so details of implementation remain uncertain. Timescale for implementation is 0–15 years. Continued use of some SVHCs may be justifiable.	4
	Supply of low volume specialty materials is discontinued.	3	Several state-of-the-art SOFC materials (esp. cathode materials) are specific to the technology and manufactured at low volume by SME suppliers. An inability to source the required materials would be prohibitive to commercial-scale production.	1	If the supply chain is unable to sustain continued supply, investment from fuel cell developers should be able to support the requirements of REACH.	3
	Cost of materials increases to a prohibitive level.	2	Cost is one barrier to commercialisation of the technology. Increased material costs may result in failure to achieve cost targets.	1	Any incremental increase in material cost arising from REACH is likely to be small relative to existing material and manufacturing costs.	2
Hazardous Waste Directive	End-of-life SOFC stack assemblies are classified as “hazardous waste”.	1	Classification of end-of-life assemblies as “hazardous waste” will have little impact in its own right. Handling and treatment of hazardous waste may incur higher charges, but unlikely to be significant compared to technology costs.	2	By existing legislation, classification is most likely to arise from nickel oxide content, but is dependent on stack design, composition and whether nickel is in oxide form at end-of-life. Should anticipate future legislation as being increasingly strict.	2
Landfill Directive	End-of-life SOFC stack requires pre-treatment prior to disposal.	1	Requires process development for pre-treatment prior to disposal OR process development for an alternative end-of-life solution. Pre-treatment requirements may be fairly minimal.	3	Requirement would be in force if disposal was attempted today.	3
	Disposal of end-of-life SOFC stack assemblies to landfill is prohibited.	2	Requires process development for an alternative end-of-life solution, requiring substantial recycling/recovery activities to allow material to be diverted from landfill.	2	The goal of zero landfill is widely accepted but legislation likely to demand progressive reduction. Also customer perception of environmental benefits of SOFC technology makes disposal to landfill unfeasible.	4

* Substance of very high concern.

The impact of waste from SOFC stack assemblies being classified as hazardous is perceived to be small. Handling, treatment and disposal fees may introduce additional cost into the assembly life cycle, although it is assumed that compared to the material and fabrication costs these will be small. Restrictions on shipments of wastes between countries may also be experienced [40], directing those handling waste to use local waste management capability. Perhaps more important is the public perception of fuel cell technology. It could be argued that the generation of hazardous waste would be damaging to the environmentally beneficial image promoted by SOFC developers. On the other hand, methodologies such as life cycle assessment should be used to evaluate the detrimental impacts of hazardous waste generation in the context of the complete technology life cycle rather than in isolation.

The second area of waste management legislation identified as having potential impacts on the SOFC stack is the legislation governing landfill activities. Without the development of alternative waste management strategies, disposal to landfill may appear to be the baseline available option. However, within the current legislative framework, some pre-treatment of waste is required prior

Table 5
Impacts of legislation on the SOFC system, evaluated using a risk-based method.

Legislation	Identified impact (i)	Magnitude (M_i)		Probability (P_i)		Risk (R_i)
REACH Regulation	Use of hazardous substances is prevented.	2	Nickel-based alloys required for some high-temperature components. Some alternative materials may be available but chromium alloys have associated technical problems.	1	Nickel in bulk metallic form is not especially hazardous, although re-classification is a possibility. Much larger users of nickel-based alloys (aerospace industry etc) have significant lobbying influence and ability to negotiate continued use.	2

Table 6
Impacts of legislation on the SOFC power and controls, evaluated using a risk-based method.

