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Life cycle design metrics for energy generation technologies: Method, data, and case study

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ABSTRACT

A method to assist in the rapid preparation of Life Cycle Assessments of emerging energy generation technologies is presented and applied to distributed proton exchange membrane fuel cell systems. The method develops life cycle environmental design metrics and allows variations in hardware materials, transportation scenarios, assembly energy use, operating performance and consumables, and fuels and fuel production scenarios to be modeled and comparisons to competing systems to be made. Data and results are based on publicly available U.S. Life Cycle Assessment data sources and are formulated to allow the environmental impact weighting scheme to be specified. A case study evaluates improvements in efficiency and in materials recycling and compares distributed proton exchange membrane fuel cell systems to other distributed generation options. The results reveal the importance of sensitivity analysis and system efficiency in interpreting case studies.

1. Introduction

Various emerging energy generation technologies are intended to produce “clean” energy. The definition of “clean” has intermittently included negligible or substantially lower operating emissions, consideration of carbon sequestration in bio-based systems, and consideration of hardware recycling (e.g., the application of the “zero-to-landfill” design principle by Plug Power [1] in the design of fuel cell systems). In comprehensive technology assessments, “clean” includes consideration of the environmental impacts of the full technology life cycle. The “life cycle” includes materials and fuels acquisition (e.g., mining and agricultural activities); materials and fuels processing; and technology manufacturing, use, maintenance, remanufacturing, and retirement including the ultimate management of materials (e.g., recycling, landfilling, and incineration). Life cycle environmental impacts include for example resource use (e.g., the use of fossil fuels or land) and contribution to climate change, acidification, or smog formation.

The assessment of life cycle environmental impacts for energy generation and other technologies is described by the International Standards Organization’s (ISO’s) Life Cycle Assessment (LCA) standards (in the ISO14040 series [2]). In the ISO LCA process, material and energy use and waste are estimated for each life cycle process and for the system as a whole (e.g., how much energy is consumed and carbon dioxide is emitted by processes throughout the life cycle). From this energy and materials inventory, the contribution of the life cycle to a variety of environmental impacts is estimated (e.g., how much do the life cycle air emissions contribute to global climate change). As technologies move from the laboratory to wide-scale use, knowing the potential life cycle contribution to environmental impacts provides valuable insights into the evaluation of design variants, in the comparison to other energy generation technologies, and in meeting corporate, community, and national goals.

In addition to protocol standardization, LCA practice has substantially changed since the early 1990s. Practitioners have developed sophisticated software tools and extensive database systems to assist in the preparation of inventory analyses and impact assessments and to interpret the results. However, the use of many of these databases and software tools requires a relatively high level of training and a relatively detailed engineering knowledge of industrial process data and modeling, chemical fate and transport

Abbreviations: PEMFC, proton exchange membrane fuel cell; LCA, Life Cycle Assessment; BEES, Building for Environmental and Economic Sustainability (tool by the U.S. National Institute for Standards and Testing); GREET, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (tool by the U.S. Department of Energy’s Argonne National Laboratory); CO_2, carbon dioxide; CH_4, methane; CO, carbon monoxide; N_2O, nitrous oxide; NO_x, nitrogen oxides; PM10, particulate matter less than 10 μm in diameter; PM2.5, particulate matter less than 2.5 μm in diameter; SO_x, sulfur oxides; NMVOC, non-methane volatile organic compounds.

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modeling, and ecosystem and human response. Further, many have been created using proprietary and unpublished computational structures and restrict the publication of the data supporting the assessment—making a detailed review of assumptions and comparative assertions impossible. Finally, many of these databases and software tools have been developed to describe a very wide variety of technologies and often lack the ability to model a specific technology. As a result, preparing technology-specific LCA models can be time consuming, making such assessments unattractive for use in rapid design cycles.

The development of a LCA-based method for rapid results is not new. Example existing methods include Pré's Eco-Indicators [3] and Arizona State University's Okala Impact Factors [4], both intended to be applicable to a wide variety of technologies. Also, the U.S. National Institute of Standards and Technology's BEES (Building for Environmental and Economic Sustainability [5][1]) tools provide LCA results specifically applicable to buildings and to bioproducts. Although each of these tools is able to produce results in a rapid timeframe, all have been developed using SimaPro,[2] a LCA software and data system with restrictions on data publication (the software must be purchased to review and repeat and the LCA results). Further, both the Pré Eco-Indicators and the Okala Impact Factors use a pre-determined valuation scheme. This means that user cannot consider their own priorities among life cycle environmental impacts (i.e., they cannot specify the relative importance among design goals such as how much more or less important climate change is when compared to smog formation).

Thus, the primary objective of this work is to provide a method to assist in the rapid preparation of LCAs that is (1) sensitive to a wide variety of design parameters specific to energy generation technologies (including variations in system hardware materials and configurations, in transportation options, in assembly energy use, in operating performance and consumables, and in fuels and fuel production scenarios, as well as in comparison to a variety of conventional systems); (2) based on highly peer reviewed and publicly available LCA data that provide results suitable for both internal decision-making and external communications (with the version described here focusing on U.S. manufacturing and operation); and (3) allows the environmental impact weighting scheme to be specified. A second objective is to demonstrate the use of the LCA method in comparing baseline and alternative designs, and in the comparison of emerging systems to conventional options.

2. Methods

No matter the system being evaluated, the ISO divides LCA into four phases. The first phase, *goal and scope definition*, describes the reasons for carrying out the study, the study scope (what processes will be included), plans for data collection and assessment, and plans for critical review. Next, in the *inventory analysis* phase, material and energy use and waste are estimated for each life cycle process and the system as a whole (e.g., how much energy is consumed and carbon dioxide is emitted by processes throughout the life cycle). In the third phase, the *impact assessment*, environmental impacts are estimated given the inventory results (e.g., how much do the life cycle air emissions contribute to global climate change) as normalized by the impacts of some system of interest (e.g., impacts per capita) on the basis of a ranking of the relative importance of impacts. Finally, the *interpretation* phase evaluates the usefulness of the LCA (including the identification of sensitive parameters and the quantification of uncertainties).

Here, we develop "component" EcoScores that represents the results of the first three phases of a separate LCA, leaving the interpretation phase to be based on the results. A "component" is broadly defined here to include not only hardware materials (e.g., graphite, steel, etc.) but also specific types of energy use, emissions, and transport. The formulation is intended to allow energy generation systems to be compared in a way similar to comparisons on the basis of cost: adding component scores or component costs gives the total environmental contribution or the total cost of the system.

2.1. Goal and scope definition

Intended for use by energy technology designers in the U.S., each component EcoScore provides ready-made LCA results for use in design. Each score includes an estimation of the following 14 life cycle environmental impacts:

- Energy consumption as (1) total energy; (2) fossil fuels; (3) coal; (4) natural gas; (5) petroleum fuels;
- The contribution to (6) climate change, (7) photochemical smog; and (8) acidification;
- Emissions of particulate matter as (9) PM10 and (10) PM2.5
- The use of recycled materials (11) in the standing system and (12) for all materials used during the operating period; and
- The potential for reuse, remanufacturing, and recycling (13) in the standing system and (14) for all materials used during the operating period.

For each environmental impact, EcoScores are divided into six categories, as listed in Table 1. As shown, although each EcoScore has its own functional unit[3] and scope, all fall within the six categories. More specifically, the scope of each LCA within each EcoScore includes as relevant the acquisition of materials and fuels (e.g., mining and agricultural activities), the processing of materials and fuels, technology hardware and consumables manufacturing, technology operation, commodities transport, technology system transport, and the transport of materials to reuse, remanufacturing, recycling, or disposal.

2.2. Life cycle inventory analysis

The computational structure for the EcoScore LCA inventory analyses is formulated sequentially such that demand for intermediate products throughout the life cycle is estimated in succession as opposed to simultaneously (as in matrix formulations of LCA). Both matrix and sequential computational structures are described by Heijungs and Suh [6]. Given this, it is the collection of the inventory data (the types and quantities of the use and waste of energy and materials for each process within the life cycle) that remains.

In total, the EcoScore inventory data have been divided into four domains: energy, logistics, materials, and technology systems. All data for processes within the energy, logistics, and materials domains are based on the U.S. Department of Energy Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (*GREET*) Model versions 1.7 (for energy and logistics) and 2.7 (for materials),[4] which forms the foundation for the EcoScores. GREET is a fuel-cycle model designed

[1] For more information on BEES, see http://www.bfrl.nist.gov/oae/software/bees.html.

[2] For more information on SimaPro, see http://www.pre.nl/simapro/default.htm.

[3] In LCA terminology, the functional unit is the quantified performance of a product system for use as a reference unit in a LCA study.

[4] For more information on GREET, see http://greet.anl.gov/.

Table 1
Goal and scope information by EcoScore category.

EcoScore category	EcoScores represent the share of the annual per capita contribution to each environmental impact of	EcoScore LCA functional unit	EcoScore LCA scope
Fuel cell energy use	the consumption of natural gas, hydrogen, etc.	mmBTU of fuel consumed	From materials acquisition to point of use
Fuel cell operating emissions	air emissions of CO_2, CH_4, etc.	kg emitted	At the point of the emission
Assembly energy	electricity or fuel use by the fuel cell manufacturer	kWh or mmBTU of energy consumed	From materials acquisition to point of use
Transport of the system to the customer	transport by truck, rail, etc.	tonne-km (or 1000 kg transported 1 km)	From materials acquisition to point of use (a.k.a. from well-to-wheel)
Fabricated hardware and consumables	the production of alumina, steel, Nafion, etc.	kg used in the system	From materials acquisition to point of use
Materials management	the transport of waste to recycling, to a landfill, etc.	kg managed for the PEMFC system when retired	From materials acquisition to point of use (a.k.a. from well-to-wheel)

for the evaluation of various automobile and fuel combinations on a full fuel-cycle basis. GREET estimates life cycle energy consumption (as the total energy, fossil, and petroleum use) and emissions of methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (N_2O), nitrogen oxides (NO_x), particulate matter (PM), sulfur oxides (SO_x), and non-methane volatile organic compounds (NMVOCs). Although GREET applications to date are primarily assessments of mobile systems (assessments of marine transport and personal vehicles including fuel cell vehicles), what is of value here are the fuel cycle, electricity production, logistics models (transport on land, through inland waters, or by sea), and materials production models contained within GREET. These include, but are not limited to, life cycle scenarios for U.S. production of several fuels used by emerging generation technologies (e.g., hydrogen, biomass, etc.). Further, because energy production, logistics, and refinery processes are part of the GREET fuel-cycle model, these data (including refinery co-products) can be used for the preparation of LCAs for industrial activities throughout the technology system life cycle. Finally, the technology systems domain data are provided by the technology designer. These data are essentially the type and quantities of fuel use, operating emissions, hardware components and consumable, energy use in system assembly, transport to the customer, and end-of-life hardware and consumables management. Note that the EcoScores presented here are based on default GREET1.7 and GREET2.7 values for the year 2010 as described by Wang et al. and Burnham et al. [7,8].

2.3. Life cycle impact assessment

In the EcoScore method, the contribution of the inventory flows to environmental impacts (described in Table 2) is measured in one of three ways:

1. *By the amount of inventory flows* (e.g., the amount of energy or the mass of particulate matter emissions) which applies to seven of environmental impacts in the EcoScore method.
2. *Using impact equivalency factors* (scoring factors based on fate, transport, and effects models) from the 1996 Intergovernmental Panel on Climate Change values (see [9]) or as compiled in the US Environmental Protection Agency's Tool for the Reduction

Table 2
EcoScore environmental impacts.

Impact category	Environmental impacts considered	Description
Ecological damage	1. Contribution to climate change**	Total carbon dioxide equivalents from life cycle air emissions of CO_2, N_2O, and CH_4 (as kg CO_2 equiv)
	2. Contribution to acidification**	Total hydrogen ion equivalents from life cycle air emissions of SO_x and NO_x (as kg H^+ equiv)
Human health damage	3. Contribution to photochemical smog**	Total nitrogen oxides equivalents from life cycle air emissions of CH_4, NO_x, CO, and NMVOCs (as kg NO_x equiv)
	4. PM10 emissions*	Sum of particulate matter emissions (as kg PM10)
	5. PM2.5 emissions*	Sum of particulate matter emissions (as kg PM2.5)
Resource depletion	6. Total energy consumption*	Sum of the total energy consumption for the life cycle (as mmBTU)
	7. Fossil energy consumption*	Sum of the fossil energy consumption for the life cycle (as mmBTU)
	8. Coal consumption*	Sum of the coal consumption for the life cycle (as mmBTU)
	9. Natural gas consumption*	Sum of the natural gas consumption for the life cycle (as mmBTU)
	10. Petroleum energy consumption*	Sum of the petroleum energy consumption for the life cycle (as mmBTU)
	11. Use of recycled components in standing system***	The mass of recycled components divided by the system mass (as a % of the standing system mass)
	12. Use of recycled components over system life (hardware and consumables)***	The mass of recycled components divided by the system mass for the operating period (as a % of the mass over the system life)
	13. Reuse/remanufacturing/recycling in standing system***	The mass of reusable/remanufacturable/recyclable components divided by the system mass (as a % of the standing system mass)
	14. Reuse/remanufacturing/recycling over system life (hardware and consumables)***	The mass of reusable/remanufacturable/recyclable components divided by the system mass for the operating period (as a % of the mass over the system life)

* The contribution of the inventory flows to the environmental impact is measured by the amount of the inventory flows.
** The contribution of the inventory flows to the environmental impact is measured using impact equivalency factors.
*** The contribution of the inventory flows to the environmental impact is measured as progress towards zero-to-landfill.

Table 3
Equivalency factors used in the EcoScores.[a].

Impacts considered	Life cycle air emissions (kg kg^{-1} emitted)							
	CH_4	CO	CO_2	N_2O	NMVOCs	NO_x	PM	SO_x
Contribution to Climate Change (CO_2 equivalents) [9]	21	0	1	310	0	0	0	0
Contribution to Acidification (H^+ equivalents) from TRACI	0	0	0	0	0	40	0	50.8
Contribution to photochemical smog (NO_x equivalents) from TRACI	0.0030	0.013	0	0	0.78	1	0	0

[a] Climate change equivalency factors are for 100-year time horizons and chosen to match the data used in the USEPA's values in the *Draft 2007 Inventory of Greenhouse Gas Emissions and Sinks* [9]. Data are from the most recent version of TRACI (developed in 2006) for the US average condition and available at http://www.epa.gov/nrmrl/std/sab/traci/.

