Report No. CSS06-09

June 30, 2006

Center for Sustainable Systems
University of Michigan

A Life Cycle Assessment of the PureCell™ Stationary Fuel Cell System: Providing a Guide for Environmental Improvement

Jaap van Rooijen

A Life Cycle Assessment of the PureCell™ Stationary Fuel Cell System:
Providing a Guide for Environmental Improvement

By:

Jaap van Rooijen

University of Michigan
Ann Arbor

June 30th, 2006

Faculty Advisors:
Gregory A. Keoleian, Associate Professor

Leiden University Advisor:
Drs. Ing. Rene Kleijn

A report of the Center for Sustainable Systems

Report No. CSS06-09

Document Description

A Life Cycle Assessment of the PureCell™ Stationary Fuel Cell System: Providing a Guide for Environmental Improvement
Jaap van Rooijen
Center for Sustainable Systems, Report No. CSS06-09
University of Michigan, Ann Arbor, Michigan
June 30, 2006
100 pp., 78 tables, 37 figures, 7 appendices

This document is available online at: http://css.snre.umich.edu

Center for Sustainable Systems
School of Natural Resources and Environment
University of Michigan
440 Church Street, Dana Building
Ann Arbor, MI 48109-1041
Phone: 734-764-1412
Fax: 734-647-5841
Email: css.info@umich.edu
Web: http://css.snre.umich.edu

Executive Summary

The PureCell™ Model 200 Power Solution (formerly the PC25™) is a stationary power system manufactured by UTC Power. It uses a 200 kW phosphoric acid fuel cell with a lifetime of 85,000 hours and it has an internal natural gas steam reforming system. The PureCell™ system can operate in both grid-connected and grid-independent mode and it also provides the option of heat recovery. When it functions as a combined heat and power (CHP) system, efficiency of 80% is achieved. Since 1991, more than 275 PureCell™ power systems have been installed at various locations around the world. UTC Power is currently redesigning the system and would value having a life cycle assessment (LCA) to highlight opportunities for improvement of its environmental performance. LCA can clarify which stages in the product life cycle and which elements of the product cause the most environmental pressure. Product development and improvement is therefore one of its direct applications.

The LCA results show that the use phase has by far the biggest environmental impact. The input of natural gas in the steam reforming process and the CO_2 emissions caused by this process are the main contributors to the use phase impact. Maximizing the hydrogen output of the steam reforming process and increasing the efficiency of the electrochemical reaction in the fuel cell stack are therefore the main opportunities to improve the environmental performance of the PureCell™ system. LCA results for a separate analysis of the manufacturing phase show that the fuel cell stack is responsible for almost half of the environmental impact of the manufacturing phase. The main cause is the high amount of energy used in the fuel cell stack manufacturing process. The biggest impacts per material in the manufacturing phase are caused by platinum used in the fuel cell stack, copper used in the power conditioning and control devices, and stainless steel 304 used for manifold applications. In the case of platinum especially it is beneficial to pursue a high recycling rate, since the environmental impact of recycled platinum is much smaller than that of raw platinum. The end-of-life phase has a small environmental impact compared to the use and manufacturing phases.

This report also includes an analysis of two scenarios as opportunities for environmental improvement of the PureCell™ system. One scenario analyzes the effect of using renewable hydrogen from wind energy instead of using hydrogen from natural gas steam reforming. The environmental impact is highly dependent on hydrogen transport from the wind turbine site to the PureCell™ system site. However, if a transport distance of 100 miles is assumed, a decrease in the total PureCell™ system life cycle environmental impact by a factor 7 is reached. The second scenario analyzes an alternative end-of-life treatment including reuse of PureCell™ system components and maximizing platinum recycling. Component reuse impacts both the end-of-life phase (less output to waste management) and the manufacturing phase (less input of materials and energy) and shows a 16% decrease in the aggregated environmental impact of the manufacturing and end-of-life phase. The use phase impact is not taken into account here because the alternative end-of-life scenario aims only at reducing the environmental impact of the manufacturing and end-of-life phase.

Acknowledgements

This research was performed at the Center for Sustainable Systems, University of Michigan. I would like to thank Gregory Keoleian for inviting me and for his guidance during my stay. I am also thankful to all other members of the Center for Sustainable Systems, especially David Spitzley and Helaine Hunscher, for their support on diverse occasions.

Furthermore I would like to thank René Kleijn, firstly for helping me find this research subject and secondly for his long-distance guidance and support in this research.

Last but certainly not least, I would like to thank the people at UTC Power, especially my ‘contact person’ Erika Herz, for their help in this research and for their hospitality during my visits to UTC Power.

Table of Contents

List of Figures

List of Tables

Chapter 1 – Introduction

More people are becoming conscious of the fact that our non-renewable energy resources are declining, and that we therefore have to switch to (more) renewable resources to satisfy our energy demand. In 2003 only 8% of the world primary energy production came from renewable sources [1]. A technology that is currently seen as a possible contribution to solve this problem and that has been subject to increasing support is fuel cell technology. Fuel cells have the potential to cover a large market, since the opportunities include stationary, mobile and portable applications.

Fuel cell stacks generally use hydrogen as a fuel (although there also exist other possible fuel types), which is at present produced through steam reforming of natural gas. Since natural gas is a non-renewable energy resource – with the exception of small volumes harvested from landfills and anaerobic digesters – one should realize that today's fuel cells are non-renewable energy systems. However, they still have a better environmental performance when compared with conventional power plants [2]. Furthermore, both the promise of steam reforming of natural gas with carbon sequestration and of an emerging hydrogen economy in which an increasing share of the hydrogen is produced by renewable resources will only enhance the environmental performance of fuel cells.

The fuel cell system that is assessed in this report is UTC Power's PureCell™ Model 200 Power Solution system (formerly the PC25™), a 200 kW stationary phosphoric acid fuel cell. The PureCell™ system has an internal natural gas steam reforming system. Since 1991, more than 275 PureCell™ power systems have been sold, with various applications including a New York City police station and a major postal facility in Alaska. The standard PureCell™ system is a grid-connected unit that operates in parallel with the electric utility grid. The unit can also be purchased to operate either in grid-connected or grid-independent mode switching between modes automatically or on command. The PureCell™ system is a source of reliable and assured power, and it can therefore be used as a back-up power system or as a power source for remote locations.

PureCell™ power systems also have the option of heat recovery. A standard PureCell™ power system is equipped with a thermal management system that provides up to 925,000 Btu/hr at 140 degrees Fahrenheit (equal to 271 kW at 60 degrees Celsius). There is also a high grade heat recovery option that provides up to 475,000 Btu/hr at up to 250 degrees Fahrenheit (equal to 139 kW at 121 degrees Celsius) [3]. Whereas the electrical efficiency of the PureCell™ system is close to 40% based on lower heating value (LHV), the total efficiency with heat recovery exceeds 80%.

UTC is in the process of redesigning the system and would value having a Life Cycle Assessment (LCA) highlight opportunities for improvement when regarding its environmental performance. LCA is a systematic analysis of product life cycles from an environmental point of view. It was developed into an ISO-standard (the ISO 14040-series) in the late 1990's [4]. An LCA can clarify which stages in the product life cycle

and which elements of the product cause the most environmental pressure. Product development and improvement is therefore one of its direct applications.
In addition to the actual LCA of the PureCell™ system this report also describes two potential changes in the product system's life cycle which lead to an improvement in its environmental performance. These two alternatives are: using renewable hydrogen from wind power and improving the end-of-life scenario from an environmental perspective by reusing components and maximizing platinum recycling. Each of these changes has been separately included in the LCA model in order to quantify the potential environmental improvement relative to the current PureCell™ system.

Chapter 2 discusses the procedures that are followed in order to provide a consistent LCA. These procedures include data collection, data allocation and impact assessment. In Chapter 3 the goal and scope of this research are defined, including a specification of the functional unit and the system boundaries. Chapter 4 provides the inventory analysis, describing how the LCA is modeled, which data are used and which calculations and assumptions were necessary for the inventory modeling. In Chapter 5 the impact assessment step in LCA is explained, and results are shown followed by an interpretation of these results. Also a contribution and sensitivity analysis is performed. Two opportunities for environmental improvement are analyzed in Chapter 6, including LCA results and interpretation. Chapter 7 provides the final conclusions of this research project.

Chapter 2 - Procedures

LCA Software

The software that was used to model the PureCell™ system LCA is SimaPro 6.0. This LCA tool was developed by PRe Consultants, an independent private company in the Netherlands. SimaPro (*System for Integrated environMental Assessment of PROducts*) is currently the most widely used software for LCA studies worldwide [5].

Data Collection

Collection of data is an important part of LCA. One could say that the scientific quality of the final LCA results can only be as high as the quality of the data that are used. The objective must therefore be to work with data as specific as possible. Since this LCA represents a UTC Power product, primary data were collected from UTC Power wherever possible. However, many of the components in the PureCell™ system are not manufactured by UTC Power but by supplying companies, which made the data collection more difficult and time-consuming. Therefore, in many cases data from generic Life Cycle Inventory (LCI) databases have been used. In general, a strategy of hierarchical preference regarding data collection has been used:

1. Data obtained from UTC Power.
2. Data from LCI databases especially derived with the geographical location of UTC Power in mind. This means: applying the hierarchy described in point 3 up to and including 7, and incorporating UTC-specific data in case they can be made more relevant to the PureCell™ system.
3. Data from the Franklin database in SimaPro. This database contains late 1990's inventory data for North American materials, energy and transport.
4. Data from the online National Renewable Energy Laboratory (NREL) Life Cycle Inventory Database [6]. This is a publicly available database developed in close cooperation with the U.S. government and industry. It includes data from the Franklin database.
5. Data from other databases in SimaPro, determined on a case-by-case basis to provide the most relevant information.
6. Data from other non-SimaPro databases.
7. Data obtained by internet research.

Even though this strategy for data collection was systematically applied, some of the data used in the LCA are still incomplete or have been subject to sometimes major assumptions. In the inventory analysis for each PureCell™ system component these data gaps and assumptions are described as transparently and precisely as possible.

Allocation Procedures

Data on overhead energy use (electricity and natural gas) could only be provided by UTC Power in aggregate for the entire plant, which precluded a bottom-up allocation. A top-down approach was used, allocating overhead energy to the PureCell™ system by determining the facility area related to PureCell™ system manufacturing as a share of the total facility area.

Impact Assessment

Impact assessment is the phase in LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system. A number of different impact assessment methods have been developed. For this report, the Eco-indicator 99 method was used. Eco-indicator 99 is an endpoint-oriented method, which means that value-based modeling assumptions are included. In SimaPro, Eco-indicator 99 offers the option to analyze the LCA results both per impact category and per damage category. Impact categories include for example carcinogens, climate change and ecotoxicity. There are three damage categories in Eco-indicator 99: human health, ecosystem quality and resources. These damage categories are obtained by grouping and adding the impact categories, in order to allow a wide variety of impacts to be aggregated to a small number of environmental scores.

The Eco-indicator 99 methodology comes in three different versions: the egalitarian, the hierarchist and the individualist perspective. These three versions are based on the perspective of cultural theory, and reflects the fact that the judgment of environmental problems is not objective [7]. In this research, the hierarchist perspective was used as the default method. The other two perspectives were used as a robustness analysis. An endpoint-oriented impact assessment method including value-based modeling assumptions was chosen to make the results more comprehensible for a wider audience. Since this research was primarily aimed at revealing the specifics of the environmental footprint of the PureCell™ system to UTC Power, comprehensibility was seen as an important criterion. Eco-indicator 99 is a widely accepted impact assessment method, and it offers a transparent overview of LCA results. Furthermore, the option of choosing one out of three perspectives provided the opportunity to do a robustness analysis of the LCA's end results. For all these reasons, Eco-indicator 99 was chosen as the impact assessment method for this research.