Legislation	Identified impact (i)	Magnitude (M_i)		Probability (P_i)		Risk (R_i)
RoHS Directive	RoHS-compliant components have reduced reliability.	2	Failure of components may cause reliability issues for the product system.	1	Unlikely to be a significant issue, since good suppliers should be able to solve any reliability problems.	2
WEEE Directive	Fuel cell developers are responsible for recovering/recycling a proportion of power and control components.	1	Recycling infrastructure is developing to support requirements of WEEE. Responsibility will belong in part to the OEM.	2	Not a current issue, since components installed within a SOFC system are excluded from WEEE. Future requirements might arise with extension in scope and/ or technology adoption in non-stationary applications.	2

to disposal to landfill. Article 6 of the Landfill Directive [30] states that, "...only waste that has been subject to treatment is (allowed to be) landfilled." In the same article, the definition of "treatment" is an operation which, "...contribute(s) to the objectives of this Directive...by reducing the quantity of the waste or the hazards to human health or the environment." The extent of pre-treatment required is not explicitly stated, and it would appear that fairly minimal levels of treatment (such as shredding or baling) are acceptable for some existing waste streams. Therefore, it is assumed that a solution for SOFC stack assemblies could be developed prior to the production of large volumes of this waste stream.

From a longer term perspective, the general policy trend indicates a move towards zero landfill, with emphasis being put on a hierarchical approach to waste management in which reduction, reuse and recycling are identified as being priority actions, with landfill being accepted only as a last resort. It is therefore probable that the legislation surrounding landfill will tighten significantly within the next 10 years. An inability to dispose of SOFC stack assemblies to landfill will require SOFC developers to invest in developing alternative waste management solutions, prior to commercialisation. In addition, the public perception of landfill as a disposal solution is contradictory to the "green" image presented by fuel cells.

Other legislation directing alternatives to landfill, such as recycling, are likely to become applicable to the entire product assembly. These are discussed in Section 4.2.4.

4.2.2. Impacts of environmental legislation on the SOFC system

In general the impacts of environmental legislation on the SOFC system have been explored in less detail. Table 5 summarises the risks identified and the scores allocated. The SOFC system incorporates conventional components, such as heat exchangers, pipe work, casing and shelving, and employs commonly used materials. Therefore, it is assumed that, for example, existing waste management processes can be adopted to manage waste arising from SOFC system components in a compliant manner. In comparison to the SOFC stack, less emphasis will fall on the SOFC community to develop bespoke approaches to waste management.

REACH legislation has been identified as having a potential future impact on the SOFC system in a manner similar to the SOFC stack. The principal area of relevance identified in the current work regards the use of high-temperature nickel-based alloys. The operating conditions for high-temperature SOFC systems are such that materials with suitable properties, including durability, are limited. It is possible that, under REACH, re-classification of nickel metal could arise, bringing it onto the list of Substances of Very High Concern. However, given the low risk associated with handling and using nickel in bulk metallic or alloyed form, it appears unlikely that the use of nickel–metal alloys would be heavily restricted. In addition, these materials are used by other large industry sectors, such as aerospace and conventional energy generation. It would be expected that these sectors possess sufficient lobbying influence to negotiate the continued use of nickel in this type of application.

4.2.3. Impacts of environmental legislation on the SOFC power and control system

Electrical and electronic equipment has been the target of recent developments in environmental legislation. Two specific directives have been introduced in Europe which control the use of hazardous substances in these applications, and prescribe recycling targets for equipment at the end of its life. The potential future impacts of these directives on the SOFC power and control systems are outlined below. This discussion is based on the impacts identified and evaluated in Table 6.

4.2.3.1. Restriction of Hazardous Substances Directive. Large SOFC product systems designed for stationary power generation do not fall within the scope of the RoHS Directive, which applies to a defined list of equipment categories. As such, compliance with the Directive is not required, and even the use of compliant components is not necessary. However, it is likely that given the requirement for RoHS-compliance across a wide range of product-types, the demand for compliant components will drive manufacturers of common components to eliminate the use of RoHS substances (namely lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and polybrominated

Table 7
Impacts of legislation on the complete SOFC product, evaluated using a risk-based method.