Table 4
Normalization factors (2010 U.S. annual per capita values).

Environmental impact		
Total energy consumption	2.19E+02	mmBTU/capita
Fossil fuel consumption	1.71E+02	mmBTU/capita
Coal consumption	7.54E+01	mmBTU/capita
Natural gas consumption	7.40E+01	mmBTU/capita
Petroleum consumption	1.38E+02	mmBTU/capita
Climate change	2.20E+04	kg CO_2 equivalents/capita
Smog formation	3.87E+02	kg NO_x equivalents/capita
Acidification	1.88E+04	kg H^+ equivalents/capita
PM10 emissions	1.95E+01	kg/capita
PM2.5 emissions	2.57E+01	kg/capita

and Assessment of Chemical and Other Environmental Impacts (TRACI).[5] When equivalency factors are used, impacts are measured relative to one of the emissions contributing to the impact. For example, contribution to climate change is measured in "CO_2 equivalents" such that each species is assumed to have some multiple of the impact of CO_2 (e.g., an emission of 1 kg of CH_4 contributes 21 times that of an emission of 1 kg of CO_2). Table 3 lists the equivalency factors used in the characterization of three of the environmental impacts in the EcoScore method.

3. *As progress towards zero-to-landfill* (seeking 100% use of recycled components and 100% reuse, remanufacturing, or recycling of all hardware and consumables) which applies to four of environmental impacts in the EcoScore method.

Next, the contribution of each environmental impact in the first two categories is *normalized* by the commensurate U.S. per capita value, as presented in Table 4. All normalization values are intended to represent U.S. per capita data for 2010 based on a projected U.S. population of 308,936,000 [10]. 2010 U.S. energy use projections are based on linear regressions of data for 1998 through 2006 from the U.S. Department of Energy' Annual Energy Review [11]. 2010 U.S. air emissions are based on linear regressions of data for 1995 through 2005 from the U.S. Environmental Protection Agency (see [12,13]) with greenhouse gases including sources and sinks. The normalized environmental impacts thus represent the results of the first three phases of a separate LCA, leaving the interpretation phase to be based on the results.

3. Calculation

3.1. Evaluation of alternative technology designs

Given the normalized environmental impacts (e.g., the share of the annual per capita contribution to climate change) for each hardware component and for each impact, what remains is the determination of a single score for each component and ultimately the energy generation system. Fig. 1 illustrates how EcoScores are formulated and how they are used to estimate the total environmental contribution. As shown, the information flow has been set up as a hierarchy, starting with *impact scores* ($i_{i,c}$: the raw LCA results for each component and the *normalization factors* (n_i as presented in Table 4) which combine to form *normalized impact scores* ($N_{i,c}$).

To calculate the EcoScore for a technology system, the normalized impact scores (provided in Appendix A), are first combined with impact *weighting factors* (w_i) to form *unit EcoScores* (ESu_c):

$$ESu_c = \sum_i w_i N_{i,c} \tag{1}$$

The weighting factors represent the relative importance of each of the 14 environmental impacts listed in Table 2 and are specified by the designer for each assessment. Weighting factors must sum to 100%, but can be used in any combination of importance: e.g., each environmental impact can be equally weighted (each contributing ∼7% to the total); fossil energy consumption can be weighted at 25%, climate change at 50%, and the use of recycled materials at 25%; climate change (or any other environmental impact) can be weighted as 100% with all other environmental impacts assigned weighting of 0%; etc. Although how the weighting factors are assigned is completely up to the discretion of the designers, methods such as objectives trees [14] or Analytical Hierarchy Process [15] might be use in the determination of weighting factors.

Unit EcoScores (i.e., the sum of the product of the impact weighting factors and the corresponding normalized impact scores) are next combined with *technology design data* (Q_c) in the estimation of *component EcoScores* (ESc_c):

$$ESc_c = ESu_c\, Q_c \tag{2}$$

design data, provided by the designer, include the identification of the type of each component (e.g., the use of natural gas or hydrogen fuel, the use of primary or recycled steel sheet, etc.) and the amount used over the operating period of interest. Design data should be systematically collected, accounting for the type and quantity of materials used, related fabrication processes, and whether materials are expected to be reused, remanufactured, recycled or disposed during system maintenance or retirement. The disassembly assessment method described by Kroll et al. [16] is particularly useful in the development of materials-related design data when during the disassembly process data are captured for (1) part mass; (2) the identification of materials and fabrication methods; (3) the identification of recyclable materials that are separable from the system; and (4) the number of replacements over operating period. Finally, *system EcoScores* (ESs_{PEMFC}) are estimated as the sum of the component EcoScores for the system:

$$ESs_{PEMFC} = \sum_c ESc_c \tag{3}$$

Appendix B demonstrates the estimation of system EcoScores through a four-step process. Again the formulation is intended to allow energy generation technologies to be compared in a way

[5] For more information on TRACI, see http://www.epa.gov/nrmrl/std/sab/traci/.

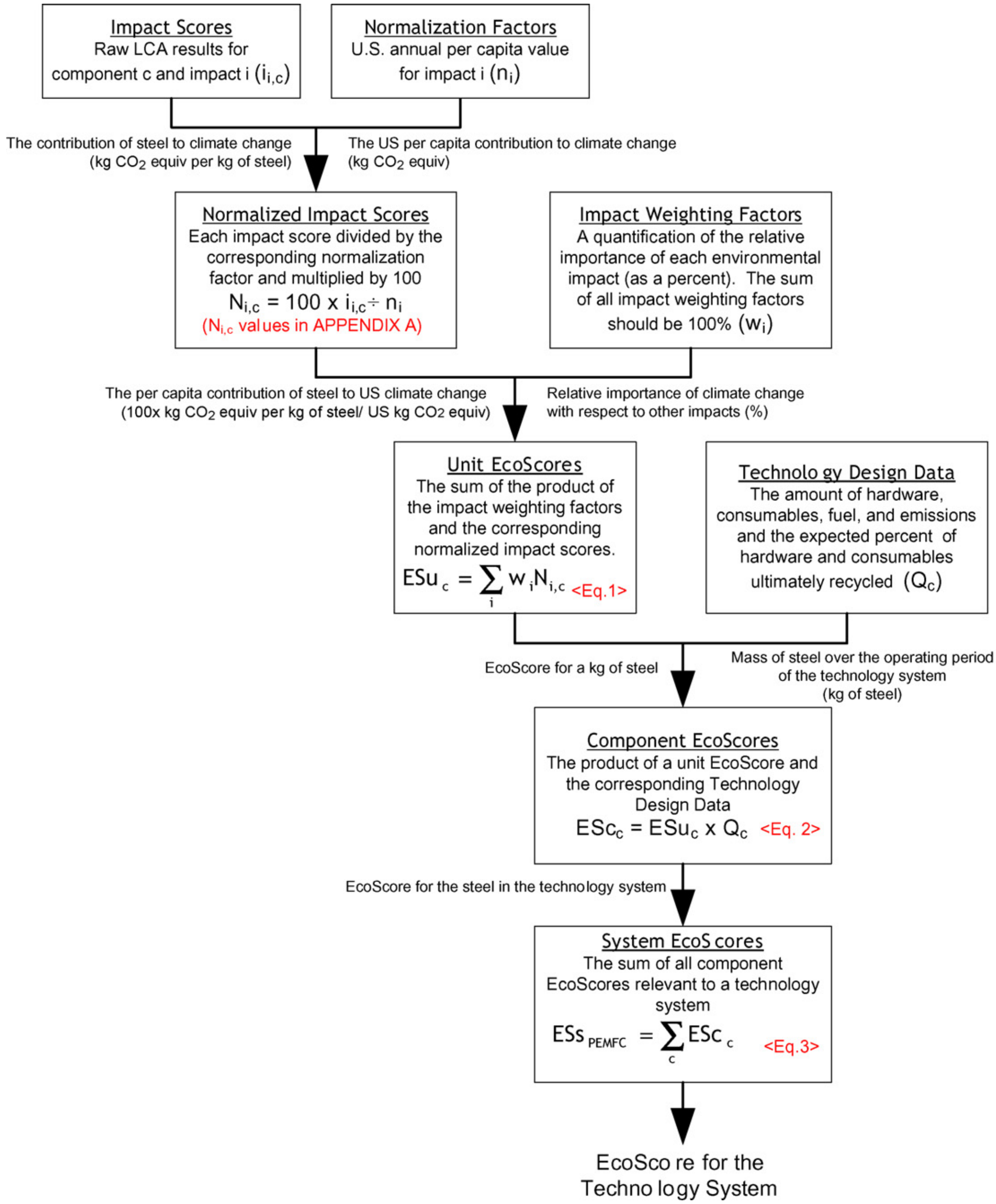


Fig. 1. Information flow in the EcoScore method.

similar to comparisons on the basis of cost. For example, if a system consumes 250 mmBTU[6] per year of natural gas at a cost of \$8/mmBTU, the fuel cost of the system is \$2000. Similarly, if the unit EcoScore for natural gas related to total energy consumption is 0.49 mmBTU^{-1} (from Appendix A), the EcoScore for the fuel is 122.5 (or 250*0.49), meaning the life cycle fuel use is estimated to represent 122.5% of the average annual U.S. *per capita* total energy use.

3.2. Comparison to alternative generation options

Next we are interested in comparing LCA results to those of conventional energy generation methods (a.k.a., reference systems, in LCA terminology). Here, we limit the scope of the assessment to the life cycle production and use of fuel (i.e., we omit consideration of hardware construction and maintenance) and to the 10 energy and emission related environmental impacts (i.e., we omit the use of recycled materials and the potential for reuse, remanufacturing, and recycling). Our formulation defines the *breakeven efficiency* as the system efficiency required such that the environmental impact of the reference system equals that of the system of interest. If this breakeven efficiency is surpassed, then the system of interest is preferred over the reference system for a given environmental impact.

Here, the breakeven efficiency is estimated for each *energy-related* life cycle environmental impact (i.e., for life cycle total energy, fossil, coal, natural gas, and petroleum) as:

$$\varepsilon n_{i,f,r} = \frac{\varepsilon_r i_{i,f}}{i_{i,r}} \quad (4)$$

[6] Energy data are presented here in British Thermal Units (BTU = 1054 J) to facilitate easier comparison with results from the GREET program.

Table 5
Case study PEMFC operating and cold-start emissions.

	kg mmBTU^{-1} fuel consumed							
	Q_{CH_4}	Q_{CO}	Q_{CO_2}	Q_{N_2O}	Q_{NMVOCs}	Q_{NO_x}	Q_{PM10}	$Q_{SO_x}Q_{SOx}$
Operation	0.237	0	58.8	0	0.0180	0	0	0
Cold start (assumed to be approximately 1/2 h in duration per cold start)	0.237	0.932	57.4	0	0.0180	0	0	0

where: $\varepsilon n_{i,f,r}$: the breakeven efficiency for the *energy-related* environmental impact i, emerging generation technology f, and reference system r (%); ε_r: the efficiency of reference system r (with $\varepsilon_r = 1$ for electricity grids); $i_{i,f}$: the LCIA result for environmental impact i and emerging generation technology *f* (tabulated in Appendix C); $i_{i,r}$: the LCIA result for environmental impact i and reference system r (tabulated in Appendix C)

For *emissions-related* life cycle environmental impacts, the breakeven efficiency considers both fuel production and operating emissions. Specifically, the design technology and reference system emissions are added to the estimation of the breakeven efficiency:

$$\varepsilon m_{i,f,r} = \frac{\varepsilon_r(i_{i,f} + \sum A_{e,f}E_{i,e})}{i_{i,r}} \quad (5)$$

where: $\varepsilon m_{i,f,r}$: the breakeven efficiency for the *emissions-related* environmental impact i, emerging generation technology f, and reference system r (%); $A_{e,f}$: the mass of air emission e during the operation of the emerging generation technology f (kg); $E_{i,e}$: the equivalency factor used to convert the mass of emission e to its contribution to environmental impact i (kg kg^{-1} reference substance, given in Table 3).

Thus, we have formulated the assessment of reference systems as a function of the impact scores ($i_{i,c}$ in Fig. 1). Normalization and weighting are not needed, as they would be identical for the PEMFC and the reference systems (i.e., computationally, they drop out of the assessment). Also, we have developed our calculations assuming the efficiencies of the reference systems and the operating emissions of the emerging generation technologies are variables.

Impact scores needed to estimate breakeven efficiencies are presented in Appendix C for select fuels (11 hydrogen generation methods, natural gas, and liquid petroleum gas (LPG)) as well as 34 stationary generation reference systems. Consider for example "Natural Gas burned in a Small Industrial Boiler (10–100 mmBTU h^{-1} input)." Appendix C lists a value of 69.1 kg CO_2 equivalents mmBTU^{-1} for life cycle contribution to climate change. This essentially means that 69.1 kg CO_2 equivalents (which here combines emissions of CO_2, CH_4, and N_2O) are emitted from the well through the combustion of 1 mmBTU of natural gas in the boiler for the generation of 0.35 mmBTU (or 0.67 kg CO_2 equivalents kWh^{-1}). As a second example and again for the reference system "Natural Gas burned in a Small Industrial Boiler (10–100 mmBTU h^{-1} input)," Appendix C lists a value of 1.07 mmBTU/mmBTU for total life cycle energy. This essentially means it takes 1.07 mmBTU to deliver 1 mmBTU of natural gas from the well-to-the-boiler. If the boiler is assumed to have an efficiency of 35%, this means that 0.35 mmBTU (or 102.5 kWh) is generated for a total energy input of 1.07 mmBTU (i.e., 0.0105 mmBTU kWh^{-1}). This equates to a well-to-electricity efficiency of 32.7%.

