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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

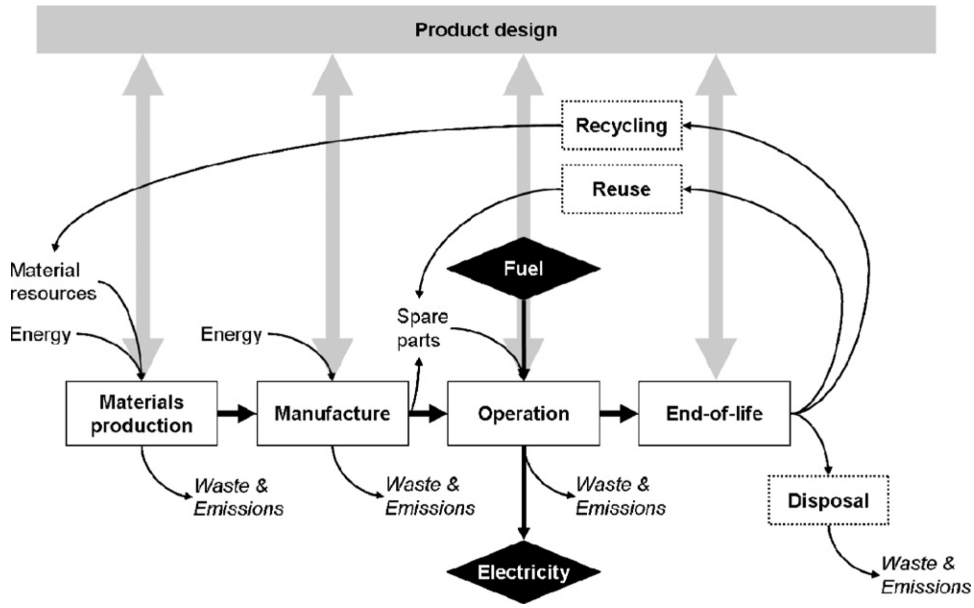

Fig. 1. A generic product life cycle for an electricity-generating product. All stages of the product life cycle are influenced by and can influence product design.

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.

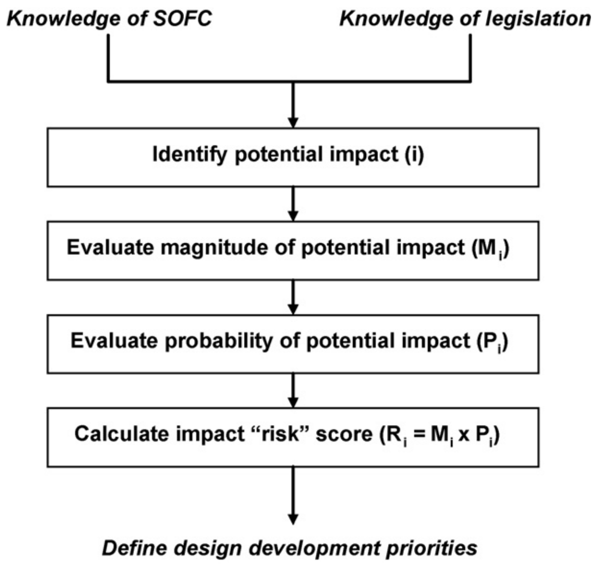

Fig. 2. The risk-based method developed to evaluate future impacts of legislation on SOFC technology. Required inputs to the process are knowledge of the SOFC product and knowledge of the relevant legislation. The process results in output which can be used to define design priorities.

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

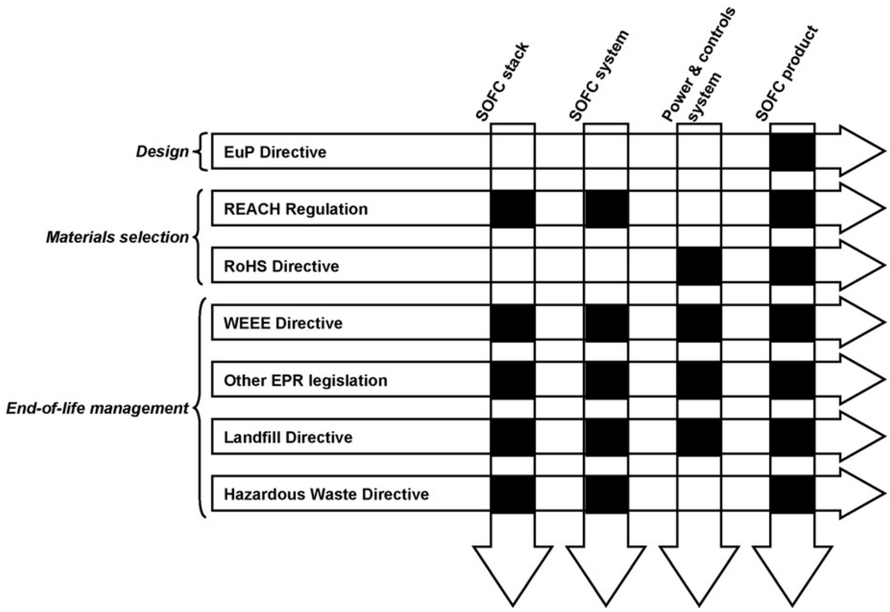

Fig. 3. A summary matrix indicating the scope of the research. Shading indicates that a specific legislative measure was found to impact upon a specific sub-assembly of the SOFC product.

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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