Legislation	Identified impact (i)	Magnitude (M_i)		Probability (P_i)		Risk (R_i)
EuP Directive	SOFC developers are required to implement and provide evidence of eco-design.	1	Does not necessarily impact technology at all, but may incur cost and bad public image if requirements are not met.	2	Not a current issue, since SOFC system is outside scope. Likely to become a direct requirement in time.	2
EPR legislation	Fuel cell developers are responsible for recovering/recycling a proportion of the complete product.	2	Requires development activity, but should be feasible. Failure to comply would have serious negative impact on the technology's image.	2	Not a current issue, since SOFC system is not covered by scope of existing legislation. Likely to become a direct requirement in time.	4

diphenyl ethers). Therefore the availability of non-compliant components is likely to reduce substantially. Although this may be regarded as a benefit, in that SOFC system developers will have ready access to more environmentally benign components, there are also potentially detrimental effects of this change in the supply chain.

In order to meet the requirements of the RoHS Directive, and national implementing legislation, material substitution will be required. This requires the replacement of tried and trusted materials, most likely selected for their suitability to a given application, with alternatives. Although suppliers will strive to maintain component standards, it is possible that some compromise in performance and/or reliability may result. Any reliability issues within the power and control systems of a SOFC power generation system will have knock-on effects for the reliability of the entire system. While important to recognise this aspect of legislative change, it is not perceived that the probability of significant issues arising is likely to be high.

4.2.3.2. Waste Electrical and Electronic Equipment Directive. The WEEE Directive establishes recycling and recovery targets for electronic waste and its aim is to place responsibility for meeting these targets on the original equipment manufacturers. An increase in the availability of recycling technologies for electrical and electronic components has grown since the introduction of WEEE, and it is anticipated that SOFC developers could utilise existing recycling infrastructure to handle any relevant wastes arising. However, under existing legislation, components installed within large stationary power generation systems are perceived to lie outside the scope of the WEEE Directive. Therefore any requirements to meet specified recycling targets would arise from future developments of this type of legislation.

4.2.4. Future impacts of environmental legislation on stationary SOFC products

As well as the impacts of legislation on individual assemblies within stationary SOFC units, additional impacts have been identified which are more relevant to the complete product. In particular these relate to the design and end-of-life stages of the product life cycle. Table 7 presents the identified impacts along with the allocated risk scores.

4.2.4.1. Energy using Products Directive. The EuP Directive represents a new approach to environmental legislation, by establishing a framework by which eco-design requirements may be implemented and regulated. Eco-design has been identified as an approach which can aim to minimise the environmental impacts of products by ensuring the complete life cycle has been considered at the design stage. This means that efforts to minimise manufacturing costs will have to be considered along with material selection and waste management, in order to achieve the solution which is best for the complete product life cycle. This Directive is aimed specifically at products which require electricity to function, and therefore requires electrical efficiency to be considered together with these other life cycle aspects.

The current Directive simply defines a framework, and as such no specific measures are required to demonstrate compliance. In addition, the scope is limited to high volume consumer products and, as such, excludes large stationary power generation systems. However, the Directive is likely to be indicative of a developing trend in environmental legislation, which shifts the emphasis from specific points within the life cycle to a more holistic consideration of the impacts of products.

Incorporating eco-design practices within SOFC development is unlikely to have a significant detrimental impact on the technology. However, SOFC developers should be aware of the likely future requirement to be able to demonstrate life cycle thinking, and therefore should dedicate resource to addressing these issues. It is encouraging to see this aspect of technology development already being addressed by the academic community and also in European consortia projects [41,42]. Continuation of these initial efforts should be part of the ongoing strategy for the SOFC industry.

4.2.4.2. Extended Producer Responsibility legislation. Environmentally responsible management of products reaching the end of their useful life has appeared as a priority issue across a number of product types. Electrical and electronic components have been previously mentioned, and similar legislation applies to batteries. The automotive sector has substantial recycling targets to meet under the End-of-life Vehicles Directive.