Again the impact scores represent the life cycle impact assessment results based on the GREET data and considering only fuel production and use. In fact, the data for fuel cell fuels from Appendix C can be obtained from the EcoScore data in Appendix A. For example, the EcoScore in Appendix A for total energy use for "Gaseous Hydrogen: GREET Combination of Technologies, at POU" is 0.795 which, as noted in Fig. 1, is equal to 100 times the corresponding impact score in Appendix C (i.e., 1.74) divided by the total energy normalization value in Table 4 (i.e., 219 mmBTU/capita) or 0.795 = 100 * 1.74/219.

4. Results

For our results, we present a case study that demonstrates the use of the EcoScores and the estimation of breakeven efficiencies in the design of proton exchange membrane fuel cell (PEMFC) systems. Our case study is loosely based on recent improvements to the Plug Power GenSys line and the composite-plate stacks described in Cooper [17]. First, we use the data in Appendix A to compare a 5-kW rated *baseline* PEMFC system at 21.6% electric efficiency[7] with 85% of the standing-system-hardware and 49% of the lifetime-hardware-and-consumables (i.e., the hardware and consumables used over the 10-year operating period) recovered (i.e., reused, remanufactured, or recycled) to a 5-kW rated *alternative* PEMFC system operating at 30% efficiency with zero-to-landfill for both the standing hardware and the lifetime-hardware-and-consumables. Both systems are assumed to operate on natural gas that is not pipeline connected (i.e., the natural gas must be transported by truck to the operating site), at a capacity of 37%[8], and with 40 cold starts over the 10-year operating period (approximated from [18]). Note also that the kWh output of both systems is 162,171 kWh over the 10-year period (i.e., the kW rating times the capacity for 10 years).

For the case study, *PEMFC operating and cold-start emissions* for both systems [18,19] are presented in Table 5. Next, Table 6 presents the design data used in the assessment of the baseline and alternative PEMFC systems. In addition to fuel consumption, operating emissions and materials use, it has been assumed that 100 kWh of *electricity is consumed in the PEMFC assembly process* ($Q_{\text{grid electricity}}$ located in the North East) and that the *transport of the PEMFC systems and service materials* to the customer is over 160 km by truck and 645 km by rail (assuming the transport of 2170 kg for the original system and subsequent materials, these equate to Q_{truck} = 347 tkm and Q_{rail} = 1400 tkm, respectively).

Next, *unit EcoScores* (ESu_c) are estimated (step 2 in Appendix B) corresponding to the design data by: (a) assigning *weighting factors* (w_i) to each of the 14 environmental impacts and (b) multiplying the weighting factors by the corresponding *normalized impact scores* for each component ($N_{i,c}$) and summing the results. For the case study, it has been assumed that all environmental impacts are equally important. This equates to a weighting factor of 7.1% (or $w_{\text{total energy}} = w_{\text{fossil energy}} = w_{\text{petroleum energy}} = w_c = w_{\text{ect.}} = 1/14$) for each environmental impact. Multiplying each of the relevant normalized impact scores presented in Appendix A by 1/14 and summing the results provides each unit EcoScores. Table 6 lists the resulting unit EcoScores applied in the case study.

Next, component EcoScores (EScc) are estimated (step 3 in Appendix B) by summing the product of the PEMFC design data and the respective unit EcoScores to determine the contribution of each

[7] See http://dodfuelcell.cecer.army.mil/res/site_summary_statistics.php4?site_id=31.

Table 6
Case study design data, unit EcoScores, and component EcoScores.

	Design data (Q_c, over system life)			Unit EcoScores[a] (ESu_c)	Component EcoScores (Esc_c)	
	PEMFC baseline	PEMFC alternative			PEMFC baseline	PEMFC alternative
Natural gas for stationary uses, at POU (pipeline + other transport)	2.6E+03	1.8E+03	mmBTU	1.9E−01 mmBTU^{-1}	4.8E+02	3.5E+02
NMVOC	4.6E+01	3.3E+01	kg	1.4E−02 kg^{-1}	6.7E−01	4.8E−01
CO	7.1E−01	5.1E−01	kg	2.5E−04 kg^{-1}	1.7E−04	1.3E−04
CH4	6.1E+02	4.4E+02	kg	6.9E−03 kg^{-1}	4.2E+00	3.0E+00
CO2	1.5E+05	1.1E+05	kg	3.3E−04 kg^{-1}	4.9E+01	3.5E+01
Assembly NE grid electricity (kWh)	1.0E+02	1.0E+02	kWh	1.7E−03 kWh^{-1}	1.7E−01	1.7E−01
US Class 6 Diesel Truck: Diesel Fuel (fuel production + operation)	3.5E+02	3.5E+02	tkm	3.2E−04 tkm^{-1}	1.1E−01	1.1E−01
US Locomotive: Diesel (fuel production + operation)	1.4E+03	1.4E+03	tkm	6.7E−05 tkm^{-1}	9.4E−02	9.4E−02
Alumina	1.0E+03	1.0E+03	kg	5.1E−03 kg^{-1}	5.1E+00	5.1E+00
Aluminum: average cast	8.0E+00	0.0E+00	kg	2.8E−02 kg^{-1}	2.2E−01	0.0E+00
Aluminum: average wrought	8.0E+00	0.0E+00	kg	5.5E−02 kg^{-1}	4.4E−01	0.0E+00
Aluminum: recycled cast	0.0E+00	8.0E+00	kg	8.4E−03 kg^{-1}	0.0E+00	6.8E−02
Aluminum: recycled wrought	0.0E+00	8.0E+00	kg	9.5E−03 kg^{-1}	0.0E+00	7.6E−02
Copper or Brass	1.7E+02	1.7E+02	kg	2.7E−02 kg^{-1}	4.6E+00	4.6E+00
Nickel: average	1.2E−02	0.0E+00	kg	2.9E−02 kg^{-1}	3.5E−04	0.0E+00
Nickel: recycled	0.0E+00	1.2E−02	kg	8.0E−03 kg^{-1}	0.0E+00	9.6E−05
Platinum	5.7E−02	5.7E−02	kg	4.5E−02 kg^{-1}	2.6E−03	2.6E−03
Steel: average	2.9E+02	0.0E+00	kg	9.8E−03 kg^{-1}	2.8E+00	0.0E+00
Steel: recycled	0.0E+00	2.9E+02	kg	7.0E−03 kg^{-1}	0.0E+00	2.0E+00
Steel: stainless	2.5E+02	2.5E+02	kg	7.7E−03 kg^{-1}	1.9E+00	1.9E+00
Zinc	4.1E−01	4.1E−01	kg	2.3E−02 kg^{-1}	9.4E−03	9.4E−03
Battery: Lead Acid	1.9E+02	1.9E+02	kg	2.2E−02 kg^{-1}	4.1E+00	4.1E+00
Carbon	1.7E+00	1.7E+00	kg	3.7E−02 kg^{-1}	6.3E−02	6.3E−02
Carbon Fiber Composite Plastic	2.3E+01	2.3E+01	kg	2.8E−02 kg^{-1}	6.4E−01	6.4E−01
Carbon Paper	1.9E+00	1.9E+00	kg	1.3E−01 kg^{-1}	2.4E−01	2.4E−01
Electronic Parts	4.1E+00	4.1E+00	kg	1.8E−02 kg^{-1}	7.4E−02	7.4E−02
Ethylene Glycol	3.8E+01	3.8E+01	kg	3.9E−03 kg^{-1}	1.5E−01	1.5E−01
Glass	7.5E−02	7.5E−02	kg	4.1E−03 kg^{-1}	3.1E−04	3.1E−04
Nafion Dry Polymer	2.2E−01	2.2E−01	kg	5.0E−03 kg^{-1}	1.1E−03	1.1E−03
Nafion117 Sheet	2.0E+00	2.0E+00	kg	5.1E−03 kg^{-1}	1.0E−02	1.0E−02
Plastic: average	1.6E+02	1.6E+02	kg	1.2E−02 kg^{-1}	1.9E+00	1.9E+00
Polypropylene	1.9E−01	1.9E−01	kg	9.9E−03 kg^{-1}	1.8E−03	1.8E−03
PVDF	2.2E+00	2.2E+00	kg	5.0E−03 kg^{-1}	1.1E−02	1.1E−02
Rubber	8.1E+00	8.1E+00	kg	8.1E−03 kg^{-1}	6.5E−02	6.5E−02
Use of recycled components in standing system	0%	40%		−7.1E+00	0.0E+00	−2.9E+00
Use of recycled components over system life (hardware & consumables)	0%	14%		−7.1E+00	0.0E+00	−1.0E+00
Materials recovery in standing system	85%	99%		−7.1E+00	−6.1E+00	−7.1E+00
Materials recovery over system life (hardware & consumables)	49%	99%		−7.1E+00	−3.5E+00	−7.1E+00
System EcoScore (as the sum of the component scores)					*5.5E+02*	*3.9E+02*

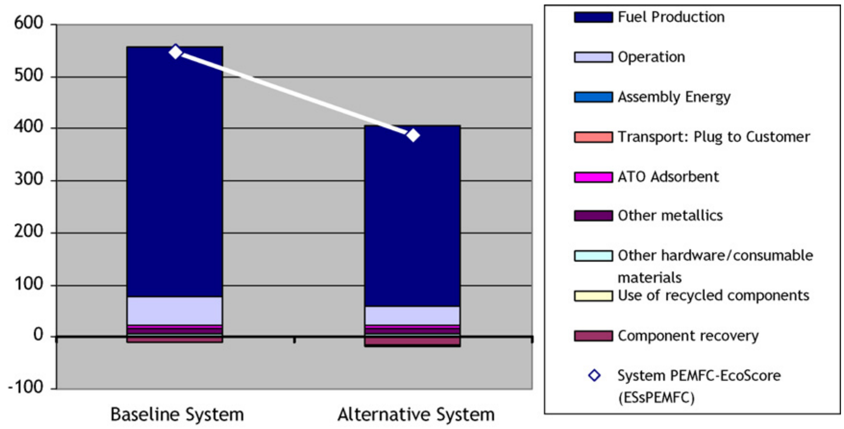
[a] As the sum of the product of the normalized impact scores in Appendix A and the weighting factors.

component to the system life cycle. Table 6 also lists the resulting component EcoScores applied in the case study. Finally, the system EcoScores (ESsPEMFC) are estimated (step 4 in Appendix B) by adding up the component EcoScores to determine the contribution of the system to the annual U.S. per capita environmental impact.

Figs. 2 and 3 illustrate the alternative system improves on all points from the baseline, with a reduction in the system EcoScore from 548 to 388 (a ∼38% reduction in environmental impacts given the chosen weighting scheme). As expected, the alternative system's reduction in fuel consumption and operating emissions (resulting from the improvement in electric efficiency) are the primary sources of this improvement followed by component recovery and component recycling. In fact, on an environmental impacts basis (see Fig. 3) the majority of the improvement comes from the reduction in natural gas, fossil, and petroleum consumption, and the reduction in the contribution to climate change.

What can be concluded from Figs. 2 and 3 is that continuing improvements in efficiency are of primary importance. Smaller gains can be seen by considering consumables and the use of recycled components. Related opportunities lie in, for example the use of recycled absorbent within the reforming subsystem, and requiring metal component suppliers to maximize their use of recycled materials or switching to suppliers that already use such materials while still providing components that meet design specifications.

Next, we estimate breakeven efficiencies for our case study natural gas PEMFCs using the operating emissions presented in Table 5 and the reference system efficiencies presented in Table 7. Fig. 4 depicts select breakeven efficiencies for the total life cycle energy per kWh not only for the small industrial natural gas boiler (again at 0.0105 mmBTU kWh^{-1}) but also for two other reference systems: LPG burned in a commercial boiler (at 0.01128 mmBTU kWh^{-1}) and electricity from the U.S. grid (at 0.00557 mmBTU kWh^{-1} and intended to represent a mix of 2.9% residual oil, 16.3% natural gas, 51.5% coal, 20% nuclear, 1.2% biomass, and 8.1% from other sources as the GREET default). Also, Fig. 4 depicts the life cycle total energy consumption of a natural gas PEMFC system as a function of electric efficiency. As shown, the for each reference system there is a PEMFC efficiency for which the total life cycle energy equals that of each reference system: 29%, 35%, and 66% for the LPG boiler, the small natural gas boiler, and the grid, respectively. If this breakeven



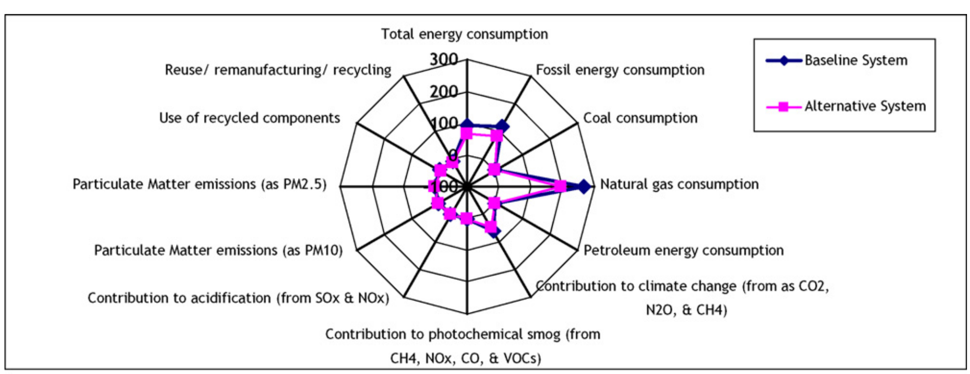
	Baseline System	Alternative System
Fuel Production	480.7	346.1
Operation	53.9	38.8
Assembly Energy	0.1	0.1
Transport: Plug to Customer	0.2	0.2
ATO Adsorbent	5.1	5.1
Other metallics	10.0	8.7
Other hardware/consumable materials	7.3	7.3
Use of recycled components	0.0	-3.9
Component recovery	-9.5	-14.1
System PEMFC-EcoScore (ESs_{PEMFC})	**547.7**	**388.2**

Lower scores are preferred

Fig. 2. Contribution analysis: system EcoScores (ESs_{PEMFC}) by SubSystem.

efficiency is surpassed by the PEMFC, then the PEMFC would be preferred over the reference system for total energy consumption.