Chapter 3 - Goal and Scope

Goal of the Study

The objective of this project is to provide a guide for environmental improvement of the PureCell™ power system. By using LCA to model the product life cycle, the 'hotspots' that contribute to the present environmental footprint of the product are identified. By targeting these hotspots, opportunities for improving the environmental footprint can be explored. An analysis of the targeted hotspots is given in Chapter 5 - Impact Assessment and Interpretation.

Subsequent to the impact assessment results, two feasible opportunities for environmental improvement within the scope of this research were modeled in SimaPro: 1) using renewable hydrogen from wind power and 2) improving the end-of-life scenario from an environmental perspective by reusing components and maximizing platinum recycling. The goal of this part of the research is to quantify the potential environmental improvement for both opportunities relative to the current PureCell™ system.

Function and Functional Unit

The primary function of the PureCell™ system is electricity production. In addition, the PureCell™ system provides the option of heat recovery. The PureCell™ system can thus be operated as a combined heat and power (CHP) system. The PureCell™ system is used as a power supply system for remote locations where there is no connection to the electricity grid, however, it still requires that a constant supply of natural gas is available. It is also used as a source for back-up power; within this application, the PureCell™ system can function as a constant or as an intermittent power supply. Also, within this application the PureCell™ system can function with a connection to the electricity grid as well as grid-independent. In the near future, the function of stationary fuel cells may become more significant, since they are constant and reliable energy conversion systems and they can therefore compensate for increased shares of fluctuating renewable energy sources used for the electricity grid.

This research aims at modelling the life cycle of one PureCell™ power system. The functional unit therefore is:

- *One PureCell™ power system, generating 200 kW of electricity, 480 Volt, 60 Hz, and providing optional heat recovery of 271 kW at 60 degrees Celsius, with a lifetime of 85,000 hrs.*

Most of the PureCell™ systems which are currently in use have a projected lifetime of 40,000 hrs, and this model is commonly referred to within UTC Power as the PC25 C. The PC25 C is now out of production, and it is planned to utilize a new cell stack design and a new low shift converter for the steam reforming process (together with some other minor design changes), which will result in the PC25 D. These design changes give the PC25 D an expected lifetime of 85,000 hrs. The data that are used in this LCA are based on the PC25 D system. The decision to study the PC25 D was made by UTC Power.

System Boundaries

Ideally an LCA includes all economic and environmental inputs and outputs that are part of the product's life cycle. However, in practice it usually turns out that this is an impossible task. Therefore it is necessary to define the system boundary and indicate which processes and/or material flows are not included in the LCA. In order to create a transparent overview of the system boundary, it is described separately for the manufacturing phase, the use phase and the End-of-Life (EoL) phase.

Manufacturing Phase

An inventory table of the PureCell™ system manufacturing phase should include:

- The materials used for components and parts
- The processes (e.g., cold transforming of steel, molding of plastic, transport) used for the product manufacturing
- Overhead energy and other non-product materials
- The emissions caused and waste generated by product manufacturing

The PureCell™ system is a product for which all components except the fuel cell stack are manufactured by external suppliers. This requires that part of the data have to be obtained from these external suppliers. Experience from previous LCA's tells that this is a difficult and time-consuming task; therefore, it was decided not to approach these external suppliers but to work with data from UTC Power and databases instead. Although all PureCell™ system components except the fuel cell stack are manufactured by external suppliers, the design of most of these components has been made by UTC Power engineers. This means that UTC Power was able to provide most of the data described above. Data that could not be obtained for the manufacturing phase are:

- Overhead energy and other non-product materials used at the facilities of the external suppliers
- Transport of materials and parts to the facilities of the external suppliers
- Manufacturing emissions and waste at the external suppliers not accounted for in the SimaPro database manufacturing processes
- Manufacturing emissions and waste at UTC Power (e.g., anode, coolers, flow fields) except for the cathode manufacturing emissions and waste

Transport of PureCell™ system components from the external suppliers to UTC Power however *is* included in the LCA. Some data on manufacturing emissions and waste at UTC Power were available, but useful data for the LCA model could not be retrieved (except for the cathode manufacturing) due to unknown waste stream concentrations and the difficulty of allocation. Capital goods used for PureCell™ system manufacturing are not included in the LCA.

Figure 3-1 indicates the manufacturing phase system boundary.

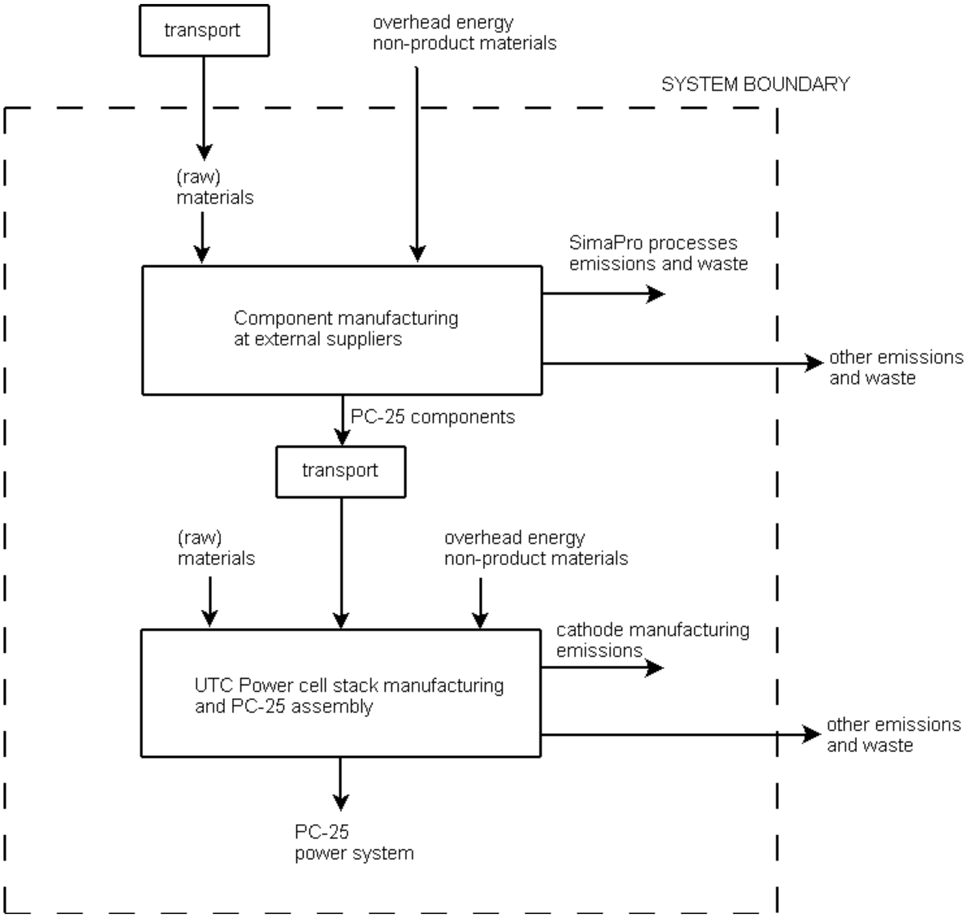


Figure 3-1: Manufacturing phase system boundary

Use Phase

An inventory table of the PureCell™ system use phase should include:

- The natural gas input for the PureCell™ system lifetime
- The emissions from the steam reforming process
- The installation materials and processes for installing the PureCell™ system at the client's site
- Components and parts that need to be replaced during the PureCell™ system lifetime
- Waste generated by maintenance activities
- Transport-related: of PureCell™ system from UTC Power to client, of installation materials to PureCell™ system site, of maintenance components to PureCell™ system site, and of replaced components and maintenance waste to waste treatment

Most of these data were obtained from UTC Power reports, manuals and personal interviews. However, obtaining the transport-related data was problematic. The PureCell™ system sites differ significantly per client. Due to the both regional and globalized market of the PureCell™ system (site locations include Hartford, CT, but also cities in Germany and Japan), making an assumption about the transport distance to the site location does not correctly reflect a realistic situation. Therefore the use phase transport data listed below are not included in the base case LCA. However, in order to get an idea of the possible significance of PureCell™ system transport from UTC Power to clients, a scenario where the PureCell™ system is transported to Koln, Germany, is included as an option in the LCA model. Koln is chosen because this is one of the actual site locations of the PureCell™ system. The results obtained by including this scenario are shown in the 'Sensitivity Analysis for Assumptions' section of Chapter 5.

Figure 3-2 indicates the use phase system boundary and activities.

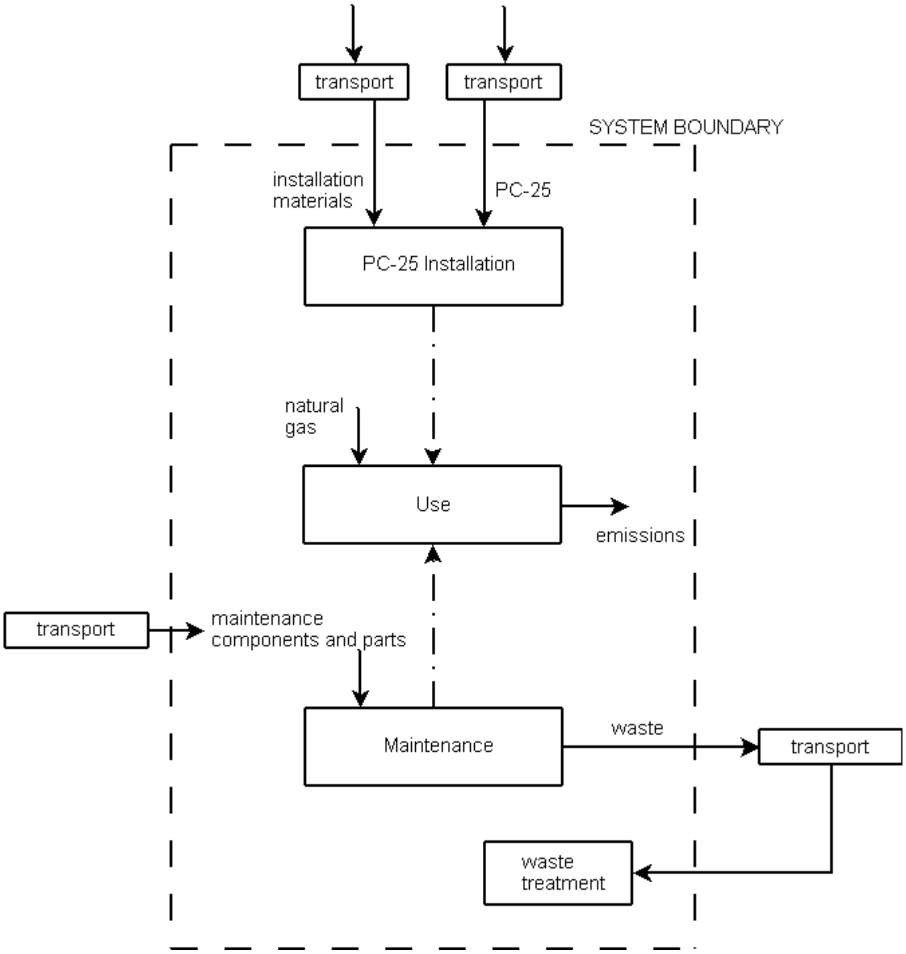


Figure 3-2: Use phase system boundary

End-of-Life Phase

An inventory table of the PureCell™ system end-of-life phase should include:

- The materials that are recycled
- The materials that are going to landfill
- The materials that are going to another waste treatment
- Transport of materials (some still as components) to waste treatment facility

For the end-of-life (EoL) phase the waste treatment processes in SimaPro databases are used. Energy use and emissions are already taken into account in these waste treatment processes, so they do not have to be included in the inventory table. Since the end-of-life phase is not yet defined, assumptions are made about which percentage of each material goes to which waste treatment process. Regarding transport, the same problem as in the use phase arises. Due to the variety of site locations, it is not realistic to make any assumptions here. Therefore the following data for the end-of-life phase are not included in the LCA:

- Transport of materials/components to their particular waste treatment facility.