Although within the current legislative climate, no legislation of this sort is directly applicable to large stationary SOFC systems, the trend indicates that this type of legislation is likely to develop in its scope. With recycling targets set at up to 85% of a product by weight (as for vehicles), SOFC developers would be advised to understand the feasibility of achieving this level of recycling within their products. Although it is likely to be several years before specific applicable targets are set, the damage to the technology's image resulting from any future non-compliance in this area is likely to be significant.

5. Conclusions

Future impacts of environmental product legislation on large stationary SOFC power generation systems have been identified for the stack and system assemblies and for the power and controls systems. In addition, impacts relevant to the complete product system have been identified. A simple scoring system has been used to identify priority issues defined by higher impact scores. Although the scores presented in this paper will contain a degree of subjectivity, the intention of the research is to direct SOFC developers towards some of the potential future risks and prompt further, more specific exploration of these issues within the industry.

In summary, the following recommendations are made, based on the identified impacts with highest calculated risks:

- With regard to material selection and supply the new REACH Regulation has potential implications, specifically for the SOFC stack. SOFC developers should familiarise themselves with this legislation as implementation progresses over the coming years. In particular, the restrictions planned for substances identified as being of very high concern (specifically nickel oxide) should be taken into account in materials selection and development activities.
- With regard to end-of-life management, increasing emphasis is being placed on legislative control. This legislation has supported the development of facilities for recycling electrical and electronic components, as found in the power and controls assembly. A reasonable existing infrastructure for recycling metals should provide the facilities for effective management of waste from system components. Therefore SOFC developers should focus on strategies for end-of-life management of the stack in order to divert waste from landfill and demonstrate pro-active pursuit of predicted future recycling requirements for this assembly and for the product as a whole.

In order that stationary SOFC power generation is suitable for adoption in a future energy network, developers should recognise that environmental legislation extends beyond emissions targets and encompasses a broad range of issues across the product life cycle. A pro-active approach to addressing these issues will remove any unnecessary additional challenges to successful commercialisation.