Again for the natural gas system operating emissions presented in Table 5 and the case study reference system efficiencies are presented in Table 7, breakeven efficiencies for 16 reference systems based on Eqs. (4) and (5) are presented in Fig. 5. We have color coded our results, assuming: green cells represent PEMFC breakeven efficiencies less than 30% (as modeled in the alternative system above),



	Baseline System	Alternative System
Total energy consumption	92.5	67.3
Fossil energy consumption	118.3	86.0
Coal consumption	3.2	2.8
Natural gas consumption	266.9	193.2
Petroleum energy consumption	1.4	1.2
Contribution to climate change (from as CO_2, N_2O, & CH_4)	63.2	46.0
Contribution to photochemical smog (from CH_4, NO_x, CO, & VOCs)	2.2	1.6
Contribution to acidification (from SO_x & NO_x)	2.5	2.1
Particulate Matter emissions (as PM10)	5.4	4.5
Particulate Matter emissions (as PM2.5)	1.7	1.5
Use of recycled components	0.0	-3.9
Reuse/ remanufacturing/ recycling	-9.5	-14.1
System PEMFC-EcoScore (ESs_{PEMFC})	**547.7**	**388.2**

Fig. 3. Contribution analysis: system EcoScores (ESs_{PEMFC}) by environmental impact.

Table 7
Case study reference system efficiencies.

Natural gas: a small industrial boiler (10–100 mmBTU h^{-1} input)	35%
Natural gas: a stationary reciprocating engine	40%
Diesel fuel: a industrial boiler	35%
Diesel fuel: a stationary reciprocating engine	40%
Gasoline: a stationary reciprocating engine	40%
Crude: a industrial boiler	35%
LPG: a industrial boiler	30%
Coal: a industrial boiler	34%
Farmed trees: industrial boiler	20%
Herbaceous biomass: a small industrial boiler	20%
Corn stover: a small industrial boiler	20%
Forest residue: in an industrial boiler	20%
Hydrogen: a boiler	35%

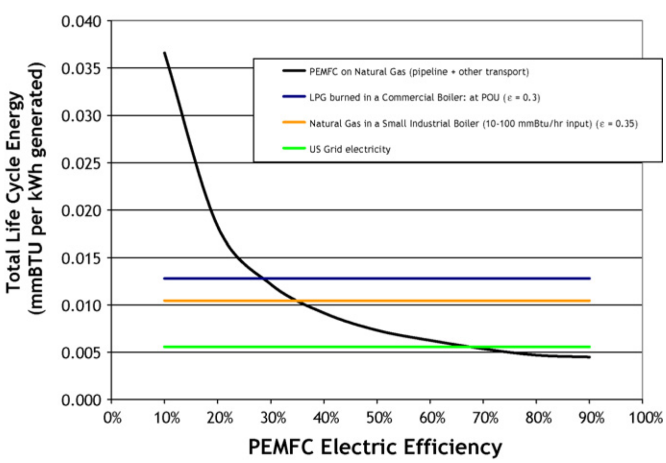


Fig. 4. Life cycle total energy: efficiency analysis.

yellow cells represent PEMFC breakeven efficiencies between 30 and 100%, and red cells represent breakeven efficiencies greater than 100%. As shown, for energy environmental impacts current natural gas PEMFC systems are found superior to the reference systems most frequently for both petroleum and coal consumption, followed by total energy, fossil, and natural gas. On the basis of emissions related environmental impacts, the current natural gas PEMFCs are found to be superior to the all reference systems.

Finally, Fig. 6 presents additional breakeven efficiencies for hydrogen PEMFCs for 11 hydrogen production methods and based on the efficiency data presented in Table 7 and assuming zero operating emission. In Fig. 6, the green and yellow cell thresholds have been raised to 40%,[8] assuming this higher PEMFC efficiency is achieved in currently available hydrogen systems. For energy-related environmental impacts, current PEMFC systems are found superior to the reference systems most frequently for petroleum consumption followed by fossil, natural gas, total energy, and coal. For the emissions related environmental impacts, current hydrogen fueled PEMFC systems are found superior to the reference systems most frequently for the contribution to smog formation followed by acidification, climate change, and finally particulate matter emissions.

5. Discussion

The case study demonstrates the ease of use of the EcoScore system. Because the method allows specification of a wide variety of energy generation technology design parameters, we found that design priorities could be established using the EcoScore system for the environmental impacts studied, including the relative importance of efficiency increases versus hardware changes and specific recycling opportunities. However, we recognize the need to increase the variety of fuel and material options and study regions available for assessment. For fuel cell hardware, the inclusion of non-fluorinate membrane materials, a variety of catalyst options, a variety of composite flow field plate compositions (including the use of recycled materials), and a variety of clean-up media are desirable. For study regions, production and operation outside of the U.S. are certainly of interest.

Given this, perhaps the most important contributions of this work lie in four areas. *First*, we have added to the set of existing technology-specific LCA-based design tools for use in rapid design cycles. Based on our experience and on an evaluation of the construction of the BEES system (again LCA tools specific to buildings and to bioproducts), we note that in general the development of technology-specific LCA-based design tools should use design data that are relevant to the technology at hand and should present results on the basis of the finished product. In BEES for buildings, this is realized through the use of design data in categories of, for example, exterior wall finishes, wall insulation, framing, roof coverings, and parking lot paving and the presentation of results on the basis of a finished square foot of building space. For the EcoScores, this is realized through the use of design data in categories of relevant fuels, operating emissions, assembly energy use, materials transport, and specific materials used in fuel cell construction and the presentation of results on the basis of fuel cell energy generated (such as in the case study, where all results combine to estimate the life cycle environmental impacts for the generation of 162,171 kWh over a 10-year period).

Tables 8 and 9 provide additional information comparing existing LCA-based scoring systems. As shown, although all of the scoring systems include more score categories and consider more environmental impacts than the EcoScores system, only EcoScores includes energy use other than fossil fuels, the use of recycled material, and the recovery (reuse, remanufacturing, or recycling) as environmental impacts contributing to the final score.[9] Further, only BEES includes an economic score in addition to their environmental score.

Second, we have based the EcoScores on *publicly available* and highly peer reviewed LCA data that are widely accepted among the U.S. LCA, DOE, and EPA communities. Thus, the data and results have been and can continue to be critiqued. In fact, un-normalized results can be obtained and reviewed from the data presented here. Specifically, multiplying the data in Appendix A and by the commensurate data in Table 4 and dividing by 100 gives the raw life cycle impact assessment results (or the impact score depicted in Fig. 1). For example, again if the unit EcoScore for natural gas related to total energy use is 0.49 mmBTU^{-1}, then the un-normalized life cycle impact result is 0.49 multiplied by 219 (the total energy normalization value given in Table 4) divided by 100 or 1.07 mmBTU/mmBTU of natural gas used (including through put).

Third, and again like BEES, we have presented our results in a way that allows the impact weighting scheme to be specified by the PEMFC designer. Although extensive research has been dedicated to developing weighting schemes as in for example the development of the Pré EcoIndicators (see [3]) and as mimicked in the

[8] See for example http://www.hydrogen.gov/taxonomy/html/hydrogen_conversion/a_proton_exchange_membrane_fuel_cells.html.

[9] All systems model the production of recycled materials differently from the production of virgin materials, however only the EcoScores carries this information through as an environmental impact in the results.

	US Grid electricity	CAL Grid electricity	NE Grid electricity	Natural Gas burned in a Small Industrial Boiler (10-100 mmBtu/hr input)	Natural Gas burned in a Stationary Reciprocating Engine	Diesel Fuel burned in a Industrial Boiler	Diesel Fuel burned in a Stationary Reciprocating Engine	Gasoline burned in a Stationary Reciprocating Engine	Crude burned in a Industrial Boiler	LPG burned in a Industrial Boiler	Coal burned in a Industrial Boiler	Farmed Trees burned in a Small Industrial Boiler	Herbaceous Biomass burned in a Small Industrial Boiler	Corn Stover burned in a Small Industrial Boiler	Forest Residue burned in a Small Industrial Boiler	Hydrogen burned in a Boiler
Total energy	66%	88%	76%	35%	40%	32%	36%	35%	36%	29%	36%	21%	20%	21%	20%	22%
Fossil	68%	94%	83%	35%	40%	32%	36%	35%	36%	29%	36%					53%
Coal	0%	1%	0%	35%	40%	3%	3%	2%	12%	3%	0%	21%	10%	14%	8%	1%
Natural gas				35%	40%											68%
Petroleum	5%	15%	2%	35%	40%	0%	0%	0%	0%	0%	24%	3%	4%	3%	1%	9%
Climate Change	4%	7%	6%	5%	5%	4%	4%	4%	4%	4%	3%	2%	2%	2%	1%	3%
Smog	12%	22%	14%	18%	1%	8%	2%	2%	5%	8%	6%	3%	4%	1%	4%	8%
Acidification	4%	11%	5%	19%	1%	9%	2%	3%	2%	8%	3%	4%	4%	1%	5%	6%
PM10	0%	1%	0%	8%	5%	1%	0%	1%	1%	3%	0%	1%	1%	1%	1%	1%
PM2.5	1%	2%	1%	5%	3%	0%	0%	1%	1%	3%	0%	1%	1%	1%	1%	1%

Fig. 5. Breakeven efficiencies: case study PEMFC system.

Table 8
Scores categories in LCA-based scoring system.

Scoring system	Score categories
BEES	For buildings: Roof sheathing; exterior wall finishes; wall insulation; framing; wall sheathing; roof coverings; ceiling insulation; partitions; fabricated toilet partitions; lockers; finishes to interior walls; floor coverings; ceiling finishes; fixed casework; chairs; table tops; counter tops; shelving; slab on grade; basement walls; beams; columns; soil treatment; parking lot paving; transformer oil For bioproducts[a]: Agricultural products and chemicals; automotive, aircraft, and marine construction/maintenance materials, chemicals, and coatings; building materials and construction/maintenance materials and chemicals; household cleaners and chemicals; industrial solvents and chemicals; molded products; oils/lubricants; packaging; personal care products; recycling and waste management; textiles; other (from toys to grease and graffiti removers, too varied to list)
Okala Impact Factors[b]	Metal components; plastic components; packaging; chemicals; building materials; electricity; heat; fuels; transport; incineration; landfilling; other (paint; coatings; batteries; mixed integrated circuitry; corn; potatoes)
EcoScores	Materials; electricity; on-site energy generation; fuel cell fuels; fuel cell operating emissions; transport; waste management (transport at retirement only)
Pré's Eco-Indicators	Metal components; plastic components; packaging; chemicals; building materials; electricity; heat; solar energy; transport; recycling; incineration; landfilling; municipal and household waste

[a] This summary was created from the 173 planned "designation items" listed at http://www.biobased.oce.usda.gov/fb4p/DesignationItems.aspx.
[b] See http://www.idsa.org/whatsnew/sections/ecosection/pdfs/IDSA_Ecodesign_Report_Oct_04.pdf list of scores for a list of the Okala scores.

Table 9
Comparison of impacts considered in score estimation.

Scoring system	Impacts considered in score estimation
Pré's Eco-Indicators	*Ecological damage*: The percentage of species that have disappeared in a certain area due to the environmental load as a function of regional and local effects on vascular plant species, acidification and eutrophication, and ecotoxicity toxic stress *Human health damage*: Disability adjusted life years as a function of climate change, ozone layer depletion, ionization radiation, respiratory effects, and carcinogenesis *Resource depletion*: Damage to fossil resources as a function of surplus energy for future extraction
Okala Impact Factors	*Ecological damage*: Global climate change, ozone depletion, acid rain, water eutrophication, habitat alteration, and ecotoxicity *Human health damage*: Photochemical smog and air pollutants, health damaging substances, and carcinogens *Resource depletion*: Fossil fuels, fresh water, minerals, and topsoil
BEES	*Ecological damage*: Global climate change, ozone depletion, acidification, eutrophication, and ecological toxicity *Human health damage*: Smog, indoor air quality, criteria air pollutants, and impacts associated with cancer and other human health issues *Resource depletion*: Fossil fuel depletion and water intake Economic performance: first and future costs
EcoScores	*Ecological damage*: Global climate change (from as CO_2, N_2O, and CH_4) and acidification (from SO_x and NO_x) *Human health damage*: Contribution to photochemical smog (from CH_4, NO_x, CO, and NMVOCs) and particulate matter emissions (as PM10 and PM2.5) *Resource depletion*: Total energy, fossil fuels, coal, natural gas, petroleum fuels, use of recycled material, recycling of end of life materials

Okala scores, we presume that there is no weighting scheme that is universally acceptable to all people or all companies.