Figure 3-3 indicates the end-of-life phase system boundary.

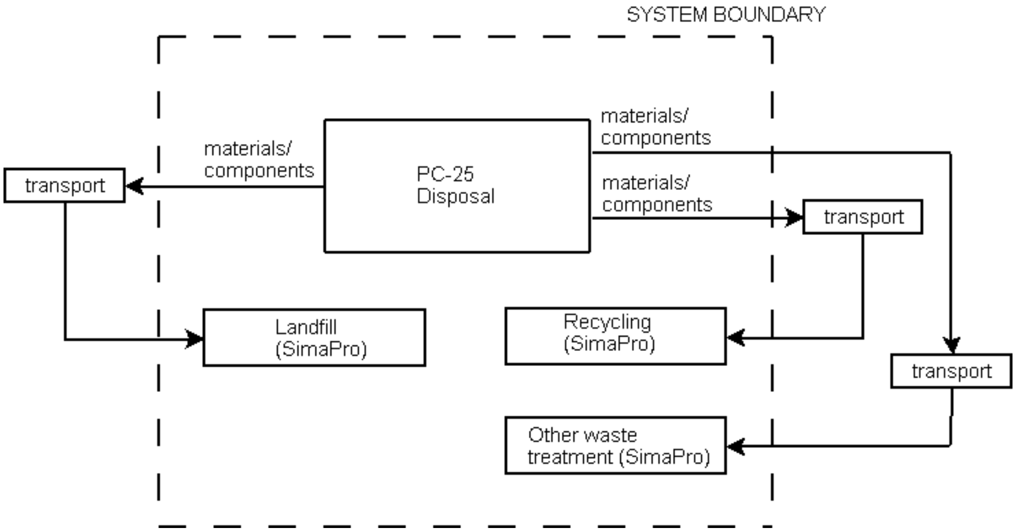


Figure 3-3: End-of-Life phase system boundary

SimaPro System Boundaries

In this LCA extensive use was made of the SimaPro databases. Boundaries for elemental flows to and from nature as well as other geographical boundaries representing the product system, are defined by these databases. As much as possible databases that were representative to the geographical location of UTC Power were used.

Chapter 4 - Inventory Analysis

This chapter shows how the LCA is modeled in SimaPro, which data are used, and which calculations and assumptions were necessary for the inventory modeling. A description of the inventory analysis is provided for each life cycle phase (manufacturing, use and end-of-life phase). First, the flow diagram of the modeled process is given, and then each distinct process is described in terms of data, calculations and assumptions.

Flow Diagram

Figure 4-1 represents processes by boxes and economic flows by arrows. Emissions are not included. Dashed lines indicate that reuse is optional in the end-of-life stage.

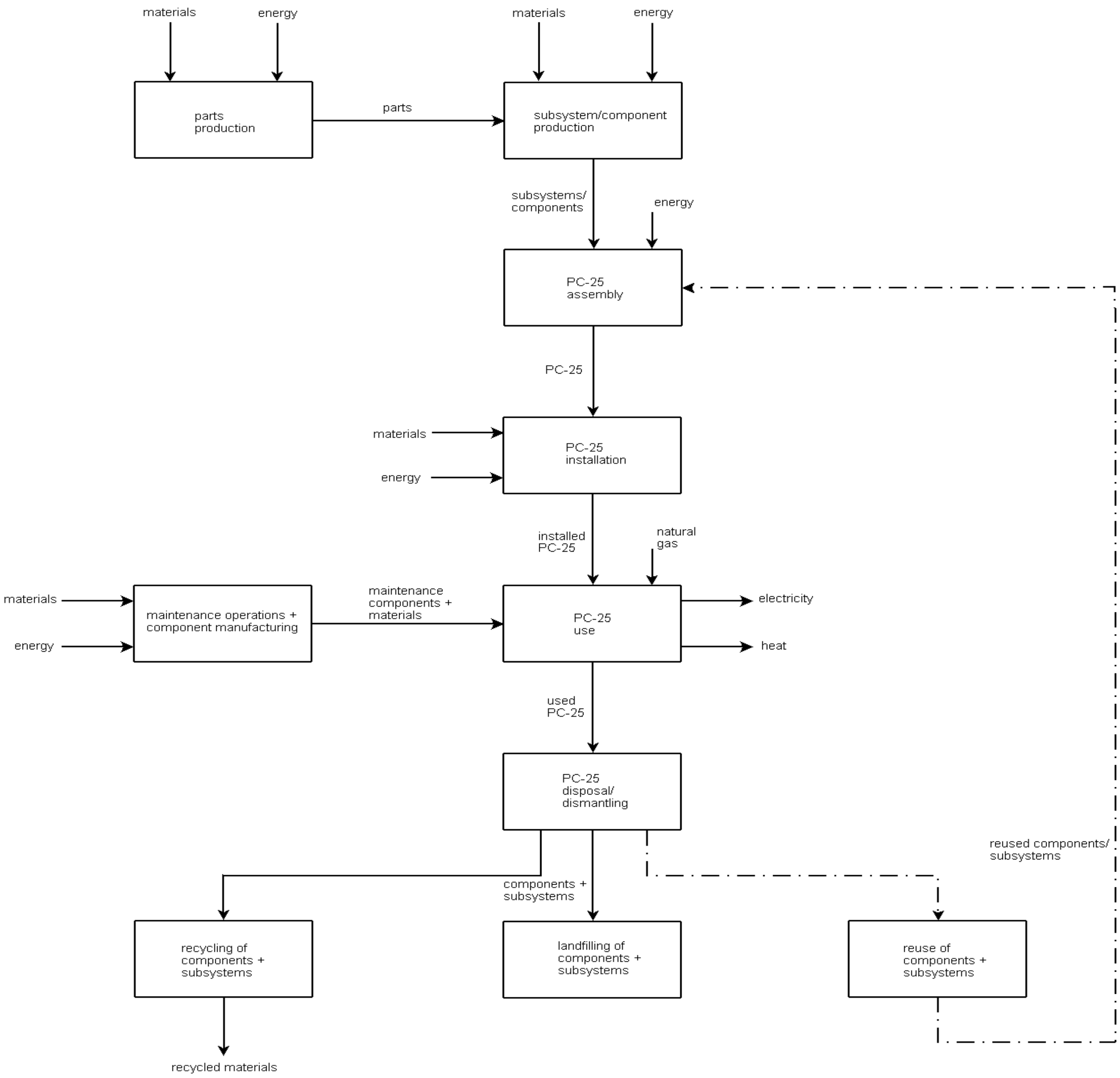


Figure 4-1: Flow diagram PureCell™ system LCA model

Inventory Tables

The inventory tables show which data are used in the SimaPro model, giving a transparent view of what assumptions are made and where the data gaps are. Also, the calculations that were necessary to obtain certain data are described. First the steel data and processing data are described separately because they appear in almost all of the PureCell™ subsystems/components inventory tables.

Steel Data

Approximately two thirds of the total weight of the PureCell™ system is made up of steel (carbon steel and stainless steel). In fact, steel is used in almost all of the PureCell™ subsystems/components. Therefore the steel data are described separately here. Three different types of steel are used in the PureCell™ system, and they appear in the inventory tables as:

- Steel cold rolled coil IISI
- Stainless Steel 304 2B IISI
- Stainless Steel 316 2B IISI

These steel data do not come from a SimaPro database, but are provided by the International Iron and Steel Institute, IISI [8]. IISI data are used in this LCA because they are reliable and up-to-date. The data include the recycled input of steel scrap into the steel manufacturing process. However, the 'recycling credit' is not included in these data. 'Recycling credit' is a methodology developed by the International Stainless Steel Forum (ISSF) in order to include the benefit of making more recycled material available for future use. The number to be assessed is obtained by the following formula:

- Recycled material released for new use at end-of-life – (minus) Recycled material used during manufacturing [9].

Because the recycled material released for new use at end-of-life is not defined for the PureCell™ system, and because subsystem/component reuse will also be part of the PureCell™ system end-of-life scenario, the 'recycling credit' is not included in the steel data for this LCA.

Processing Data

In most of the inventory tables, data on material processing appears. Except for the Cell Stack Assembly (CSA), all subsystems and components were manufactured at an external supplier's facility. All the material processing data are therefore based on personal interviews with UTC Power and modeled using the generic SimaPro databases.

Manufacturing Phase

For the SimaPro model, the PureCell™ system is divided into a number of subsystems and components, as shown in Figure 4-2.

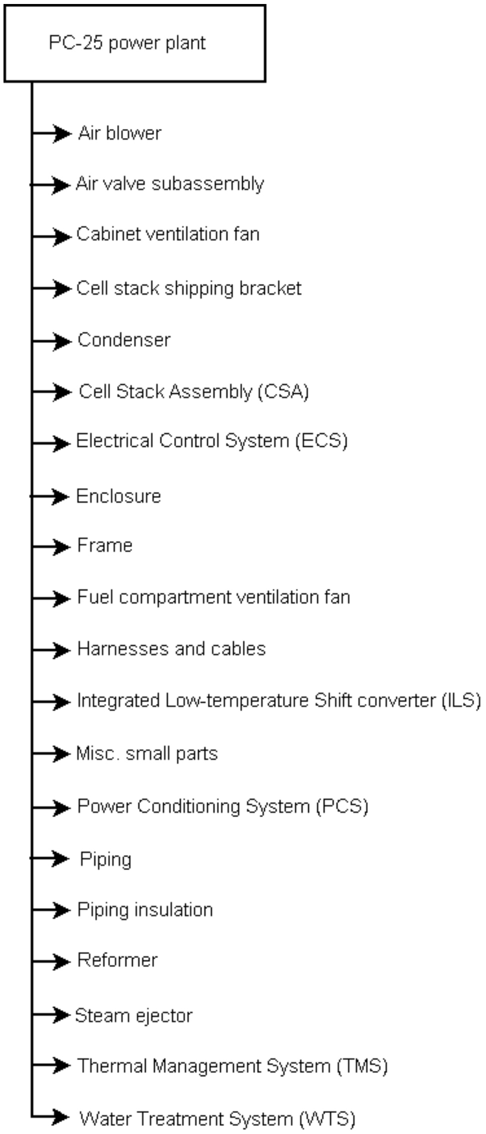


Figure 4-2: PureCell™ subsystem and component breakdown

For each of these subsystems/components the LCI data is described. It should be noted here that the cooling module is not included in the LCA. The cooling module is a 1700 lb three fan air device with the function to reject power plant waste heat to the atmosphere. On the one hand, the cooling module is not part of the PureCell™ system, and it is neither manufactured nor assembled by UTC Power. Furthermore, the proposed 1700 lb cooling module is merely optional; it is also possible to use a cooling tower or other heat sink in lieu of the cooling module [10]. On the other hand, the function of the cooling module within the system cannot be denied, and should therefore theoretically be included when this LCA is to be regarded as representative for a stationary fuel cell system. However, no cooling module data are available, and it is deemed to be more valuable to exclude the cooling module from the LCA, and explicitly state this, than to include it by making coarse assumptions.