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References

[1] European Commission, Green Paper on Integrated Product Policy, COM(2001) 68 final, Brussels, 07.02.2001.
[2] Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), OJ L 396, 30.12.2006, pp. 1–849.
[3] Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, OJ L 37, 13.2.2003, pp. 19–23.
[4] Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE), OJ L 37, 13.02.2003, pp. 24–39.
[5] Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles, OJ L 269, 21.10.2000, pp. 34–43.
[6] Rolls-Royce Plc., Fuel Cells Fact Sheet, http://www.rolls-royce.com/energy/tech/fuelcell.pdf, accessed 14.09.2008.
[7] Siemens AG., Fuel Cells, http://www.powergeneration.siemens.com/products-solutions-services/products-packages/fuel-cells/, accessed 14.09.2008.
[8] Mitsubishi Heavy Industries Ltd., Solid Oxide Fuel Cell, http://www.mhi.co.jp/en/products/detail/sofc_micro_gas_turbine_combined_power_generating_system.html, accessed 19.09.2008.
[9] V. Karakoussis, N.P. Brandon, A. Leach, M. Leach, R. van der Vorst, J. Power Sources 101 (1) (2001) 10–26.
[10] N.Q. Minh, Solid State Ionics 174 (1–4) (2004) 271–277.
[11] P. Bance, N.P. Brandon, B. Girvan, P. Holbeche, S. O'Dea, B.C.H. Steel, J. Power Sources 131 (2004) 86–90.
[12] P. Costamagna, A. Selimovic, M. del Borghi, G. Agnew, Chem. Eng. J. 102 (2004) 61–69.
[13] N.Q. Minh, J. Am. Ceram. Soc. 76 (3) (1993) 563–588.
[14] S.M. Haile, Acta Mater. 51 (2003) 5981–6000.
[15] A.B. Stambouli, E. Traversa, Renew. Sust. Energy Rev. 6 (2002) 433–455.
[16] S.C. Singhal, K. Kendall (Eds.), High Temperature Solid Oxide Fuel Cells—Fundamentals, Design and Applications, Elsevier, 2003.
[17] A. Bauen, D. Hart, J. Power Sources 86 (1–2) (2000) 482–494.
[18] M. Pehnt, Int. J. LCA 8 (6) (2003) 365–378.
[19] A. Tukker, J. Ind. Ecol. 10 (3) (2006) 1–4.
[20] Japanese Ministry of Economy, Trade and Industry (METI), 3R Policies, http://www.meti.go.jp/policy/recycle/main/english/law/legislation.html, accessed 14.09.2008.
[21] Design Chain Associates, China RoHS Solutions, http://www.chinarohs.com/docs.html, accessed 14.09.2008.
[22] Republic of Korea, Ministry of Environment, Promotion of Resource Recycling of Electrical and Electronic Equipment and Vehicles, http://www.designchainassociates.com/pdf/MOE_JaeYoungLEE.pdf, accessed 14.09.2008.
[23] U.S. Environmental Protection Agency (EPA), eCycling, http://www.epa.gov/epawaste/conserve/materials/ecycling/rules.htm, accessed 14.09.2008.
[24] Electronics TakeBack Coalition, Corporate Responsibility, http://www.computertakeback.com/corporate_accountability/index.cfm, accessed 18.09.2008.
[25] European Commission Enterprise and Industry, Eco-design of Energy Using Products, http://ec.europa.eu/enterprise/eco_design/index_en.htm, accessed 18.09.2008.
[26] European Commission Environment, REACH, http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm, accessed 14.09.2008.
[27] European Commission Environment, Waste Electrical and Electronic Equipment, http://ec.europa.eu/environment/waste/weee/index_en.htm, accessed 14.09.2008.
[28] Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products, OJ L 191, 22.07.2005, pp. 29–58.
[29] European Commission Environment, Waste, http://ec.europa.eu/environment/waste/index.htm, accessed 14.09.08.
[30] Directive 1999/31/EC of 26 April 1999 on the landfill of waste, OJ L 182, 16.07.1999, pp. 1–19.
[31] Directive 91/689/EEC of 12 December 1991 on hazardous waste, OJ L 377, 31.12.1991, pp. 20–27.
[32] European Commission Environment, End-of-life Vehicles, http://ec.europa.eu/environment/waste/elv_index.htm, accessed 14.09.2008.
[33] Directive 2006/66/EC of the European Parliament and or the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators, OJ L 266, 26.9.2006, pp. 1–14.
[34] European Commission Environment, Batteries, http://ec.europa.eu/environment/waste/batteries/index.htm, accessed 14.09.2008.
[35] European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, OJ L 365, 31.12.1994, pp. 10–23.
[36] European Commission Environment, Packaging and Packaging Waste, http://ec.europa.eu/environment/waste/packaging_index.htm, accessed 14.09.2008.
[37] European Commission Environment, Landfill of Waste, http://ec.europa.eu/environment/waste/landfill_index.htm, accessed 14.09.2008.
[38] European Commission Environment, Hazardous Waste, http://ec.europa.eu/environment/waste/hazardous_index.htm, accessed 14.09.2008.
[39] J. Thijssen, The Impact of Scale-Up and Production Volume on SOFC Manufacturing Cost, Solid State Energy Conversion Alliance (SECA), April 2007.
[40] Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste, OJ L 190, 12.7.2006, pp. 1–98.
[41] REAL-SOFC, Realising Reliable, Durable, Energy Efficient and Cost Effective SOFC Systems, Project Flyers 2005 and 2006, available online at http://www.real-sofc.org/download/flyers, accessed 11.09.2008.
[42] Community Research and Development Information Service (CORDIS), Towards a Large SOFC Power Plant (LARGE-SOFC), Project Fact Sheet, available online at http://cordis.europa.eu/, accessed 11.09.2008.