Fourth, we have presented breakeven efficiencies as a method for setting energy generation technology performance targets based on LCA and alternative distributed generation methods. We presume this will assist in the continuing development activities as well as in design. For the case study breakeven efficiencies given in Figs. 4 and 5, *clearly the high end of the yellow zone is not possible*

		US Grid electricity	CAL Grid electricity	NE Grid electricity	Natural Gas burned in a Small Industrial Boiler (10-100 mmBtu/hr input)	Natural Gas burned in a Stationary Reciprocating Engine	Diesel Fuel burned in a Industrial Boiler	Diesel Fuel burned in a Stationary Reciprocating Engine	Gasoline burned in a Stationary Reciprocating Engine	Crude burned in a Industrial Boiler	LPG burned in a Industrial Boiler	Coal burned in a Industrial Boiler	Farmed Trees burned in a Small Industrial Boiler	Herbaceous Biomass burned in a Small Industrial Boiler	Corn Stover burned in a Small Industrial Boiler	Forest Residue burned in a Small Industrial Boiler	Hydrogen burned in a Boiler
Gaseous Hydrogen: GREET Combination of Technologies	Total energy				57%	65%	51%	59%	57%	59%	46%	58%	34%	33%	33%	32%	35%
	Fossil	45%	62%	55%	23%	26%	21%	24%	23%	24%	19%	24%					35%
	Coal	13%	44%	20%								5%					35%
	Natural gas		70%		18%	21%											35%
	Petroleum	18%	54%	9%			1%	1%	1%	1%	0%	88%	13%	13%	12%	4%	35%
Gaseous Hydrogen: central generation from NG	Total energy				57%	65%	52%	59%	57%	59%	47%	59%	34%	33%	33%	32%	35%
	Fossil	45%	63%	55%	23%	27%	21%	24%	23%	24%	19%	24%					35%
	Coal	13%	47%	21%								5%					37%
	Natural gas		69%		18%	20%											34%
	Petroleum	26%	80%	13%			1%	1%	1%	1%	1%		18%	19%	18%	7%	51%
Gaseous Hydrogen: central generation from Solar Energy	Total energy				54%	62%	49%	56%	54%	56%	44%	56%	32%	31%	32%	31%	33%
	Fossil	14%	20%	17%	7%	8%	7%	8%	7%	8%	6%	8%		75%		54%	11%
	Coal	13%	46%	21%								5%					36%
	Natural gas	16%	8%	15%	2%	2%	34%	39%	32%		42%			38%	95%		4%
	Petroleum	20%	59%	10%			1%	1%	1%	1%	0%	95%	14%	14%	13%	5%	38%
Gaseous Hydrogen: central generation from Nuclear	Total energy	80%		92%	43%	49%	39%	44%	43%	44%	35%	44%	25%	25%	25%	24%	26%
	Fossil	17%	24%	21%	9%	10%	8%	9%	9%	9%	7%	9%		91%		66%	13%
	Coal	16%	55%	25%								6%					43%
	Natural gas	20%	9%	18%	2%	3%	42%	48%	39%		52%			47%			5%
	Petroleum	24%	74%	13%			1%	1%	1%	1%	1%		17%	18%	16%	6%	48%
Gaseous Hydrogen: central generation from Electrolysis (HTGR)	Total energy	96%			51%	59%	47%	53%	51%	53%	42%	53%	30%	30%	30%	29%	32%
	Fossil	18%	25%	22%	9%	11%	8%	10%	9%	10%	8%	10%		95%		69%	14%
	Coal	16%	57%	26%								6%					45%
	Natural gas	21%	10%	19%	3%	3%	44%	50%	41%		55%			50%			5%
	Petroleum	26%	78%	13%			1%	1%	1%	1%	1%		18%	19%	17%	6%	50%
Gaseous Hydrogen: central generation from Coal	Total energy				63%	72%	57%	65%	63%	65%	51%	65%	37%	36%	37%	35%	39%
	Fossil	56%	78%	68%	29%	33%	26%	30%	29%	30%	24%	30%					44%
	Coal	71%										27%					
	Natural gas	18%	8%	16%	2%	2%	36%	42%	34%		45%			41%			4%
	Petroleum	31%	95%	16%			1%	1%	1%	1%	1%		22%	23%	21%	8%	61%
Gaseous Hydrogen: central generation from Biomass	Total energy				78%	89%	71%	81%	78%	81%	64%	80%	46%	45%	46%	44%	48%
	Fossil	27%	37%	33%	14%	16%	13%	14%	14%	14%	11%	14%					21%
	Coal	19%	67%	30%								7%					54%
	Natural gas	39%	18%	35%	5%	5%	80%	91%	74%		99%			90%			9%
	Petroleum	77%		39%			2%	2%	2%	2%	2%		54%	56%	51%	19%	
Gaseous Hydrogen: on-site generation from NG	Total energy	96%			51%	59%	46%	53%	51%	53%	42%	53%	30%	30%	30%	29%	32%
	Fossil	36%	49%	43%	18%	21%	17%	19%	18%	19%	15%	19%					28%
	Coal	3%	12%	5%			41%	47%	38%		53%	1%					9%
	Natural gas		65%		17%	19%											33%
	Petroleum	10%	29%	5%	69%	79%	0%	0%	0%	0%	0%	47%	7%	7%	6%	2%	19%
Gaseous Hydrogen: on-site generation from Electricity	Total energy												75%	73%	74%	71%	78%
	Fossil						100%				90%						
	Coal											81%					
	Natural gas				27%	30%											51%
	Petroleum			98%			5%	6%	6%	6%	5%					48%	
Gaseous Hydrogen: on-site generation from EtOH	Total energy																
	Fossil				91%		83%	95%	91%	94%	75%	94%					
	Coal	97%										37%					
	Natural gas				47%	53%											90%
	Petroleum						9%	10%	10%	10%	8%					78%	
Gaseous Hydrogen: on-site generation from MeOH	Total energy				98%		89%		98%		80%		58%	57%	58%	55%	60%
	Fossil				63%	72%	58%	66%	63%	65%	52%	65%					96%
	Coal	28%	99%	45%								11%					79%
	Natural gas				51%	58%											98%
	Petroleum	91%		46%			3%	3%	3%	3%	2%		64%	67%	61%	23%	

Fig. 6. Breakeven efficiencies: hydrogen PEMFCs.

		US Grid electricity	CAL Grid electricity	NE Grid electricity	Natural Gas burned in a Small Industrial Boiler (10-100 mmBtu/hr input)	Natural Gas burned in a Stationary Reciprocating Engine	Diesel Fuel burned in a Industrial Boiler	Diesel Fuel burned in a Stationary Reciprocating Engine	Gasoline burned in a Stationary Reciprocating Engine	Crude burned in a Industrial Boiler	LPG burned in a Industrial Boiler	Coal burned in a Industrial Boiler	Farmed Trees burned in a Small Industrial Boiler	Herbaceous Biomass burned in a Small Industrial Boiler	Corn Stover burned in a Small Industrial Boiler	Forest Residue burned in a Small Industrial Boiler	Hydrogen burned in a Boiler
Gaseous Hydrogen: GREET Combination of Technologies	Climate Change	52%	89%	67%	60%	62%	43%	50%	49%	49%	43%	36%	23%	23%	21%	17%	35%
	Smog	32%	59%	37%	49%	3%	22%	4%	5%	14%	21%	17%	9%	10%	3%	10%	20%
	Acidification	16%	45%	20%	78%	5%	34%	8%	11%	7%	34%	12%	17%	17%	5%	18%	25%
	PM10	13%	44%	20%			26%	22%	43%	42%		5%	54%	51%	52%	45%	35%
	PM2.5	25%	79%	38%			16%	13%	29%	34%		7%	53%	51%	50%	41%	35%
Gaseous Hydrogen: central generation from NG	Climate Change	51%	88%	66%	59%	62%	43%	49%	48%	49%	43%	35%	23%	23%	21%	17%	35%
	Smog	40%	73%	45%	60%	3%	27%	5%	6%	17%	26%	21%	11%	12%	4%	13%	25%
	Acidification	19%	53%	23%	91%	6%	40%	9%	13%	9%	40%	14%	19%	20%	6%	22%	29%
	PM10	14%	46%	21%			27%	23%	45%	44%		5%	57%	54%	54%	47%	37%
	PM2.5	26%	82%	40%			17%	14%	30%	35%		7%	55%	52%	52%	43%	36%
Gaseous Hydrogen: central generation from Solar Energy	Climate Change	10%	16%	12%	11%	12%	8%	9%	9%	9%	8%	7%	4%	4%	4%	3%	6%
	Smog	14%	25%	16%	21%	1%	9%	2%	2%	6%	9%	7%	4%	4%	1%	4%	9%
	Acidification	11%	29%	13%	51%	3%	22%	5%	7%	5%	22%	8%	11%	11%	3%	12%	16%
	PM10	9%	31%	14%			18%	15%	30%	29%	86%	3%	37%	36%	36%	31%	24%
	PM2.5	9%	29%	14%	71%	47%	6%	5%	10%	12%	37%	3%	19%	18%	18%	15%	13%
Gaseous Hydrogen: central generation from Nuclear	Climate Change	12%	20%	15%	13%	14%	10%	11%	11%	11%	10%	8%	5%	5%	5%	4%	8%
	Smog	17%	31%	19%	26%	1%	12%	2%	3%	7%	11%	9%	5%	5%	2%	5%	11%
	Acidification	13%	35%	15%	61%	4%	27%	6%	8%	6%	26%	9%	13%	13%	4%	14%	19%
	PM10	11%	37%	17%			22%	18%	36%	35%		4%	45%	43%	43%	37%	29%
	PM2.5	11%	35%	17%	86%	56%	7%	6%	13%	15%	45%	3%	23%	22%	22%	18%	15%
Gaseous Hydrogen: central generation from Electrolysis (HTGR)	Climate Change	12%	21%	16%	14%	15%	10%	12%	11%	11%	10%	8%	5%	5%	5%	4%	8%
	Smog	18%	33%	20%	27%	1%	12%	2%	3%	8%	12%	9%	5%	5%	2%	6%	11%
	Acidification	13%	36%	16%	63%	4%	28%	6%	9%	6%	27%	10%	13%	14%	4%	15%	20%
	PM10	11%	38%	18%			23%	19%	37%	36%		4%	47%	45%	45%	39%	30%
	PM2.5	12%	36%	18%	90%	59%	8%	6%	13%	15%	47%	3%	24%	23%	23%	19%	16%
Gaseous Hydrogen: central generation from Coal	Climate Change	93%					78%	89%	88%	88%	77%	64%	42%	42%	38%	30%	63%
	Smog	21%	38%	24%	31%	2%	14%	3%	3%	9%	14%	11%	6%	6%	2%	7%	13%
	Acidification	15%	41%	18%	71%	4%	31%	7%	10%	7%	31%	11%	15%	16%	5%	17%	23%
	PM10											38%					
	PM2.5	100%					64%	51%				28%					
Gaseous Hydrogen: central generation from Biomass	Climate Change	19%	32%	24%	22%	23%	16%	18%	18%	18%	16%	13%	8%	9%	8%	6%	13%
	Smog	42%	77%	48%	63%	3%	28%	5%	7%	18%	27%	22%	12%	12%	4%	13%	26%
	Acidification	23%	64%	28%		7%	49%	11%	15%	10%	48%	17%	24%	25%	8%	26%	35%
	PM10	14%	48%	22%			28%	23%	46%	46%		5%	59%	56%	56%	49%	38%
	PM2.5	16%	51%	25%		83%	11%	8%	18%	22%	66%	5%	34%	33%	32%	27%	23%
Gaseous Hydrogen: on-site generation from NG	Climate Change	45%	78%	59%	52%	55%	38%	43%	43%	43%	38%	31%	20%	21%	18%	15%	31%
	Smog	26%	48%	30%	39%	2%	18%	3%	4%	11%	17%	14%	7%	8%	2%	8%	16%
	Acidification	10%	27%	12%	48%	3%	21%	5%	7%	4%	21%	7%	10%	11%	3%	11%	15%
	PM10	7%	23%	10%			13%	11%	22%	22%	64%	2%	28%	26%	27%	23%	18%
	PM2.5	19%	59%	29%		96%	12%	10%	21%	25%	76%	5%	40%	38%	37%	31%	26%
Gaseous Hydrogen: on-site generation from Electricity	Climate Change												65%	66%	59%	47%	99%
	Smog					12%	99%	19%	24%	63%	95%	76%	42%	43%	14%	46%	92%
	Acidification					43%		71%	96%	65%					47%		
	PM10											53%					
	PM2.5						94%	75%				41%					
Gaseous Hydrogen: on-site generation from EtOH	Climate Change											85%	55%	56%	50%	40%	84%
	Smog					19%		30%	38%				67%	69%	22%	74%	
	Acidification					33%		54%	73%	49%		82%			36%		
	PM10	95%										35%					
	PM2.5						78%	62%				34%					
Gaseous Hydrogen: on-site generation from MeOH	Climate Change	80%			92%	97%	67%	77%	75%	76%	67%	55%	36%	36%	33%	26%	54%
	Smog					8%	70%	13%	17%	44%	67%	54%	30%	31%	10%	33%	65%
	Acidification	47%		56%		14%	98%	23%	31%	21%	97%	34%	47%	49%	15%	53%	71%
	PM10	32%		49%			63%	52%				12%					85%
	PM2.5	65%		98%			42%	33%	73%	86%		18%					89%

Fig. 6. (*Continued*).

and in fact since the life cycle PEMFC performance is dependent upon fuel production energy use and emissions it is not only the PEMFC technologies that should strive for further improvements. Improvements to the fuel delivery infrastructure are expected to substantially change the breakeven efficiency results. Further analysis is expected in later versions of the EcoScore method, which will seek to investigate the role of infrastructure changes and energy use and emissions over time.

Finally, although we recognize that the scope and assumptions of each LCA dictate the results (e.g., whether or not infrastructure processes have been included, the study region, etc.), we were very interested in making an order of magnitude comparisons of the un-normalized EcoScore results to existing LCA data in an attempt to ensure the results are at least in line with LCA data published in other contexts. So, although consistently representing a different scope, we compared the un-normalized EcoScore results to data available through the EcoInvent LCA database.[10] Because not all the EcoScore fuels and materials are covered by EcoInvent (nor to our knowledge anywhere else in the public domain), our comparison is limited to 23 materials, 2 fuels, 2 methods of on-site energy generation, and 4 modes of transport.[11] For our comparison, we chose life cycle fossil energy use and contribution to climate change as representative of the calculation methods for the non-recycling environmental impacts. Overall, we found that the data compared well, with the exception of that for platinum and PTFE. Specifically and for a moment eliminating platinum and PTFE from the assessment, our data comparison found a correlation coefficient of 0.95 and 0.94 for life cycle fossil consumption and climate change, respectively. When platinum and PTFE are included, all correlation essentially disappears. Further investigation found substantial data quality issues documented in both GREET and EcoInvent concerning these data sets (e.g., see especially [8] for more details). As a result, the EcoScores suffer from the same data quality issues so that we conclude that a sensitivity analysis is needed when using the EcoScores. As an example, our case study results are insensitive to changes in the platinum EcoScore up to five orders of magnitude.

6. Conclusions

In conclusion, we present the EcoScores as a method for the rapid preparation of LCA results keyed to emerging energy generation technologies for use in setting design change priorities and efficiency targets. We recognize that the specification of weighting factors and sensitivity analysis is critical to interpreting case studies using EcoScores. For the breakeven efficiencies, we also note that results are dependent upon the assumed reference system efficiencies and will change with changes in the fuel delivery infrastructure. We further note that because the data supporting the development of the scores and breakeven efficiencies are publicly available, our results can be critiqued and any related case studies interpreted.