Air blower

The process air blower provides high capacity air flows to key components like the CSA and the reformer in the PureCell™ system. Table 4-1 shows the air blower inventory data.[1]

Materials/Assemblies	Amount	Unit
Electric motor PureCell™ system	80	lb
Steel cold rolled coil IISI	50	lb
Aluminum (primary) produced in the USA (NREL)	17.5	lb
Aluminum 100% recycled ETH U PureCell™ system	17.5	lb
Total	165	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	74	tmi[2]
Rolling steel I PureCell™ system	50	lb
Cold transforming steel PureCell™ system	50	lb
Turning steel PureCell™ system	50	lb
Cold transforming Al I, PureCell™ system	35	lb
Turning aluminum I, PureCell™ system	35	lb

Table 4-1: Air blower inventory data

- The air blower electric motor has a power of 5 hp and is estimated to weigh 80 lb. Internet research led to the assumption that a 5 hp electric motor weighs approximately 80 lb. The data used to model this electric motor in SimaPro came from a published environmental product declaration by ABB Motors [11].
- The percentage of recycled aluminum as input for the aluminum manufacturing process is assumed to 50%. This assumption is based on the recycling rate of aluminum cans in the United States in 2004 [12]. In the inventory table therefore two types of aluminum appear (primary and 100% recycled) in order to include this 50% recycled input in the LCA model.
- The approved source of supply is 900 miles from UTC Power, transporting 165 lb, which is equal to 74 tmi.

---

[1] The origin of the processes in the inventory tables is described in more detail in Appendix A through D.

[2] tmi = ton-mile; 1 tmi transports 1 ton over 1 mile. Note that this is an American ton (or short ton), which is 2000 lb or 907.18474 kg.

Air valve subassembly

The air valve subassembly includes the control valves of the PureCell™ air processing system.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	65	lb
Stainless Steel 316 2B IISI	30	lb
PP granulate average B250 PureCell™ system	10	lb
Total	105	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	4.2	tmi
Injection molding PureCell™ system	10	lb
Forging steel PureCell™ system	95	lb

Table 4-2: Air valve subassembly inventory data

- PP granulate average B250 represents the production process of polypropylene into components for the air valve assembly by injection molding.
- The control valves are manufactured 80 miles from UTC Power, transporting 105 lb, which is equal to 4.2 tmi.

Cabinet ventilation fan

The cabinet ventilation fan blows filtered ambient air into and through the PureCell™ system's cabinet compartment.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	250	lb
Electric motor PureCell™ system	50	lb
Total	300	lb
Processes	Amount	Unit
Rolling steel I PureCell™ system	250	lb
Cold transforming steel PureCell™ system	250	lb
Turning steel PureCell™ system	250	lb

Table 4-3: Cabinet ventilation fan inventory data

- Electric motor was assumed to weigh 50 lb and to be of the same power as the motor in the fuel compartment ventilation fan (1.5 hp). Internet research led to the assumption that a 1.5 hp electric motor weighs approximately 50 lb.
- Transport unknown.

Cell stack shipping bracket

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	120	lb
Total	120	lb
Processes	Amount	Unit
Cold transforming steel PureCell™ system	120	lb
Electric welding steel 5 PureCell™ system	2	m

Table 4-4: Cell stack shipping bracket inventory data

- Transport unknown

Condenser

The function of the condenser is to condense water vapor as a product of combustion upon exit from the reformer burner and from the cathode. The reformer and cathode exhaust products including uncondensed steam exit the condenser through the roof of the power plant.

Materials/Assemblies	Amount	Unit
Stainless Steel 304 2B IISI	1150	lb
Stainless Steel 316 2B IISI	200	lb
Total	1350	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	606	tmi
Rolling steel I PureCell™ system	1350	lb
Cold transforming steel PureCell™ system	1350	lb
Electric welding steel 3 PureCell™ system	10	m

Table 4-5: Condenser inventory data

- The estimate of 10 m electric welding was based on the size of the condenser.
- The condenser is manufactured 900 miles from UTC Power, transporting 1350 lb, which is equal to 606 tmi.

Cell Stack Assembly (CSA)

The CSA is where the electrochemical reaction between hydrogen and oxygen takes place to produce electric power. The waste heat that is produced is removed by cooling water and can be recovered in order to provide heating or cooling energy. The depleted fuel stream is used to provide heat required for the steam reforming process.

Materials/Assemblies	Amount	Unit
Platinum I PureCell™ system	proprietary	g
Platinum recycled PureCell™ system	proprietary	g
Steel cold rolled coil IISI	3535	lb
Stainless Steel 304 2B IISI	425	lb
PTFE (Teflon®) PureCell™ system	0	lb
PE granulate average B250 PureCell™ system	467.7	lb
Carbon black ETH U PureCell™ system	179.9	lb
Graphite PureCell™ system	3784	lb
Copper ETH U PureCell™ system	74	lb
Glass fiber I PureCell™ system	500	lb
Phosphoric acid ETH U PureCell™ system	251	lb
Silicium carbide PureCell™ system	1903	lb
Total	11123	lb
Processes	Amount	Unit
Cold transforming steel PureCell™ system	3535	lb
Cold transforming steel PureCell™ system	425	lb
UTC South Windsor electricity mix	66180	kWh
Heat from natural gas FAL	311000000	Btu
Waste to treatment		
LT waste to chemical landfill	681.4	kg
Waste to chemical landfill	681.4	kg

Table 4-6: Cell Stack Assembly (CSA) inventory data

Some of the materials and numbers in the inventory table need further explanation. The manufacturing phase of the CSA is described in more detail than the other subassemblies/components since the CSA is manufactured by UTC Power at the facility in South Windsor.

Platinum

The use of platinum in the PureCell™ system's fuel cell stack was modeled in a special way in order to make the LCA results more synoptic and transparent. Platinum has an extremely high environmental impact, and as a result the platinum input has a high contribution to the environmental impact of the CSA. SimaPro only offers the option to model platinum input from primary production (i.e., 0% recycling), although the recycling rate for a fuel cell is likely to be up to 98% [13]. One option is to model the platinum input from primary production and to include the 98% recycling rate in the PureCell™ system end-of-life phase. This leads to a high environmental impact in the manufacturing phase and a high negative environmental impact in the end-of-life phase because of platinum recycling. It does however not represent the platinum cycle for the PureCell™ system correctly. UTC Power aims to recollect the CSA's and extract the platinum for reuse, resulting in a UTC Power internal recycling process. A schematic of this 'internal lease' cycle is shown in Figure 4-3.

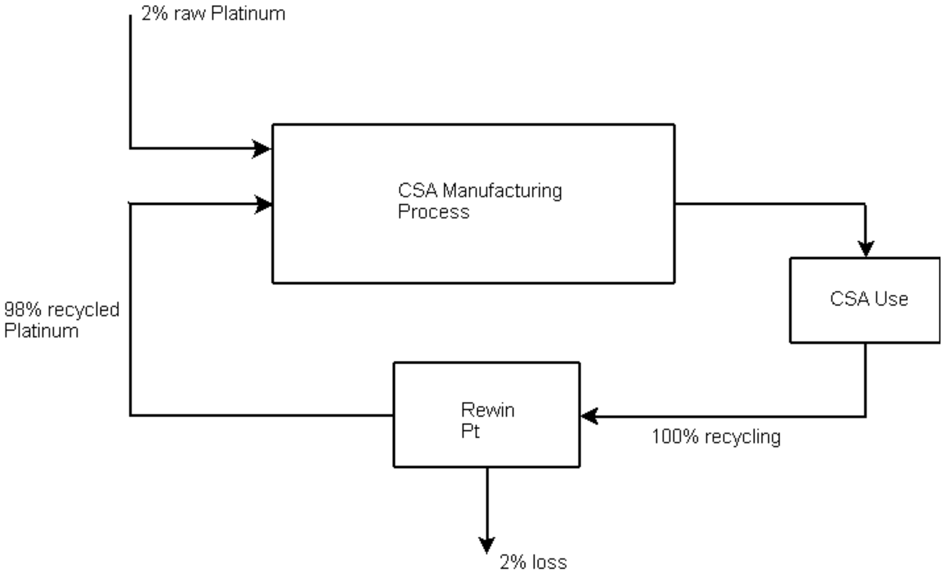


Figure 4-3: UTC Power platinum internal recycling

Thus, 2% of the platinum input into the CSA manufacturing process was raw platinum and 98% was recycled. Recycled platinum was modeled in SimaPro with LCI data from [13].

Teflon®

LCI data for the production of Teflon® could not be found. Polyethylene (PE granulate average B250 PureCell™ system) was used in the LCA model instead. An investigation by the United States EPA is running regarding the chemical PFOA (perfluorooctanoic acid) [14], which is both used and emitted in the production process of Teflon®. PFOA is very persistent in the environment, and is shown to cause developmental and other adverse effects in laboratory animals. Recognizing the fact that a significant amount of Teflon® is used (467.7 lb), one must realize that substituting Teflon® with polyethylene probably leads to an underestimation of the modeled environmental impact of Teflon®.

Graphite

LCI data for modeling the graphite production process was obtained by EIO-LCA (Economic Input-Output LCA) [15] because no process for graphite was included in the SimaPro databases and no other literature containing LCI data on graphite production could be found. With this method LCI data are calculated based on a product category and the cost in dollar value to make the output. For graphite, the category 'Carbon and graphite product manufacturing' was selected with a product value of $6,924 (UTC

Power data for 2005 value, which was converted to 1997 value to match the EIO-LCA model). Although this value is the cost price for UTC Power and not the output value, the application of this economic value to EIO-LCA was seen as the best way to obtain LCI data on the graphite production process.

Electricity and natural gas allocation

Data on electricity and natural gas usage were only available as one number for the entire UTC Power facility. Therefore they had to be allocated to the PureCell™ system production. The allocation was done by area; 43,224 ft^2 out of 300,000 ft^2 (total facility area) is used for PureCell™ system manufacturing, which is 14.4%. Because 2001 was the last full year of PureCell™ system production the electricity and natural gas usage data for this year were used. In 2001, 29 PureCell™ system power plants were produced.

- 2001 electricity usage: 13,328,000 kWh. This means that $\left(\frac{0.144}{29}\right)*13{,}328{,}000kWh = 66180kWh$ was used per produced PureCell™ system. The electricity is specified as 'UTC South Windsor electricity mix', representing the grid electricity mix applicable to Connecticut (see Appendix F).

- 2001 natural gas usage: 608,000 CCF. One CCF is equal to 100 cubic feet, which means that $\left(\frac{0.144}{29}\right)*608{,}000CCF*100 = 301{,}900cuft$ is used per produced PureCell™ system. Given the fact that the heating value of natural gas is 1030 Btu/cuft this leads to the number of 311,000,000 Btu per produced PureCell™ system.

The electricity and natural gas data are included in the CSA inventory table although part of the electricity and natural gas consumption is used for PureCell™ system assembly and for overhead like facility heating and lighting. However, cell stack manufacturing is an energy intensive process and therefore it is assumed that by far the largest part of the electricity and natural gas consumption is used for CSA manufacturing.

Cathode production waste

In the cathode production process a large amount of hazardous waste water is produced. This waste water is hazardous because the hexavalent chromium ($Cr(VI)$) concentration is 10.2 mg/liter, which exceeds the allowed concentration by law of 5.0 mg/liter. (NOTE: An internal review questioned the valence of the chromium.) The cathode production for 15 power plants resulted in 2700 gallons of hazardous waste water (2006 data). 2700 Gallons is equal to 10221 liter, and divided by 15 this gives a hazardous waste water production of 681.4 liter or 681.4 kg per power plant. In SimaPro it is not possible to specify the concentration of $Cr(VI)$ in the waste water; it is only possible to specify the amount of waste that is sent to a particular waste treatment process. Hence, 681.4 kg waste is sent for chemical treatment and disposal (modeled as landfill disposal although liquid waste cannot be landfilled directly). This number appears twice in the inventory table because both the short-term and long-term effects are taken into account. The short-term process describes the emissions during waste treatment. Long term emissions are those expected after 150 years, when the landfill site is not controlled anymore.