Future work will include the development of EcoScores for more membranes and catalysts (as defined in [20]), coolants, and absorbents, and the inclusion of paints, coatings, solvents used in metal component fabrication, and landfilling, incineration processes, and component remanufacturing processes and data for the evaluation of renewable reference systems. Further, we intend to develop time series and geographically specific EcoScores and to include a wider range of sustainability metrics (starting with the assessment of life cycle costs and the role of toxics). Finally, we anticipate the use of EcoScores to develop design targets, the integration of EcoScores into stack and system performance estimation

[10] See http://www.ecoinvent.ch/.

[11] EcoInvent data used in the comparison were: for materials (data sets 244, 261, 352, 402, 550, 1054, 1057, 1058, 1060, 1069, 1072, 1074, 1098, 1103, 1106, 1109, 1133, 1151, 1153, 1154, 1156, 1816, and 1834 for alumina, six types of aluminum, carbon black, iron, stainless, copper, electronics, ethylene glycol, nickel, fiberglass, lead, magnesium, manganese, platinum, polypropylene, three types of carbon steel, PTFE, and zinc), for fuels (data sets 1413 and 1576 for natural gas and LPG and noting that EcoInvent does not include data for gaseous hydrogen), for on-site energy generation (data sets 1345 and 1584 for natural gas and diesel boilers and noting that EcoInvent does not include data for the U.S. electricity grid), and for transport (data sets 1918, 1920, 1923, 1925, 1958, 1969, and 1979 for barges, trains, and two types of trucks).

Table A.1
Stationary fuels (per mmBTU fuel used).

	Total energy	Fossil fuels	Coal	Natural gas	Petroleum	Climate change	Smog formation	Acidification	PM10	PM2.5
Gaseous hydrogen: GREET combination of technologies, at POU	7.95E−01	4.15E−01	1.88E−01	7.45E−01	1.15E−02	5.35E−01	2.15E−02	3.19E−02	1.95E−01	7.54E−02
Gaseous hydrogen: central generation from NG, at POU	7.99E−01	4.19E−01	2.01E−01	7.30E−01	1.69E−02	5.29E−01	2.64E−02	3.74E−02	2.05E−01	7.82E−02
Gaseous hydrogen: central generation from solar energy, at POU	7.56E−01	1.31E−01	1.95E−01	8.09E−02	1.25E−02	9.91E−02	9.23E−03	2.07E−02	1.35E−01	2.75E−02
Gaseous hydrogen: central generation from nuclear, at POU	5.98E−01	1.59E−01	2.34E−01	1.00E−01	1.56E−02	1.20E−01	1.13E−02	2.49E−02	1.62E−01	3.32E−02
Gaseous hydrogen: central generation from electrolysis (HTGR), at POU	7.19E−01	1.66E−01	2.43E−01	1.05E−01	1.64E−02	1.25E−01	1.19E−02	2.59E−02	1.69E−01	3.46E−02
Gaseous Hydrogen: central generation from coal, at POU	8.78E−01	5.20E−01	1.05E+00	8.68E−02	2.01E−02	9.62E−01	1.39E−02	2.90E−02	1.56E+00	2.96E−01
Gaseous hydrogen: central generation from biomass, at POU	1.09E+00	2.49E−01	2.88E−01	1.90E−01	4.90E−02	1.95E−01	2.78E−02	4.53E−02	2.12E−01	4.86E−02
Gaseous hydrogen: on-site generation from NG (no compression), at POU	7.18E−01	3.30E−01	5.03E−02	6.97E−01	6.16E−03	4.70E−01	1.72E−02	1.95E−02	1.00E−01	5.65E−02
Gaseous hydrogen: on-site generation from electricity (no compression), at POU	1.76E+00	1.97E+00	3.16E+00	1.09E+00	1.22E−01	1.51E+00	9.70E−02	2.83E−01	2.17E+00	4.34E−01
Gaseous hydrogen: on-site generation from ethanol (no compression), at POU	2.57E+00	1.63E+00	1.45E+00	1.92E+00	2.01E−01	1.28E+00	1.55E−01	2.15E−01	1.41E+00	3.59E−01
Gaseous hydrogen: on-site generation from methanol (no compression), at POU	1.37E+00	1.14E+00	4.24E−01	2.08E+00	5.80E−02	8.29E−01	6.86E−02	9.11E−02	4.71E−01	1.92E−01
Liquid Petroleum Gas (LPG), at POU	5.14E−01	6.57E−01	2.83E−02	5.79E−02	7.67E−01	5.61E−02	1.18E−02	1.30E−02	3.05E−02	9.55E−03
Natural gas for electricity generation, at POU (pipeline only)	4.89E−01	6.26E−01	3.04E−03	1.44E+00	3.10E−03	4.04E−02	6.95E−03	7.77E−03	4.25E−03	1.92E−03
Natural gas for stationary uses, at POU (pipeline + other transport)	4.90E−01	6.28E−01	3.18E−03	1.44E+00	3.11E−03	4.28E−02	7.14E−03	7.91E−03	4.41E−03	1.99E−03

models and models for Reliability, Availability, and Maintainability analyses.

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Appendix A

Normalized Life Cycle Assessment results ($N_{i,c}$): U.S. annual per capita contribution[12]

Tables A.1, A.2, A.3, A.4, A.5, A.6, A.7 and A.8.

Appendix B

Example EcoScore calculations

Consider the following example intended to illustrate the use of the EcoScores in four steps:

Step 1. Estimate the PEMFC design data (Q_c) for the baseline system components and the components of any design variants of interest.

Suppose two 5 kW PEMFC systems are being compared:

(1) a baseline system containing 290 kg of typical U.S. steel (such that Q_{steel} = 290 kg), operates at 21.6% electric efficiency with operating air emissions of 150,000 kg CO_2 over a 10-year operating period;
(2) an alternative system specifying that the 290 kg of steel be recycled material (again such that Q_{steel} = 290 kg), operates at 30% electric efficiency with operating air emissions of 110,000 kg CO_2 over the same 10-year period.

Both systems are assumed to operate at a capacity of 37% on natural gas that must be transported to the operating site (i.e., the systems are not pipeline connected). Also, assume for the moment that all other system emissions and materials are the same (so that other components can be omitted from this brief example).

Given this, *PEMFC fuel consumption* is based on the electric efficiency, the system kW-rating and capacity, and the operating period:

$$Q_{\text{PEMFC fuel}} = \frac{3412\,PCO}{\varepsilon} \quad \text{(B.1)}$$

where: $Q_{\text{PEMFC fuel}}$: the PEMFC fuel use over the operating period (BTU); 3412: conversion factor (kW to BTU h^{-1}); P: the PEMFC power rating (kW) over the operating period; C: the PEMFC capacity (%); O: length of operating period (h); ε: the PEMFC electric efficiency (%).

such that for the baseline and alternative systems, $Q_{\text{PEMFC fuel}}$ is estimated as 2562 mmBTU and 1845 mmBTU, respectively. Thus, the design data for the example is given in Table B.1 with the kWh output of both systems estimated as *PCO* or 162,171 kWh over the 10-year period.

Step 2. Estimate the unit EcoScores (ESu_c) for the design data by:

[12] POU stands for "point-of-use".

Table A.2
Mobile fuels (per mmBTU fuel used).

	Total energy	Fossil fuels	Coal	Natural gas	Petroleum	Climate change	Smog formation	Acidification	PM10	PM2.5
Conventional gasoline and RFG, at Pump	5.68E−01	7.25E−01	1.38E+00	1.47E+00	8.05E−01	9.18E−02	1.85E−02	1.75E−02	6.14E−02	1.79E−02
CA RFG, at Pump	5.70E−01	7.27E−01	1.39E+00	1.47E+00	8.01E−01	8.89E−02	1.64E−02	1.54E−02	5.50E−02	1.47E−02
Low-level EtOH blend with gasoline, at pump	5.77E−01	7.36E−01	1.39E+00	1.49E+00	8.03E−01	8.61E−02	1.96E−02	1.89E−02	7.19E−02	2.04E−02
Conventional and LS diesel, at pump	5.54E−01	7.07E−01	1.38E+00	1.45E+00	7.98E−01	8.62E−02	1.35E−02	1.58E−02	5.12E−02	1.52E−02
Compressed natural gas, at pump	5.29E−01	6.72E−01	1.40E+00	1.47E+00	7.32E−01	7.95E−02	9.58E−03	1.42E−02	5.07E−02	1.13E−02
Liquid natural gas, at pump	5.44E−01	6.96E−01	1.33E+00	1.58E+00	7.36E−01	7.72E−02	1.33E−02	1.36E−02	1.01E−02	4.37E−03
LPG, at pump	5.11E−01	6.53E−01	1.34E+00	1.45E+00	7.48E−01	5.19E−02	1.13E−02	1.31E−02	1.67E−02	5.76E−03
Naphtha, at pump	7.81E−01	1.00E+00	1.33E+00	2.27E+00	7.42E−01	1.46E−01	2.62E−02	2.47E−02	7.77E−02	5.61E−02
M85, nNA NG, at pump	6.93E−01	8.86E−01	1.35E+00	1.95E+00	7.67E−01	1.26E−01	2.94E−02	2.88E−02	7.61E−02	4.72E−02
M90, nNA NG, at pump	7.06E−01	9.04E−01	1.34E+00	2.00E+00	7.63E−01	1.29E−01	3.06E−02	3.00E−02	7.77E−02	5.03E−02
Methanol, nNA NG, at pump	7.37E−01	9.43E−01	1.33E+00	2.12E+00	7.53E−01	1.37E−01	3.33E−02	3.27E−02	8.14E−02	5.76E−02
E85, corn, at pump	7.48E−01	9.49E−01	1.54E+00	1.84E+00	7.95E−01	3.08E−02	4.04E−02	4.52E−02	2.51E−01	6.37E−02
E90, corn, at pump	7.63E−01	9.67E−01	1.55E+00	1.87E+00	7.94E−01	2.56E−02	4.22E−02	4.75E−02	2.67E−01	6.75E−02
Ethanol: corn, at pump	8.12E−01	1.03E+00	1.60E+00	1.98E+00	7.91E−01	8.25E−03	4.82E−02	5.52E−02	3.19E−01	8.01E−02
DME, nNA NG, at pump	7.10E−01	9.09E−01	1.33E+00	2.04E+00	7.51E−01	1.30E−01	2.80E−02	3.22E−02	7.58E−02	5.33E−02
FT100, nNA NG, at pump	7.80E−01	9.99E−01	1.33E+00	2.27E+00	7.42E−01	1.47E−01	2.26E−02	2.49E−02	7.77E−02	5.61E−02
BD20, at pump	5.91E−01	7.53E−01	1.39E+00	1.53E+00	8.06E−01	4.01E−02	2.28E−02	2.26E−02	6.33E−02	2.05E−02
E-diesel, at pump	5.71E−01	7.28E−01	1.39E+00	1.48E+00	7.97E−01	8.19E−02	1.56E−02	1.83E−02	6.82E−02	1.93E−02
Gaseous hydrogen, at pump	7.95E−01	1.00E+00	1.51E+00	2.10E+00	7.38E−01	5.35E−01	2.15E−02	3.19E−02	1.95E−01	7.54E−02
Liquid hydrogen, at pump	1.31E+00	1.58E+00	2.42E+00	2.43E+00	7.73E−01	9.60E−01	4.86E−02	1.11E−01	8.00E−01	1.97E−01

Table A.3
Generation technology operating air emissions (per kg).

	Total energy	Fossil fuels	Coal	Natural gas	Petroleum	Climate change	Smog formation	Acidification	PM10	PM2.5
NMVOC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.02E−01	0.00E+00	0.00E+00	0.00E+00
CO	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.46E−03	0.00E+00	0.00E+00	0.00E+00
NO_x	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.59E−01	2.13E−01	0.00E+00	0.00E+00
PM10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.13E+00	0.00E+00
PM2.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.89E+00
SO_x	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.71E−01	0.00E+00	0.00E+00
CH_4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.56E−02	7.66E−04	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.41E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO_2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.55E−03	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.4
Grid electricity (per kWh).

	Total energy	Fossil fuels	Coal	Natural gas	Petroleum	Climate change	Smog formation	Acidification	PM10	PM2.5
U.S. average grid electric generation: electricity available, at POU	2.55E−03	3.15E−03	5.08E−03	1.68E−03	2.18E−04	3.52E−03	2.26E−04	6.61E−04	5.07E−03	1.01E−03
California grid electric generation: electricity available, at POU	2.21E−03	2.59E−03	3.24E−03	1.88E−03	4.26E−04	2.73E−03	1.99E−04	5.53E−04	3.27E−03	6.69E−04
North east grid electric generation: electricity available, at POU	1.90E−03	2.28E−03	1.46E−03	3.63E−03	7.21E−05	2.06E−03	1.23E−04	2.43E−04	1.51E−03	3.24E−04

Table A.5
Transport (per tkm).

	Total energy	Fossil fuels	Coal	Natural gas	Petroleum	Climate change	Smog formation	Acidification	PM10	PM2.5
Bulk carriers and tankers, 40,820 dry weight tonne – 80% load	3.64E−05	4.65E−05	1.62E−06	3.41E−06	5.49E−05	3.16E−05	2.48E−05	5.00E−05	1.35E−05	5.02E−06
Cargo ships, 40,820 dry weight tonne – 80% load	4.27E−05	5.46E−05	1.90E−06	4.01E−06	6.45E−05	3.72E−05	2.92E−05	5.87E−05	1.59E−05	5.90E−06
Container/RORO/refrigerated ships, 40,820 dry weight tonne – 80% load	6.88E−05	8.80E−05	3.06E−06	6.46E−06	1.04E−04	5.99E−05	4.70E−05	9.46E−05	2.56E−05	9.51E−06
Transport – barge, average payload 1500 tonnes (US), 80% load	1.39E−04	1.77E−04	6.16E−06	1.30E−05	2.09E−04	1.20E−04	8.04E−05	8.55E−05	4.37E−05	1.62E−05
Transport by diesel freight train (US)	1.37E−04	1.75E−04	1.08E−05	2.12E−05	2.00E−04	1.10E−04	1.07E−04	8.64E−05	5.80E−05	3.53E−05
Transport by medium-heavy truck-class 6 or 7 (7.3 tonnes cargo), 7.3 mpg, 100% load	8.34E−04	1.07E−03	7.47E−05	1.44E−04	1.20E−03	6.71E−04	1.46E−04	1.23E−04	1.38E−04	6.57E−05
Transport by heavy–heavy truck – class 8a or 8b (18 tonnes cargo), 5.0mpg, 100% load	4.87E−04	6.22E−04	4.36E−05	8.43E−05	7.02E−04	3.90E−04	1.02E−04	8.52E−05	7.91E−05	3.72E−05
Transport by medium-heavy truck – class 6 or 7 (7.3 tonnes cargo), 7.3 mpg, 0% load	5.67E−04	7.24E−04	5.08E−05	9.82E−05	8.17E−04	4.56E−04	9.94E−05	8.37E−05	9.41E−05	4.47E−05
Transport by heavy–heavy truck – class 8a or 8b (18 tonnes cargo), 5.0 mpg, 0% load	3.31E−04	4.23E−04	2.97E−05	5.73E−05	4.77E−04	2.65E−04	6.93E−05	5.79E−05	5.38E−05	2.53E−05

Table A.6
Waste transport (per kg).

	Total energy	Fossil fuels	Coal	Natural gas	Petroleum	Climate change	Smog formation	Acidification	PM10	PM2.5
Transport of metallic waste to landfill or recycling	1.27E−04	1.62E−04	1.03E−05	2.01E−05	1.84E−04	1.03E−04	3.98E−05	3.56E−05	2.81E−05	1.36E−05
Transport of non-metallic waste to landfill or recycling	3.16E−04	4.04E−04	2.73E−05	5.30E−05	4.57E−04	2.54E−04	1.11E−04	9.12E−05	7.62E−05	4.14E−05

Table A.7
Materials (per kg material).

	Total energy	Fossil fuels	Coal	Natural gas	Petroleum	Climate change	Smog formation	Acidification	PM10	PM2.5
Alumina	5.63E−03	7.08E−03	2.05E−03	1.40E−02	1.15E−04	3.89E−03	2.76E−04	3.63E−04	2.76E−02	1.03E−02
Aluminum: average cast	4.76E−02	5.66E−02	5.11E−02	6.44E−02	7.57E−03	3.76E−02	2.78E−03	7.55E−03	8.43E−02	2.59E−02
Aluminum: average wrought	9.16E−02	1.07E−01	1.21E−01	9.42E−02	1.58E−02	7.52E−02	5.40E−03	1.65E−02	1.89E−01	5.72E−02
Aluminum: recycled cast	1.97E−02	2.52E−02	4.27E−04	5.51E−02	1.30E−03	1.28E−02	1.03E−03	9.36E−04	1.09E−03	6.46E−04
Aluminum: recycled wrought	2.08E−02	2.56E−02	1.19E−02	4.37E−02	1.74E−03	1.49E−02	1.12E−03	1.79E−03	9.07E−03	2.25E−03
Aluminum: virgin cast	8.78E−02	1.02E−01	1.24E−01	7.77E−02	1.66E−02	7.33E−02	5.29E−03	1.71E−02	2.04E−01	6.23E−02
Aluminum: virgin wrought	1.00E−01	1.17E−01	1.34E−01	1.00E−01	1.76E−02	8.26E−02	5.93E−03	1.83E−02	2.12E−01	6.40E−02
Cast iron	1.42E−02	1.81E−02	3.78E−02	5.29E−04	1.40E−03	2.41E−03	4.66E−04	5.35E−04	2.74E−02	5.89E−03
Cobalt oxide: average	4.37E−02	5.04E−02	6.24E−02	3.47E−02	9.64E−03	3.66E−02	2.52E−03	6.65E−03	4.53E−02	9.81E−03
Cobalt oxide: recycled	1.63E−02	1.88E−02	2.33E−02	1.29E−02	3.60E−03	1.37E−02	9.42E−04	2.48E−03	1.69E−02	3.66E−03
Cobalt oxide: virgin	6.52E−02	7.52E−02	9.31E−02	5.17E−02	1.44E−02	5.47E−02	3.77E−03	9.93E−03	6.75E−02	1.46E−02
Copper or brass	4.84E−02	5.86E−02	3.84E−02	5.57E−02	2.16E−02	3.86E−02	2.97E−03	6.07E−02	4.24E−02	1.05E−02
Lead: average	4.99E−03	6.26E−03	1.31E−02	5.53E−04	2.63E−04	2.86E−03	2.72E−04	3.46E−03	1.66E−02	4.24E−03
Lead: recycled	2.13E−03	2.73E−03	6.07E−03	1.10E−05	4.66E−05	2.35E−03	2.11E−04	1.51E−03	6.31E−03	1.64E−03
Lead: virgin	1.27E−02	1.58E−02	3.22E−02	2.02E−03	8.47E−04	4.25E−03	4.38E−04	8.74E−03	4.45E−02	1.13E−02
Magnesium	1.64E−01	1.90E−01	2.25E−01	1.93E−01	8.94E−03	1.33E−01	8.70E−03	2.18E−02	1.56E−01	3.20E−02
Manganese	5.17E−02	6.55E−02	8.43E−03	7.33E−02	3.71E−02	3.95E−02	3.48E−03	6.20E−03	2.73E−02	9.19E−03
Nickel hydroxide: average	2.67E−02	3.08E−02	3.75E−02	2.26E−02	5.46E−03	2.22E−02	1.53E−03	6.87E−02	3.04E−02	6.48E−03
Nickel hydroxide: recycled	2.52E−03	2.90E−03	3.59E−03	1.99E−03	5.55E−04	2.11E−03	1.45E−04	3.83E−04	2.60E−03	5.64E−04
Nickel hydroxide: virgin	4.57E−02	5.27E−02	6.42E−02	3.89E−02	9.32E−03	3.81E−02	2.61E−03	1.22E−01	5.23E−02	1.11E−02
Nickel: average	4.37E−02	5.04E−02	6.24E−02	3.47E−02	9.64E−03	3.66E−02	2.52E−03	1.09E−01	5.04E−02	1.08E−02
Nickel: recycled	1.63E−02	1.88E−02	2.33E−02	1.29E−02	3.60E−03	1.37E−02	9.42E−04	2.48E−03	1.69E−02	3.66E−03
Nickel: virgin	6.52E−02	7.52E−02	9.31E−02	5.17E−02	1.44E−02	5.47E−02	3.77E−03	1.92E−01	7.68E−02	1.64E−02
Platinum	8.85E−02	1.00E−01	1.46E−01	6.78E−02	7.65E−03	7.47E−02	5.04E−03	1.36E−02	1.10E−01	2.21E−02
Potassium hydroxide (KOH)	4.58E−03	5.86E−03	1.18E−04	6.85E−03	3.51E−03	3.46E−03	3.07E−04	5.31E−04	1.26E−03	6.22E−04
Rare earth	1.49E−01	1.67E−01	2.68E−01	9.28E−02	1.04E−02	1.28E−01	8.24E−03	2.41E−02	1.84E−01	3.69E−02
Steel: average	1.64E−02	2.00E−02	1.92E-02	2.51E−02	8.35E−04	1.47E−02	9.63E−04	1.40E−03	3.13E−02	6.92E-03
Steel: recycled	1.50E−02	1.81E−02	1.22E−02	2.82E−02	5.66E−04	1.04E−02	7.00E−04	1.37E-03	9.41E−03	2.16E−03
Steel: stainless	1.64E−02	1.96E−02	1.46E−02	2.93E−02	6.13E−04	1.11E-02	7.58E−04	1.59E−03	1.10E−02	2.47E−03
Steel: virgin	1.96E−02	2.46E−02	3.54E-02	1.78E−02	1.46E−03	2.46E−02	1.58E−03	1.47E−03	8.25E-02	1.80E−02
Zinc	5.17E−02	6.55E−02	8.43E−03	7.33E−02	3.71E-02	3.95E−02	3.48E−03	6.20E−03	2.73E−02	9.19E−03
Zirconium	9.92E−02	1.20E−01	8.14E−02	1.87E−01	3.47E−03	7.35E−02	4.96E−03	9.49E−03	5.80E−02	1.27E−02
Adhesives	2.64E−02	3.24E−02	1.56E−02	2.41E−02	1.87E−02	2.15E−02	1.83E−03	3.86E−03	1.67E−02	5.14E−03
Battery: lead acid	4.14E−02	4.69E−02	7.57E−02	2.49E−02	3.30E−03	3.45E−02	2.35E−03	8.59E−03	5.74E−02	1.22E−02
Battery: lithium ion	9.36E−02	1.09E−01	1.21E−01	8.71E−02	2.23E−02	7.73E−02	5.49E−03	3.58E−02	1.16E−01	2.93E−02
Battery: nickel-metal-hydride	8.48E−02	9.69E−02	1.36E−01	6.13E−02	1.24E−02	7.10E−02	4.78E−03	4.38E−02	1.03E−01	2.16E−02
Carbon	8.76E−02	1.12E−01	2.25E−03	1.31E−01	6.72E−02	6.63E−02	5.87E−03	1.02E−02	2.41E−02	1.19E−02
Carbon fiber composite plastic	6.49E−02	8.20E−02	1.31E−02	6.97E−02	5.70E−02	5.15E−02	4.63E−03	8.95E−03	2.75E−02	1.12E−02
Carbon paper	3.07E−01	3.92E−01	7.88E−03	4.59E−01	2.35E−01	2.32E−01	2.06E−02	3.56E−02	8.45E−02	4.17E−02
Electronic parts	3.54E−02	4.31E−02	2.49E−02	3.70E−02	1.99E−02	2.85E−02	2.30E−03	2.72E−02	2.72E−02	7.35E−03
Ethylene glycol	8.41E−03	1.07E−02	1.12E−03	1.21E−02	6.09E−03	7.79E−03	2.59E−03	1.21E−03	3.36E−03	1.41E−03
Fiberglass	9.01E−03	1.11E−02	4.39E−03	2.06E−02	3.26E−04	7.02E−03	3.42E−03	5.30E−03	3.30E−03	8.07E−04
Glass	8.73E−03	1.10E−02	2.21E−03	2.22E−02	4.77E−04	6.99E−03	4.23E−04	7.81E−04	3.45E−03	1.15E−03
Glass fiber composite plastic	3.16E−02	3.94E−02	1.23E−02	3.12E−02	2.53E−02	2.58E−02	3.92E−03	7.13E−03	1.66E−02	5.79E−03
Lithium oxide	4.37E−02	5.04E−02	6.24E−02	3.47E−02	9.64E−03	3.66E−02	2.52E−03	1.09E−01	5.04E−02	1.08E−02
Nafion dry polymer	1.04E−02	1.23E−02	1.18E−02	1.53E−02	4.81E−04	8.11E−03	5.38E−04	1.22E−03	8.28E−03	1.74E−03
Nafion117 sheet	1.06E−02	1.25E−02	1.21E−02	1.56E−02	4.91E−04	8.28E−03	5.49E−04	1.24E−03	8.46E−03	1.77E−03
Plastic: average	2.64E−02	3.24E−02	1.56E−02	2.41E−02	1.87E−02	2.15E−02	1.83E−03	3.86E−03	1.67E−02	5.14E−03
Polypropylene	2.13E−02	2.57E−02	1.79E−02	2.33E−02	9.50E−03	1.71E−02	1.35E−03	2.91E−03	1.53E−02	4.00E−03
PTFE	4.88E−02	6.13E−02	1.35E−02	6.69E−02	3.26E−02	3.76E−02	3.19E−03	5.97E−03	2.01E−02	7.39E−03
PVDF	1.04E−02	1.23E−02	1.18E−02	1.53E−02	4.81E−04	8.11E−03	5.38E−04	1.22E−03	8.28E−03	1.74E−03
Rubber	1.88E−02	2.40E−02	1.28E−03	2.77E−02	1.41E−02	1.43E−02	2.43E−03	2.20E−03	5.61E−03	2.60E−03
Thermal insulation	9.01E−03	1.11E−02	4.39E−03	2.06E−02	3.26E−04	7.02E−03	3.42E−03	5.30E−03	3.30E−03	8.07E−04

Table A.8
Use of recycled components and fuel cell hardware recycling (per mass % of system).

	Use of recycled components in standing system	Use of recycled components over system life (hardware and consumables)	Materials recovery from standing system	Materials recovery over system life (hardware and consumables)
All materials	−1	−1	−1	−1

Table B.1
Design data for example EcoScore calculations.

	PEMFC baseline	PEMFC alternative	
Natural gas for stationary uses, at POU (pipeline + other transport)	2,562	1,845	mmBTU
CO_2 operating air emissions	150,000	110,000	kg
Steel: average	290	0	kg
Steel: recycled	0	290	kg

Table C.1
Select fuels (per mmBTU) ($i_{i,f}$).