Electrical Control System (ECS)

The electrical control system provides complete control over the PureCell™ system's DC power system. It also functions as a power distribution system, distributing power internally for CSA maintenance and distributing power to the PureCell™ system site or to the grid.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	1000	lb
Copper ETH U PureCell™ system	300	lb
Electric Components PureCell™ system	150	lb
Total	1450	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	725	tmi
Cold transforming steel PureCell™ system	1000	lb
Electric welding steel 5 PureCell™ system	5	m
Copper wire PureCell™ system	300	lb

Table 4-7: Electrical Control System (ECS) inventory data

- 300 lb of copper is used in the ECS. Most of this copper is used for copper wire; therefore it is assumed that 300 lb of copper is processed into copper wire.
- The electric components in the ECS are modeled in SimaPro by using data for a 250W inverter. This inverter is used in a photovoltaic system, and an inventory list for the production was made for an earlier study performed at the Center for Sustainable Systems, University of Michigan [16]. The inverter electric components give a relatively accurate representation of the electric components used in the PureCell™ system, because they have the same function in both systems. The semiconductor devices in the inverter were however only specified in number. Therefore, another study is used to obtain and model the semiconductor production inventory data in SimaPro [17]. Both sets of inventory data are combined and scaled up linearly by mass in order to model the PureCell™ system electric components.
- The ECS is manufactured 1000 miles from UTC Power, transporting 1450 lb, which is equal to 725 tmi.

Enclosure

The enclosure shelters the power plant from the ambient environment. It also separates the fuel cell stack compartment from the other PureCell™ subsystems and components.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	3490	lb
Paint ETH U PureCell™ system	10	lb
Total	3500	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	805	tmi
Rolling steel I PureCell™ system	3490	lb
Cold transforming steel PureCell™ system	3490	lb

Table 4-8: Enclosure inventory data

- The steel enclosure is covered with powder paint. The amount of paint used for the enclosure is estimated at 10 lb. Data from the SimaPro ETH-ESU database are used here, which gives a rough estimate of the composition of paint.
- The enclosure is manufactured 460 miles from UTC Power, transporting 3500 lb, which is equal to 805 tmi.

Frame

The frame functions as the skeleton of the PureCell™ system and provides attachment points for the different components.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	3795	lb
Paint ETH U PureCell™ system	5	lb
Total	3800	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	760	tmi
Cold transforming steel PureCell™ system	3795	lb
Electric welding steel 5 PureCell™ system	10	m

Table 4-9: Frame inventory data

- The amount of paint used for the enclosure is estimated at 5 lb.
- The frame is manufactured 400 miles from UTC Power, transporting 3800 lb, which is equal to 760 tmi.

Fuel compartment ventilation fan

The fuel compartment ventilation fan draws ambient air out of the fuel cell stack compartment to prevent buildup of combustible gases.

Materials/Assemblies	Amount	Unit
Electric motor PureCell™ system	50	lb
Aluminum (primary) produced in the USA	25	lb
Aluminum 100% recycled ETH U PureCell™ system	25	lb
Steel cold rolled coil IISI	50	lb
Total	150	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	56	tmi
Cold transforming steel PureCell™ system	50	lb
Turning steel PureCell™ system	50	lb
Cast work, non-ferro, PureCell™ system	50	lb

Table 4-10: Fuel compartment ventilation fan inventory data

- A 1.5 hp electric motor is used and was assumed to weigh 50 lb.
- The fuel compartment ventilation fan is manufactured 750 miles from UTC Power, transporting 150 lb, which is equal to 56 tmi.
- The ventilation fan has a cast aluminum housing; steel is used for the rest of the construction. The 'Cast work, non-ferro, PureCell™ system' represents the casting of the aluminum.

Harnesses and cables

This inventory table represents the materials that are used for the manifold applications of wires, cables and their insulation.

Materials/Assemblies	Amount	Unit
Copper ETH U PureCell™ system	100	lb
PET ETH U PureCell™ system	85	lb
Total	185	lb
Processes	Amount	Unit
Copper wire PureCell™ system	100	lb
Extrusion I	85	lb

Table 4-11: Harnesses and cables inventory data

- The ‘PET ETH U, adapted to US represents the plastic that is used for insulation. This plastic is assumed to be polyester, since the material properties of polyester allow it to be used in temperatures up to 200 degrees Celsius (unlike PVC) [18], which is the operating temperature of a phosphoric acid fuel cell.
- Copper was processed into copper wire, and polyester was assumed to be extruded into the required form.
- Transport unknown.

Integrated Low-temperature Shift converter (ILS)

The ILS is part of the fuel processing system. Its functions include: fuel desulphurization via the hydrodesulphurizer catalyst bed, carbon monoxide reduction via the shift converter catalyst bed and process steam superheating by removing heat from the reformer process fuel exit gas.

Materials/Assemblies	Amount	Unit
Stainless Steel 304 2B IISI	2683	lb
Steel cold rolled coil IISI	2029	lb
Copper ETH U PureCell™ system	268	lb
Zinc oxide PureCell™ system	174	lb
(Zinc)	139.2	lb
Aluminum oxide PureCell™ system	63.8	lb
Platinum I PureCell™ system	22.6	g
Palladium I PureCell™ system	8.8	g
Aluminum oxide PureCell™ system	137.9	lb
Zinc oxide PureCell™ system	1074	lb
(Zinc)	859.2	lb
Glass fiber I PureCell™ system	85	lb
Total	6515	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	1303	tmi
Rolling steel I PureCell™ system	2683	lb
Rolling steel I PureCell™ system	2029	lb
Cold transforming steel PureCell™ system	2683	lb
Cold transforming steel PureCell™ system	2029	lb
Electric welding steel 5 PureCell™ system	5	m

Table 4-12: Integrated Low-temperature Shift converter (ILS) inventory data

The steel is used to manufacture the vessel which contains the catalyst beds. The glass fiber is used as insulation. The hydrodesulphurizer catalyst bed is an alumina substrate (137.9 lb) with platinum and palladium catalyst (22.6 g and 8.8 g respectively). A zinc-oxide bed (1074 lb) is used to remove the hydrogen sulfide. The shift converter catalyst bed is made of copper (268 lb) on an alumina substrate (63.8 lb) and zinc-oxide (174 lb).

- Zinc-oxide is not included in the SimaPro databases, and no data on zinc-oxide production were found elsewhere. Although zinc-oxide appears as such in the inventory table, this process only includes zinc input and no emissions. The amount of zinc in zinc-oxide is determined by stoichiometric calculations: zinc-oxide (ZnO) has a total molecular mass of 81 u, since the atomic mass of zinc is 65 u and oxygen is 16 u. The mass ratio of zinc in zinc-oxide is therefore 65/81, which is 80%. In the zinc-oxide process the zinc input is therefore modeled as 0.8 lb zinc per 1 lb zinc-oxide, which leads to 139.2 lb and 859.2 lb zinc for the ILS catalyst beds. It should be noted that the use of this zinc-oxide process leads to a significant underestimation of the contribution of zinc-oxide to the environmental footprint of the PureCell™ system.
- The ILS is manufactured 400 miles from UTC Power, transporting 6515 lb, which is equal to 1303 tmi.

Misc. small parts

This inventory table represents the miscellaneous small parts that are used in the PureCell™ system.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	35	lb
Stainless Steel 304 2B IISI	15	lb
Stainless Steel 316 2B IISI	15	lb
PP granulate average B250 PureCell™ system	35	lb
Total	100	lb
Processes	Amount	Unit
Cold transforming steel PureCell™ system	65	lb
Injection molding PureCell™ system	35	lb

Table 4-13: Misc. small parts inventory table

- ‘PP granulate average B250 PureCell™ system’ represents the polypropylene parts, which are processed by injection molding.
- Transport unknown.

Power Conditioning System (PCS)

The PCS converts unregulated DC power into three phase utility grade power. It provides harmonic control and protects the power plant from out of limits conditions.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	3950	lb
Copper ETH U PureCell™ system	1800	lb
Electric Components PureCell™ system	200	lb
Total	5950	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	2977	tmi
Cold transforming steel PureCell™ system	3950	lb
Electric welding steel 5 PureCell™ system	5	m
Copper wire PureCell™ system	1800	lb

Table 4-14: Power Conditioning System (PCS) inventory data

- The electric components in the PCS are modeled in the same way as the electric components in the ECS, based on the inventory data of a 250 W inverter in a photovoltaic system.
- The PCS is manufactured 1000 miles from UTC Power, transporting 5950 lb, which is equal to 2977 tmi.

Piping

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	430	lb
Total	430	lb
Processes	Amount	Unit
Cold transforming steel PureCell™ system	430	lb
Truck (single) diesel FAL (Franklin)	54	tmi

Table 4-15: Piping inventory data

- The pipes are manufactured 250 miles from UTC Power, transporting 430 lb, which is equal to 54 tmi.

Piping insulation

Materials/Assemblies	Amount	Unit
Glass fiber I PureCell™ system	200	lb
Total	200	lb

Table 4-16: Piping insulation inventory data

- Transport unknown.

Reformer

The reformer is a vessel that converts superheated steam and desulphurized natural gas (from the ILS) into a hydrogen-rich stream by steam reforming. A nickel on lanthanum stabilized alumina catalyst is used.

Materials/Assemblies	Amount	Unit
Lanthanum PureCell™ system	proprietary	
Stainless Steel 304 2B IISI	2615	lb
Steel cold rolled coil IISI	195	lb
Zeolite ETH U PureCell™ system	326	lb
Aluminum oxide PureCell™ system	273	lb
Nickel enriched ETH U PureCell™ system	proprietary	
Total	3500	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	700	tmi
Rolling steel I PureCell™ system	2615	lb
Electric welding steel 5 PureCell™ system	5	m
Cold transforming steel PureCell™ system	2615	lb
Cold transforming steel PureCell™ system	195	lb

Table 4-17: Reformer inventory list

The reformer vessel is made of stainless steel 304; the vessel is insulated internally with zeolite. The reformer catalyst for the steam reforming reaction is nickel on lanthanum stabilized alumina. The total weight of the catalyst materials is 364 lb. The remaining 273 lb is alumina.

- The reformer is manufactured 400 miles from UTC Power, transporting 3500 lb, which is equal to 700 tmi.

Steam ejector

The steam ejector is a mechanical device that mixes desulphurized natural gas and steam for the steam reforming reaction in the reformer.

Materials/Assemblies	Amount	Unit
Stainless Steel 304 2B IISI	100	lb
Total	100	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	50	tmi
Cast work PureCell™ system	100	lb

Table 4-18: Steam ejector inventory data

- The steam ejector is manufactured 1000 miles from UTC Power, transporting 100 lb, which is equal to 50 tmi.

Thermal Management System (TMS)

The TMS maintains a proper cell stack temperature, it supplies steam to the fuel processing system (ILS and reformer) and it provides the customer with the heat recovery option.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	880	lb
Stainless Steel 304 2B IISI	150	lb
Stainless Steel 316 2B IISI	20	lb
Steel cold rolled coil IISI	950	lb
Stainless Steel 316 2B IISI	250	lb
Total	2250	lb
Processes	Amount	Unit
Truck (single) diesel FAL (Franklin)	281	tmi
Rolling steel I PureCell™ system	1050	lb
Cold transforming steel PureCell™ system	1050	lb
Electric welding steel 3 PureCell™ system	5	m
Cold transforming steel PureCell™ system	1200	lb

Table 4-19: Thermal Management System (TMS) inventory data

The TMS consists of a steam drum subassembly (with a total weight of 1050 lb; 880 lb carbon steel, 150 lb SS 304 and 20 lb SS 316) and other complementary components (950 lb carbon steel and 250 lb SS 316).

- The TMS is manufactured 250 miles from UTC Power, transporting 2250 lb, which is equal to 281 tmi.

Water Treatment System (WTS)

The WTS provides high purity water to the cell stack assembly (CSA) cooling loop. It also collects condensate from the condenser, strips CO_2 from the entering condensate, removes organic particles and minerals and filters out particulates.