	Total energy (mmBTU)	Fossil fuels (mmBTU)	Coal (mmBTU)	Natural gas (mmBTU)	Petroleum (mmBTU)	Climate change (kg)	Smog formation (kg)	Acidification (kg)	PM10 (kg)	PM2.5 (kg)
Gaseous hydrogen: GREET combination of technologies, at POU	1.74E+00	7.09E−01	1.42E−01	5.51E−01	1.58E−02	1.18E+02	8.30E−02	5.99E+00	3.80E−02	1.94E−02
Gaseous hydrogen: central generation from NG, at POU	1.75E+00	7.15E−01	1.52E−01	5.41E−01	2.32E−02	1.16E+02	1.02E−01	7.02E+00	4.00E−02	2.01E−02
Gaseous hydrogen: central generation from solar energy, at POU	1.65E+00	2.24E−01	1.47E−01	5.99E−02	1.72E−02	2.18E+01	3.57E−02	3.88E+00	2.64E−02	7.07E−03
Gaseous hydrogen: central generation from nuclear, at POU	1.31E+00	2.72E−01	1.76E−01	7.43E−02	2.15E−02	2.63E+01	4.39E−02	4.66E+00	3.16E−02	8.52E−03
Gaseous hydrogen: central generation from electrolysis (HTGR), at POU	1.57E+00	2.84E−01	1.84E−01	7.78E−02	2.26E−02	2.74E+01	4.59E−02	4.86E+00	3.29E−02	8.88E−03
Gaseous hydrogen: central generation from coal, at POU	1.92E+00	8.87E−01	7.95E−01	6.43E−02	2.77E−02	2.11E+02	5.38E−02	5.44E+00	3.04E−01	7.60E−02
Gaseous hydrogen: central generation from biomass, at POU	2.39E+00	4.26E−01	2.17E−01	1.41E−01	6.75E−02	4.29E+01	1.07E−01	8.50E+00	4.13E−02	1.25E−02
Gaseous hydrogen: on-site generation from NG (no compression), at POU	1.57E+00	5.62E−01	3.79E−02	5.16E−01	8.49E−03	1.03E+02	6.67E−02	3.67E+00	1.95E−02	1.45E−02
Gaseous hydrogen: on-site generation from electricity (no compression), at POU	3.85E+00	3.36E+00	2.38E+00	8.09E−01	1.68E−01	3.32E+02	3.75E−01	5.32E+01	4.24E−01	1.12E−01
Gaseous hydrogen: on-site generation from ethanol (no compression), at POU	5.62E+00	2.79E+00	1.09E+00	1.42E+00	2.77E−01	2.81E+02	6.00E−01	4.04E+01	2.75E−01	9.23E−02
Gaseous hydrogen: on-site generation from methanol (no compression), at POU	3.00E+00	1.94E+00	3.20E−01	1.54E+00	7.99E−02	1.82E+02	2.65E−01	1.71E+01	9.18E−02	4.93E−02
Liquid petroleum gas (LPG), at POU	1.12E+00	1.12E+00	2.14E−02	4.28E−02	1.06E+00	1.23E+01	4.57E−02	2.44E+00	5.95E−03	2.45E−03
Natural gas for electricity generation, at POU (pipeline only)	1.07E+00	1.07E+00	2.29E−03	1.06E+00	4.27E−03	8.87E+00	2.69E−02	1.46E+00	8.29E−04	4.93E−04
Natural gas for stationary uses, at POU (pipeline + other transport)	1.07E+00	1.07E+00	2.40E−03	1.06E+00	4.29E−03	9.39E+00	2.76E−02	1.48E+00	8.61E−04	5.11E−04

a. Assigning *weighting factors* (w_i) to each of the 14 environmental impacts and
b. Multiplying the weighting factors by the corresponding *normalized impact scores* for each component ($N_{i,c}$) listed in Appendix A and summing the results

Assume that only the environmental impacts of "contribution to climate change" and "contribution to photochemical smog" are of interest and that they are equally important to the design such that $w_{\text{climate change}} = 0.5$ and $w_{\text{photochemical smog}} = 0.5$. The unit EcoScores corresponding to the *baseline* design are thus estimated from Eq. (1) as:

$$\begin{aligned}\text{ESu}_{\text{steel}} &= (w_{\text{clim chang}} N_{\text{clim chang, steel: ave}}) \\ &\quad + (w_{\text{photo smog}} N_{\text{photo smog, steel: ave}}) \\ &= (0.5 * 0.0147) + (0.5 * 0.000963) = 0.00783 \end{aligned} \quad \text{(B.2)}$$

$$\begin{aligned}\text{ESu}_{\text{PEMFC fuel}} &= (w_{\text{clim chang}} N_{\text{clim chang, NG for stationary uses}}) \\ &\quad + (w_{\text{photo smog}} N_{\text{photo smog, NG for stationary uses}})) \\ &= (0.5 * 0.0428) + (0.5 * 0.00714) = 0.0250 \end{aligned} \quad \text{(B.3)}$$

$$\begin{aligned}\text{ESu}_{CO_2\text{ emissions}} &= (w_{\text{clim chang}} N_{\text{clim chang, }CO_2}) \\ &\quad + (w_{\text{photo smog}} N_{\text{photo smog, }CO_2}) \\ &= (0.5 * (0.00455)) + (0.5 * (0)) = 0.00228 \end{aligned} \quad \text{(B.4)}$$

Similarly, the unit EcoScores corresponding to the *alternative* design are:

$$\begin{aligned}\text{ESu}_{\text{steel}} &= (w_{\text{clim chang}} N_{\text{clim chang, steel: recycled}}) \\ &\quad + (w_{\text{photo smog}} N_{\text{photo smog, steel: recycled}}) \\ &= (0.5 * 0.00104) + (0.5 * 0.000700) = 0.00087 \end{aligned} \quad \text{(B.5)}$$

with $\text{ESu}_{\text{PEMFC fuel}}$ and $\text{ESu}_{CO_2\text{ emissions}}$ as in the baseline design.

Step 3. Estimate the *component EcoScores* (ESc_c) by finding the product of the PEMFC design data and the respective unit EcoScore to determine the contribution of each component to the system life cycle.

From Eq. (2) and for the *baseline* design:

$$\text{Esc}_{\text{steel}} = Q_{\text{steel}}\, \text{ESu}_{\text{steel}} = 290 * 0.00783 = 2.27 \quad \text{(B.6)}$$

$$\text{ESc}_{\text{PEMFCfuel}} = Q_{\text{PEMFC fuel}}\, \text{ESu}_{\text{PEMFCfuel}} = 2,562 * 0.0250 = 64.0 \quad \text{(B.7)}$$

$$\text{ESc}_{CO_2\text{ emissions}} = Q_{CO_2\text{ emissions}}\, \text{ESu}_{CO_2\text{ emissions}} = 341 \quad \text{(B.8)}$$

and for the alternative design, a similar procedures yields values of 0.252, 46.1, and 250, respectively.

Step 4. Estimate the *system EcoScores* ($\text{ESs}_{\text{PEMFC}}$) by adding up the component EcoScores to determine the contribution of the system to the annual U.S. per capita environmental impact.

Finally, from Eq. (3):

$$\text{ESs}_{\text{baseline PEMFC}} = 407 \quad \text{(B.9)}$$

$$\text{ESs}_{\text{alternative PEMFC}} = 297 \quad \text{(B.10)}$$

Thus, in this example, the alternative PEMFC with a lower system EcoScore is preferred over the baseline design. In both cases, the

Table C.2
Grid electricity (per kWh) ($i_{i,r}$).

	Total energy (mmBTU)	Fossil fuels (mmBTU)	Coal (mmBTU)	Natural gas (mmBTU)	Petroleum (mmBTU)	Climate change (kg)	Smog formation (kg)	Acidification (kg)	PM10 (kg)	PM2.5 (kg)
U.S. average grid	5.57E−03	5.38E−03	3.83E−03	1.24E−03	3.00E−04	7.74E−01	8.76E−04	1.24E−01	9.88E−04	2.60E−04
California grid	4.16E−03	3.89E−03	1.10E−03	2.69E−03	9.93E−05	4.52E−01	4.78E−04	4.55E−02	2.94E−04	8.33E−05
North East U.S. grid	4.84E−03	4.42E−03	2.45E−03	1.39E−03	5.87E−04	5.99E−01	7.70E−04	1.04E−01	6.38E−04	1.72E−04

Table C.3
Stationary generation reference systems (per mmBTU throughput) ($i_{i,r}$).

	Total energy (mmBTU)	Fossil fuels (mmBTU)	Coal (mmBTU)	Natural gas (mmBTU)	Petroleum (mmBTU)	Climate change (kg)	Smog formation (kg)	Acidification (kg)	PM10 (kg)	PM2.5 (kg)
Natural gas burned in a/industrial boiler (>100 mmBtu h^{-1} input): at POU	1.07E+00	1.07E+00	2.29E−03	1.06E+00	4.27E−03	6.86E+01	8.59E−02	3.76E+00	4.04E−03	3.70E−03
Natural gas burned in a small industrial boiler (10–100 mmBTU h^{-1} input): at POU	1.07E+00	1.07E+00	2.40E−03	1.06E+00	4.29E−03	6.91E+01	5.99E−02	2.69E+00	3.82E−03	3.47E−03
Natural gas burned in a large gas turbine: at POU	1.07E+00	1.07E+00	2.29E−03	1.06E+00	4.27E−03	6.88E+01	1.41E−01	5.98E+00	3.93E−03	3.59E−03
Natural gas burned in a CC gas turbine: at POU	1.07E+00	1.07E+00	2.29E−03	1.06E+00	4.27E−03	6.88E+01	4.59E−02	2.10E+00	2.83E−03	2.49E−03
Natural gas burned in a small turbine: at POU	1.07E+00	1.07E+00	2.40E−03	1.06E+00	4.29E−03	6.93E+01	1.42E−01	6.01E+00	3.96E−03	3.61E−03
Natural gas burned in a stationary reciprocating engine: at POU	1.07E+00	1.07E+00	2.40E−03	1.06E+00	4.29E−03	7.53E+01	1.27E+00	4.95E+01	6.39E−03	6.04E−03
Residual oil burned in a industrial boiler: at POU	1.10E+00	1.10E+00	1.68E−02	3.49E−02	1.04E+00	9.56E+01	1.71E−01	1.78E+01	4.93E−02	3.09E−02
Residual oil burned in a commercial boiler: at POU	1.10E+00	1.10E+00	1.68E−02	3.49E−02	1.04E+00	9.56E+01	1.71E−01	1.78E+01	6.49E−02	4.11E−02
Diesel fuel burned in a industrial boiler: at POU	1.18E+00	1.18E+00	3.22E−02	6.19E−02	1.08E+00	9.51E+01	1.33E−01	6.08E+00	5.12E−02	4.14E−02
Diesel fuel burned in a commercial boiler: at POU	1.18E+00	1.18E+00	3.22E−02	6.19E−02	1.08E+00	9.51E+01	1.33E−01	6.08E+00	5.12E−02	4.14E−02
Diesel fuel burned in a stationary reciprocating engine: at POU	1.18E+00	1.18E+00	3.22E−02	6.19E−02	1.08E+00	9.49E+01	7.91E−01	3.01E+01	7.05E−02	5.91E−02
Diesel fuel burned in a turbine: at POU	1.18E+00	1.18E+00	3.22E−02	6.19E−02	1.08E+00	9.56E+01	1.82E−01	8.06E+00	2.57E−02	1.70E−02
Gasoline burned in a stationary reciprocating engine: at POU	1.23E+00	1.22E+00	4.01E−02	7.57E−02	1.11E+00	9.66E+01	6.36E−01	2.23E+01	3.56E−02	2.71E−02
Crude burned in a industrial boiler: at POU	1.04E+00	1.04E+00	7.10E−03	1.76E−02	1.01E+00	8.36E+01	2.10E−01	2.88E+01	3.16E−02	2.02E−02
LPG burned in a industrial boiler: at POU	1.12E+00	1.12E+00	2.14E−02	4.28E−02	1.06E+00	8.19E+01	1.19E−01	5.31E+00	9.19E−03	5.70E−03
LPG burned in a commercial boiler: at POU	1.12E+00	1.12E+00	2.14E−02	4.28E−02	1.06E+00	8.19E+01	1.32E−01	5.83E+00	8.38E−03	4.88E−03
Coal burned in a IGCC turbine: at POU	1.01E+00	1.01E+00	1.00E+00	1.38E−03	6.14E−03	1.14E+02	5.45E−02	4.48E+00	1.76E−01	4.52E−02
Coal burned in a industrial boiler: at POU	1.01E+00	1.01E+00	1.00E+00	1.38E−03	6.14E−03	1.12E+02	1.67E−01	1.69E+01	2.69E−01	9.20E−02
Farmed trees burned in a small industrial boiler: at POU	1.03E+00	3.13E−02	2.33E−03	3.79E−03	2.51E−02	1.02E+02	1.80E−01	7.23E+00	1.41E−02	7.32E−03
Farmed trees burned in a large industrial boiler: at POU	1.03E+00	3.13E−02	2.33E−03	3.79E−03	2.51E−02	1.02E+02	1.80E−01	7.23E+00	1.41E−02	7.32E−03
Farmed trees burned in a boiler: at POU	1.03E+00	3.13E−02	2.33E−03	3.79E−03	2.51E−02	1.02E+02	1.80E−01	7.23E+00	1.41E−02	7.32E−03
Farmed trees converted using a gasification turbine: at POU	1.03E+00	3.13E−02	2.33E−03	3.79E−03	2.51E−02	1.02E+02	7.48E−02	4.90E+00	6.98E−03	3.77E−03
Herbaceous biomass burned in a small industrial boiler: at POU	1.06E+00	5.98E−02	4.59E−03	3.13E−02	2.39E−02	1.00E+02	1.73E−01	6.91E+00	1.48E−02	7.66E−03
Herbaceous biomass burned in a large industrial boiler: at POU	1.06E+00	5.98E−02	4.59E−03	3.13E−02	2.39E−02	1.00E+02	1.73E−01	6.91E+00	1.48E−02	7.66E−03
Herbaceous biomass burned in a boiler: at POU	1.06E+00	5.98E−02	4.59E−03	3.13E−02	2.39E−02	1.00E+02	1.73E−01	6.91E+00	1.48E−02	7.66E−03
Herbaceous biomass converted using a gasification turbine: at POU	1.06E+00	5.98E−02	4.59E−03	3.13E−02	2.39E−02	1.00E+02	6.85E−02	4.58E+00	7.66E−03	4.11E−03
Corn stover burned in a small industrial boiler: at POU	1.04E+00	4.24E−02	3.45E−03	1.26E−02	2.63E−02	1.12E+02	5.51E−01	2.24E+01	1.47E−02	7.74E−03
Corn stover burned in a large industrial boiler: at POU	1.04E+00	4.24E−02	3.45E−03	1.26E−02	2.63E−02	1.12E+02	5.51E−01	2.24E+01	1.47E−02	7.74E−03
Forest residue burned in a small industrial boiler: at POU	1.08E+00	8.27E−02	6.39E−03	5.48E−03	7.08E−02	1.40E+02	1.62E−01	6.48E+00	1.69E−02	9.35E−03
Forest residue burned in a large industrial boiler: at POU	1.08E+00	8.27E−02	6.39E−03	5.48E−03	7.08E−02	1.40E+02	1.62E−01	6.48E+00	1.69E−02	9.35E−03
Hydrogen burned in a boiler: at POU	1.74E+00	7.09E−01	1.42E−01	5.51E−01	1.58E−02	1.18E+02	1.43E−01	8.39E+00	3.80E−02	1.94E−02

CO_2 emissions contribute most to the overall result. Note that lower EcoScores are always preferred.

Appendix C

PEMFC and reference system LCIA results[13] Tables C.1, C.2 and C.3.

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[13] POU stands for “point-of-use”.