Materials/Assemblies	Amount	Unit
Steel cold rolled coil IISI	200	lb
Glass fiber I PureCell™ system	135	lb
Total	335	lb
Processes	Amount	Unit
Cold transforming steel PureCell™ system	200	lb
Electric welding steel 3 PureCell™ system	5	m

Table 4-20: Water Treatment System (WTS) inventory data

- Glass fiber is used as insulation material.
- Transport unknown.

Scrap Rates

Most of the materials that appear in the inventory tables are not raw materials, but materials that already went through a manufacturing process (e.g., steel and aluminum). These material manufacturing processes, including, for example, emissions and energy input, are generally included in the way these materials are modeled in SimaPro. However, the weights that appear in the inventory tables described in this chapter are based on a weight breakdown of the PureCell™ system. Thus, so far only the materials that actually end up in the final product have been taken into account. But in the manufacturing processes of the PureCell™ subsystems and components a certain amount of scrap is produced which does not end up in the final product. Scrap rates for the majority of the materials were not included in the PureCell™ system LCA model at all. Many of the PureCell™ subsystem and component manufacturing processes are very specific, and due to the fact that the PureCell™ subsystems and components come from external suppliers these data are simply not available. The scrap rates that are included in this LCA are for steel and copper. The criterion to include the steel scrap rate is its high weight percentage relative to the total PureCell™ system; the copper scrap rate is included because it has a significant weight contribution and a relatively high environmental impact.

Steel scrap

The scrap rate that was used to calculate the inventory data for the LCA comes from the automotive industry [19]. The scrap rate is defined as:

- Amount of scrap produced divided by amount of input material used in manufacturing process.

For steel in the automotive industry this rate is 0.35, so for every 65 lb of steel in the final product, 35 lb steel scrap is produced. The amount of steel in the final PureCell™ system is:

- Steel cold rolled coil IISI: 21142 lb
- Stainless Steel 304 2B IISI: 7143 lb
- Stainless Steel 316 2B IISI: 515 lb
- Aggregated this is 28800 lb steel.

A scrap rate of 0.35 means that total steel used in the manufacturing process is:

$\frac{28800lb}{0.65} = 44300lb$, from which $0.35 * 44300lb = 15505lb$ is produced into steel scrap.

This 15505 lb steel scrap consists of:

- 11385 lb Steel cold rolled coil IISI
- 3845 lb Stainless Steel 304 2B IISI
- 275 lb Stainless Steel 316 2B IISI.

The steel that is scrapped also went through the steel manufacturing processes, so these also have to be taken into account. From the 28800 lb steel that is in the PureCell™ system,

- 28660 underwent the ‘Cold transforming steel PureCell™ system’ process (99.5%)
- 13500 underwent the ‘Rolling steel I PureCell™ system’ process (47%)
- Other steel manufacturing processes are negligible and are not taken into account.

So, to the SimaPro steel scrap process, the following numbers have to be added:

- $0.995 * 15505lb = 15430lb$ ‘Cold transforming steel PureCell™ system’
- $0.47 * 15505lb = 7290lb$ ‘Rolling steel I PureCell™ system’.

Finally, the produced steel scrap is assumed to be recycled. This recycling process includes the transport, shredding and melting of the steel to be recycled.

These numbers result in the SimaPro inventory in Table 4-21.

Materials	Amount	Unit
Steel cold rolled coil IISI	11385	lb
Stainless Steel 304 2B IISI	3845	lb
Stainless Steel 316 2B IISI	275	lb
Total	15505	lb
Processes		
Cold transforming steel PureCell™ system	15430	lb
Rolling steel I PureCell™ system	7290	lb
Waste to treatment		
Steel scrap to Recycling Ferro metals	15505	lb

Table 4-21: Steel scrap inventory data

Copper scrap

For the copper scrap production only the copper processing for the PCS (1800 lb), ECS (300 lb) and Harnesses and Cables (100 lb) are taken into account. Together this is 2200 lb of copper. The copper scrap rate for the manufacturing of the electric components is already included in the 'Electric Components PureCell™ system' process. The other processes are unknown. A copper scrap rate of 0.1 for the copper wiring process is assumed. The total amount of copper used in the copper wiring process then becomes:

$\frac{2200lb}{0.9} = 2444lb$, from which $0.1 * 2444lb = 244lb$ is produced into copper scrap.

This 244 lb of copper scrap also underwent the copper wiring process, which is therefore also included in the copper scrap process. Like the steel scrap, the copper scrap is also assumed to be recycled.

These numbers result in the inventory table below.

Materials	Amount	Unit
Copper ETH U PureCell™ system	244	lb
Total	244	lb
Processes		
Copper wire, adapted to USA	244	lb
Waste to treatment		
Copper scrap to Recycling Non-ferro metals	244	lb

Table 4-22: Copper scrap inventory data

Use Phase

In SimaPro, the use phase is divided into PureCell™ system installation, electricity generation and PureCell™ system maintenance processes. For each of these three processes the LCI data are described.

PureCell™ System Installation

To install the PureCell™ system at its site location several preparations are needed. The installation materials below are included in the PureCell™ system inventory.

Materials	Amount	Unit
Steel cold rolled coil IISI	132	lb
Stainless Steel 304 2B IISI	114	lb
Propylene glycol ETH U PureCell™ system	476	lb
Activated carbon PureCell™ system	60	lb
Concrete PureCell™ system	7940	lb
Water decarbonized ETH U	992	lb
Nitrogen	185	lb
Total	9899	lb
Processes		
Cold transforming steel PureCell™ system	132	lb
Cold transforming steel PureCell™ system	114	lb

Table 4-23: PureCell™ system installation inventory data

The steel (132 lb) is used for 12 nitrogen bottles, containing 200 cubic feet of standard industrial grade nitrogen each. In total this is 2400 cubic feet of nitrogen, which is equal to 185 lb. The nitrogen is used to purge the fuel processing system and the anode and cathode spaces during power plant startup and shutdown. The stainless steel 304 (114 lb) is used for two 55-gallon drums that are used for storing waste liquid. Propylene glycol, which is used in the thermal management system, is typically stored in plastic or painted CSTL drums. The density of propylene glycol is 1.04 times the density of water, leading to a weight of 476 lb. The activated carbon (60 lb) is used for water treatment. Data for modeling the activated carbon production in SimaPro come from an internet source [20]. The concrete is used for the foundation. The ground area of the PureCell™ system is 15.6 m^2; assuming the thickness of the concrete layer to be 0.1 m, then roughly 1.5 m^3 concrete (equal to 7940 lb) is needed. 75 Gallons of decarbonized water are needed to fill up the thermal management system, and another 45 gallons to fill up the water storage, which equals 992 lb of decarbonized water in total. Also a minimum of 11 ft^3 of nuclear mixed resin (Rohm and Haas IRN-150) is needed to fill the water treatment system bottles. However, data on this type or an equal type of resin could not be found; this 11 ft^3 of nuclear mixed resin is therefore not included in the LCA.

Electricity Generation

The input of natural gas and the emissions caused by the steam reforming process are taken into account here. Table 4-24 gives the natural gas input and the emissions for the production of 200 kWh, which is equal to running the PureCell™ system for one hour. These data are given to show which calculations were used to determine the emissions. Thereafter these data are scaled up to the PureCell™ system lifetime of 85,000 hrs in order to provide the inventory data which are needed to describe the PureCell™ system's total life cycle.

Products	Amount	Unit
Generated electricity, 480 Volt, 60 Hz	200	kWh
Produced heat at 140 F	271.025	kWh
Materials/fuels		
Natural gas FAL (Franklin)	2050	cuft [3]
Emissions to air		
NOx	0.0032	lb
CO	0.0046	lb
CO2	112.2	kg
non-methane hydrocarbon (NMHC)	0.000072	lb

Table 4-24: 200 kWh electricity generation inventory data

The natural gas input and the emission of NO_x, CO and NMHC are data measured by UTC Power [21]. The CO_2 emissions however are calculated, since no measured data are available. The calculations are based on the assumption that natural gas is $100\% CH_4$. In practice, this is usually around 95%, with the other 5% mainly including ethane, nitrogen, and higher order hydrocarbons. Another assumption is that all the carbon input results in CO_2 output, thereby neglecting the CO and NMHC emissions. The calculations are based on the steam reforming and low shift reactions:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \text{(steam reforming)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{(shift reaction)}$$

This results in the following overall reaction:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

---

[3] cuft = cubic feet

The specific gravity of natural gas is 0.585 [22]. The density of air at sea level is 1.2 kg/m^3, which means that the density of natural gas is $0.585 * 1.2 kg/m^3 = 0.702 kg/m^3$. Converting cuft into m^3, $2050 cuft/hr = 58.03 m^3/hr$, it can be calculated that

$0.702 kg/m^3 * 58.05 m^3/hr = 40.75 kg/hr$ natural gas is consumed.

With the assumption that natural gas is 100% CH_4, and recognizing that CH_4 has a atomic mass of 16 u (C is 12 u, H is 1 u), it can be calculated that

$(12/16) * 40.75 kg/hr = 30.6 kg/hr$ of carbon enters the PureCell™ system.

Since CO_2 has a molecular mass of 44 u (C is 12 u, O_2 is 32 u), a carbon emission rate of $30.6 kg/hr$ leads to a CO_2 emission rate of

$(44/12) * 30.6 kg/hr = 112.2 kg/hr$.

This is the value indicated in the electricity generation inventory table.

Since this LCA aims at covering the entire PureCell™ system life cycle, these inventory data have to be scaled up. The PC25 D lifetime is expected to be 85,000 hrs, and in this LCA it is assumed that the PureCell™ system will run at full power (200 kW) over its lifetime. Therefore the inventory data for 200 kWh electricity production are multiplied by 85,000.

Products	Amount	Unit
Generated electricity, 480 Volt, 60 Hz	17000000	kWh
Produced heat at 140 F	23037125	kWh
Materials/fuels		
Natural gas FAL (Franklin)	174250000	cuft
Emissions to air		
NOx	272	lb
CO	391	lb
CO2	9537000	kg
non-methane hydrocarbon (NMHC)	6.12	lb

Table 4-25: 17,000,000 kWh electricity generation inventory data

The extraction and transport of natural gas is already taken into account in the SimaPro process, and does therefore not appear separately in the inventory table.

PureCell™ System Maintenance

Several maintenance activities are needed to keep the fuel cell functioning properly over its entire lifetime. Maintenance activities included in the inventory table are the replacement of activated carbon for water treatment and the hexavalent chromium emissions caused by cleaning the condenser. Other maintenance activities include replacing the Rohm and Haas resin for water treatment, a quarterly replacement of air filters and other replacements which are done on a case-by-case basis (e.g., blowers and fans). These are however not included in the LCA because no data on these activities are available.

Materials	Amount	Unit	Waste treatment
Activated carbon PureCell™ system	1852.5	lb	
Total	1852.5	lb	
Waste to treatment			
inorganic general	1852.5	lb	Landfill Compostables
chromium compounds	570	kg	LT waste to chemical landfill
chromium compounds	570	kg	Waste to chemical landfill

Table 4-26: PureCell™ system maintenance inventory data

The activated carbon for water treatment is replaced three times a year. Initially, 60 lb activated carbon is used in the PureCell™ system. The maintenance data are based on a PureCell™ system lifetime of 85,000 hrs. In the definition of the PureCell™ system lifetime 8000 hrs is regarded as one year (vs. 8760 actual hours); this means that the lifetime in years is 10 5/8 year. The total amount of activated carbon needed for maintenance then becomes: $120lb + (9*180)lb + \frac{5}{8}*180lb = 1852.5lb$.

The activated carbon waste is indicated as 'inorganic general' and is assumed to end up in landfills.

The condenser is cleaned annually resulting in waste water containing hexavalent chromium. Per annual cleaning 15 to 30 gallons of waste water are produced with a hexavalent chromium concentration below 5%. For the calculations it is assumed that 15 gallons with a 5% hexavalent chromium concentration are produced annually.
15 Gallons is equal to 57 liter or 57 kg. With 10 annual cleanings, this results in 570 kg waste water to treatment, containing 28.5 kg $Cr(VI)$. This is a conservative estimate: it is expected that most of this is *Cr (III)*. Although the waste is described as 'chromium compounds', the SimaPro software only recognizes the amount of waste and the waste treatment it is sent to. This means that it is not possible in SimaPro to include the exact amount of hexavalent chromium in the model. The 570 kg waste is assumed to go to landfill; it appears twice in the inventory table because both the short-term and long-term effects are taken into account.

End-of-Life Phase

For every PureCell™ subassembly or component a waste scenario has been defined in SimaPro. These waste scenarios determine to which type of waste treatment a particular material is sent. Thus, every PureCell™ subassembly/component is broken down into materials again, which are thereafter sent to a waste treatment process. SimaPro databases are used to model these waste treatment processes. The energy and emissions related to the disassembly of the PureCell™ system into the materials which are sent to waste treatment are not taken into account.

In SimaPro, the amount of material that is sent to a certain waste treatment process is not specified in absolute weight but in a percentage of the total amount of the material. For instance, in the model 90% of all copper is sent to a recycling process and 10% is sent to landfill. This percentage is then applied to every PureCell™ subassembly/component waste scenario. The table below is therefore not an inventory table, but a table that indicates to which waste treatment process the materials of every PureCell™ subassembly/component are sent.

Material	Waste treatment	Percentage
Steel cold rolled coil IISI	Recycling Ferro metals	100%
Stainless Steel 304 2B IISI	Recycling Ferro metals	100%
Stainless Steel 316 2B IISI	Recycling Ferro metals	100%
Copper ETH U PureCell™ system	Recycling Non-ferro	90%
Copper ETH U PureCell™ system	Copper (inert) to landfill	10%
Aluminum (primary) produced in the USA	Recycling aluminum B250	90%
Aluminum (primary) produced in the USA	Landfill Aluminum B250 (1998)	10%
Aluminum 100% recycled ETH U PureCell™ system	Recycling aluminum B250	90%
Aluminum 100% recycled ETH U PureCell™ system	Landfill Aluminum B250 (1998)	10%
Nickel enriched ETH U PureCell™ system	Recycling Non-ferro	90%
Nickel enriched ETH U PureCell™ system	Unspecified	10%
Graphite PureCell™ system	Waste to special waste incinerator	100%
Carbon black ETH U PureCell™ system	Waste to special waste incinerator	100%
PTFE (Teflon®)	Waste to special waste incinerator	100%
Glass fiber I PureCell™ system	Landfill Glass B250 (1998)	100%
Zeolite ETH U PureCell™ system	Zeolite (inert) to landfill	100%
PP granulate average B250 PureCell™ system	Landfill PP B250 (1998)	100%
PET ETH U PureCell™ system	Landfill PET B250	100%
Electric Components PureCell™ system	Unspecified	100%
Other materials	Unspecified	100%

Table 4-27: PureCell™ system end-of-life phase, materials to waste treatment

The end-of-life phase of the PureCell™ system is at present undefined except for the fact that the CSA platinum is recycled. The recycling rates in Table 4-27 are based on rates that are common in the end-of-life management of automobiles. Approximately two thirds of the total weight of an automobile is made up of steel. Other significant materials in an automobile are non-ferrous metals (e.g., aluminum and copper), plastics and fluids. From an end-of-life perspective the PureCell™ system is therefore assumed to resemble an automobile in order to include recycling rates in the SimaPro model. In the automobile industry virtually all steel is recovered for reuse and recycling. As a result, over recent years the recycling rate has approached 100% [23]. Therefore the PureCell™ system steel recycling rate is assumed to be 100%.

Regarding aluminum, nearly 90% of automotive aluminum is recovered and recycled [24]. The remaining 10% is part of the automobile shredder residue (ASR) which is disposed in landfills. For both copper and nickel no recycling rates for the automobile industry were found. It is therefore assumed that copper and nickel waste management is comparable to aluminum waste management, which means that 90% is recycled and 10% disposed in landfills. Landfill of nickel is left unspecified because no appropriate waste treatment process in SimaPro is available.

Graphite, carbon black and Teflon® are not considered to be within the scope of automobile end-of-life management. In the SimaPro model they are assumed to be incinerated. Graphite and Teflon® are mixed together before they are manufactured into bipolar and cooling plates. The carbon black is a porous structure to disperse the platinum catalyst and to provide maximum gas diffusion. In a 2002 journal article [25] possibilities are explored for chemical extraction and subsequent recycling of membrane and bipolar plate materials. This is however not (yet) representative for today's situation; at present these materials most probably end up in waste incineration.

Glass fiber, zeolite, polypropylene (PP) and polyethylene (PET) are assumed to end up in landfill, because in the automobile industry these are the kind of materials that are part of the ASR. Furthermore, relatively small amounts of these materials are used in the PureCell™ system and they are relatively inexpensive, which increases the probability that they end up in landfill.

Since the exact composition of the PureCell™ system electrical components is unknown, it is decided to leave the waste treatment unspecified. This means that the mass of the waste stream is taken into account, but no inputs and emissions are defined for the waste treatment process. The same method is applied for remaining materials.

As explained in the description of the CSA inventory table, platinum recycling is already taken into account as an 'internal recycling' in the manufacturing phase. It does therefore not appear in the waste treatment table.

Chapter 5 - Impact Assessment and Interpretation

Impact assessment is the phase in which the set of results of the inventory analysis is further processed and interpreted in terms of environmental impacts and societal preferences [26]. These environmental impacts and societal preferences are expressed in a list of impact categories. For this LCA the Eco-indicator 99 impact assessment method is used. Within the Eco-indicator 99 method the impact categories are already defined. Furthermore, Eco-indicator 99 groups the results of the impact categories into three damage categories.

In this chapter, first a description of the impact and damage categories is given. Thereafter the different steps in impact assessment are explained as well as how these steps lead to LCA results. Then the actual PureCell™ system LCA results are shown followed by an interpretation of these results. For the LCA results the default hierarchist version of Eco-indicator 99 is used. Finally, a contribution and sensitivity analysis is performed, followed by conclusions based on the results in this chapter.

Impact and Damage Categories

The following impact categories are defined in Eco-indicator 99 (every impact category is concisely explained) [7]:

- *Carcinogens* (substances which are cancer-causing upon exposure)
- *Respiratory organics* (can also be described as summer smog; summer smog is caused by a mixture of pollutants from road vehicles, fuels to provide electricity and heating, and vapors from petrol and certain industrial premises. Summer smog occurs as nitrogen dioxide and particles in urban areas; action of sunlight on these pollutants forms low-level ozone close to the ground. It also occurs in rural and suburban areas, mainly as ozone and particles.) [27]
- *Respiratory inorganics* (can also be described as winter smog; winter smog is caused by a mixture of pollutants from road vehicles and from fuels used to provide electricity and heating. Pollutants build up at ground level in urban areas because a 'lid' of cold air above the warm air traps the pollutants.) [27]
- *Climate change* (a change in temperature and weather patterns. Current science indicates a link between climate change over the last century and human activity, specifically the burning of fossil fuels)
- *Radiation* (ionizing radiation related to the releases of radioactive material to the environment)
- *Ozone layer* (the release of substances such as CFC's which break down stratospheric ozone and result in increased UV radiation levels)
- *Ecotoxicity* (the toxic stress on ecosystems denoted as a Potentially Affected Fraction (PAF) of species)
- *Acidification/Eutrophication* (acidification and eutrophication are caused by depositions of inorganic substances such as sulphates, nitrates and phosphates. These depositions occur mainly through air and directly into water. The primary effect is the change in nutrient level and acidity in the soil.)

- *Land use* (this impact category assesses the impact of land-cover changes on ecosystems. Also land occupation and land transformation is distinguished.)
- *Minerals* (impact category that assesses the relation between availability and quality of minerals. In this category the decrease in mineral concentration as a result of extraction is modeled.)
- *Fossil fuels* (impact category that assesses the relation between availability and quality of fossil fuels. In this category the decrease in fossil fuel concentration as a result of extraction is modeled.)

Eco-indicator 99 provides the option to group the results of the impact categories into three damage categories: human health, ecosystem quality and resources. The results of the impact categories can be added because all impact categories that refer to the same damage category, e.g., human health, have the same unit, e.g., DALY, Disability Adjusted Life Years. The human health result is obtained by adding the results of the carcinogens, respiratory organics, respiratory inorganics, climate change, radiation and ozone layer impact categories. The ecosystem quality result is obtained by adding the results of the ecotoxicity, acidification/eutrophication and land use impact categories. The resources result is obtained by adding the results of the minerals and fossil fuels impact categories.

Impact Assessment Steps

Generally impact assessment includes four steps: classification, characterization, normalization and weighting. The grouping of impact category results into damage categories in Eco-indicator 99 can be seen as a fifth step. These impact assessment steps are already defined and modeled in Eco-indicator 99; therefore only a generic description of these steps is given here. For a more detailed description of the impact assessment steps in Eco-indicator 99 the reader is referred to [7].

In the classification step the environmental interventions qualified and quantified by the input of data in the inventory analysis are assigned on a qualitative basis to the aforementioned impact categories [26]. Environmental interventions are defined as human interventions in the environment, either physical, chemical or biological. Environmental interventions are linked to the materials, assemblies, processes and waste treatments that are selected in SimaPro, and they include in particular resource extraction, emissions and land use.

The characterization step quantifies the environmental interventions assigned to an impact category in terms of a common unit for that impact category, allowing aggregation into a single score [26]. For instance, the common unit used in the climate change impact category is ‘kg CO_2 equivalents’. In this way the contribution of all relevant substances to climate change can be quantified into one number of kg CO_2 equivalents.

In the normalization step the magnitude of the characterization results is calculated relative to reference information. The main aim of normalization is to better understand the relative importance and magnitude of the results of the characterization step. Eco-indicator 99 uses European normalization values. In SimaPro no impact assessment method with U.S. normalization values is available; the optional normalization value sets either reflect Europe or the world. It was therefore decided that using European normalization values gives the best approximation of the U.S. situation.

Weighting is based on value choices, as numerical factors are assigned to the normalized impact category results (e.g., by an expert panel) according to their relative importance. The normalized results are multiplied by these factors, leading to either a set of weighted results for the impact categories or a single aggregated result reflecting the complete life cycle of the product system.

PureCell™ System LCA Results and Interpretation

In the SimaPro model the life cycle of the PureCell™ system was divided into three phases: the manufacturing phase, the use phase and the end-of-life phase. Weighted LCA results indicate the contribution of each life cycle phase to the impact and damage categories.

Single score results show the environmental impact of the three life cycle phases relative to each other.

Also, in order to create a more transparent view on what contributes to the environmental impact of the use phase and the manufacturing phase, the LCA results for these two life cycle phases are shown separately.

The end-of-life phase will receive more attention in Chapter 6. Furthermore, based on the LCA results for the manufacturing phase, to show the results for the CSA (Cell Stack Assembly) separately too.

PureCell™ System Life Cycle LCA Results

In Figure 5-1 the weighted results for the impact categories are shown. In Figure 5-2 the results for the impact categories are aggregated in order to show the damage categories.

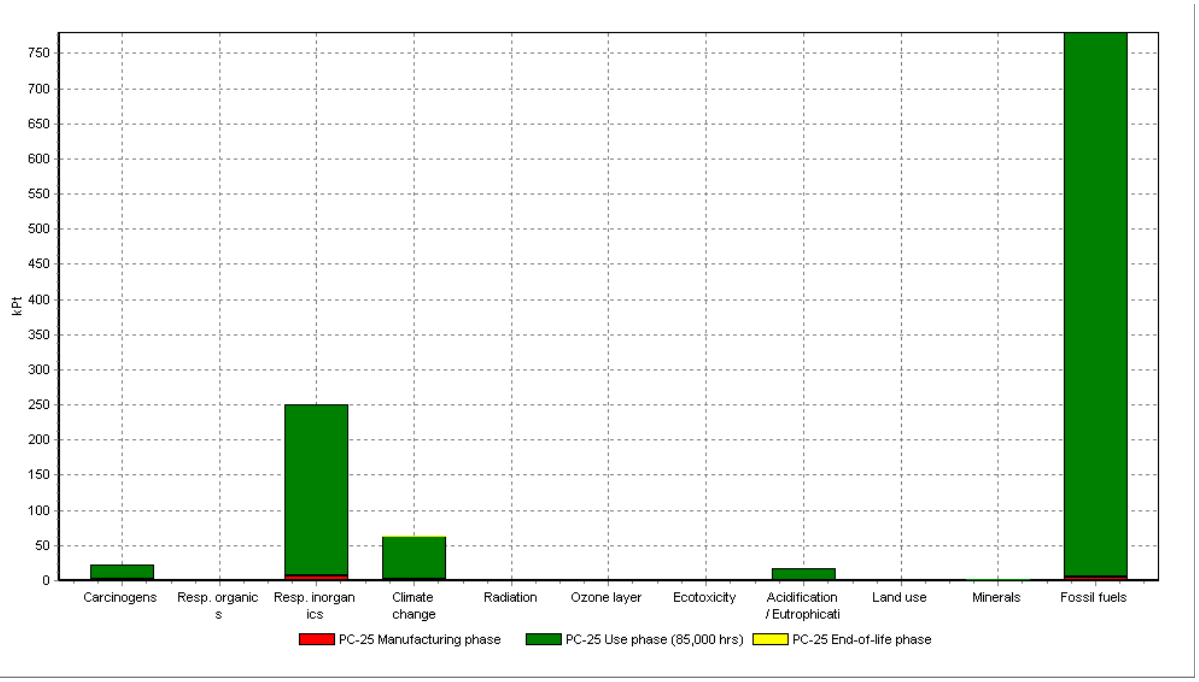


Figure 5-1: PureCell™ system life cycle, weighted results for the impact categories

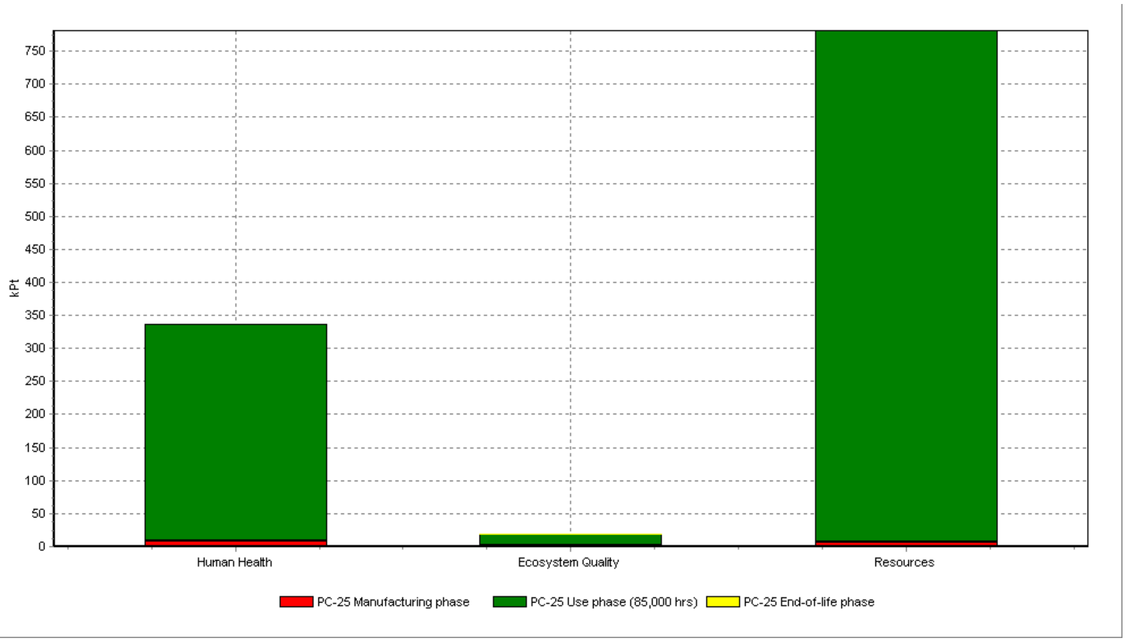


Figure 5-2: PureCell™ system life cycle, weighted results for the damage categories

It becomes clear that the ‘Fossil fuels’ impact category is by far the largest contributor to the PureCell™ system life cycle’s environmental impact. The second most significant contribution to the environmental impact comes from the ‘Respiratory inorganics’ impact category.

In Figures 5-3 and 5-4 a more direct view is given on the relative magnitude of the environmental impacts of the three life cycle phases.

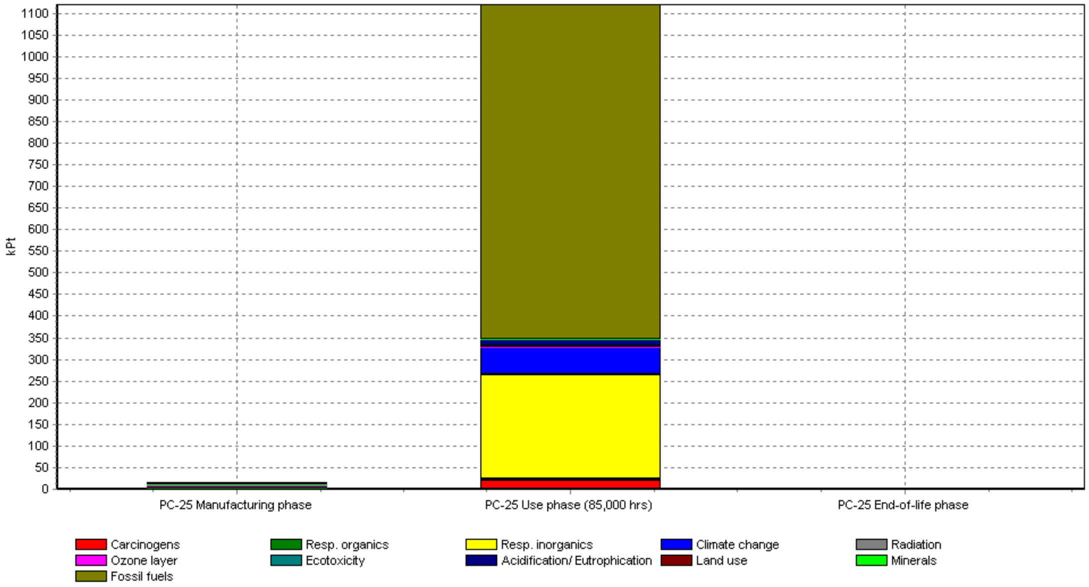


Figure 5-3: PureCell™ system life cycle, single score results showing contribution of impact categories

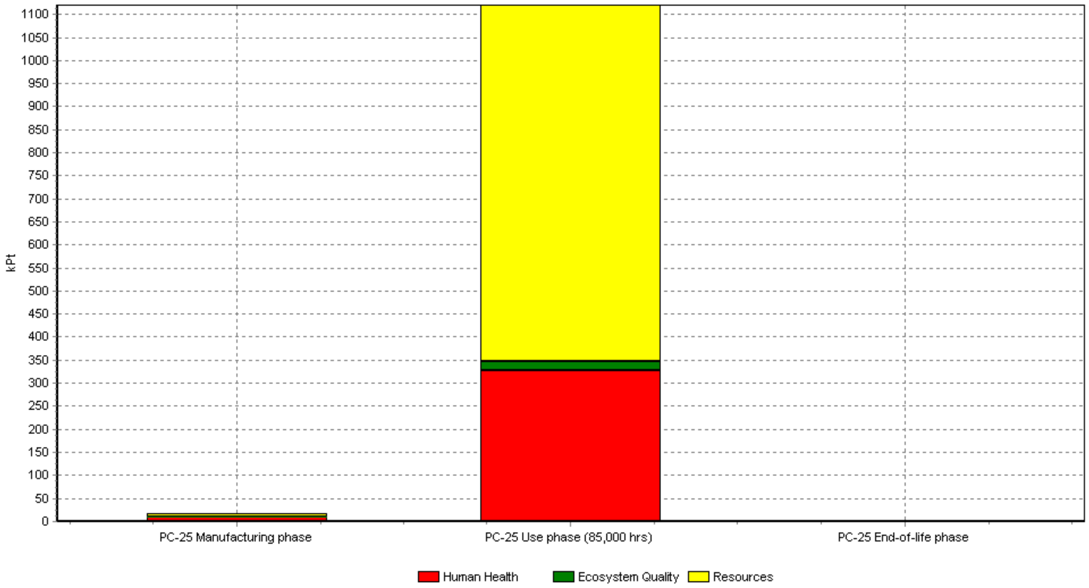


Figure 5-4: PureCell™ system life cycle, single score results showing contribution of damage categories

The use phase of 85,000 hrs has an extremely high environmental impact relative to the manufacturing and end-of-life phase. Therefore the LCA results for the PureCell™ system use phase are analyzed separately in the next section.

PureCell™ System Use Phase LCA Results

Figure 5-5 shows the weighted results for the impact categories and Figure 5-6 shows the weighted results for the damage categories.

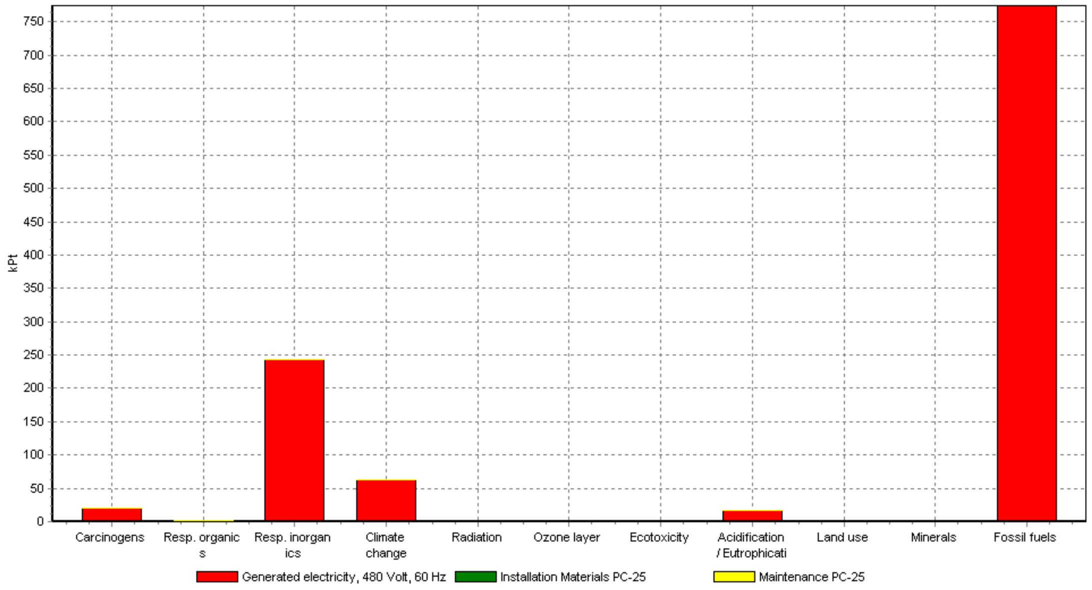


Figure 5-5: PureCell™ system use phase, weighted results for the impact categories

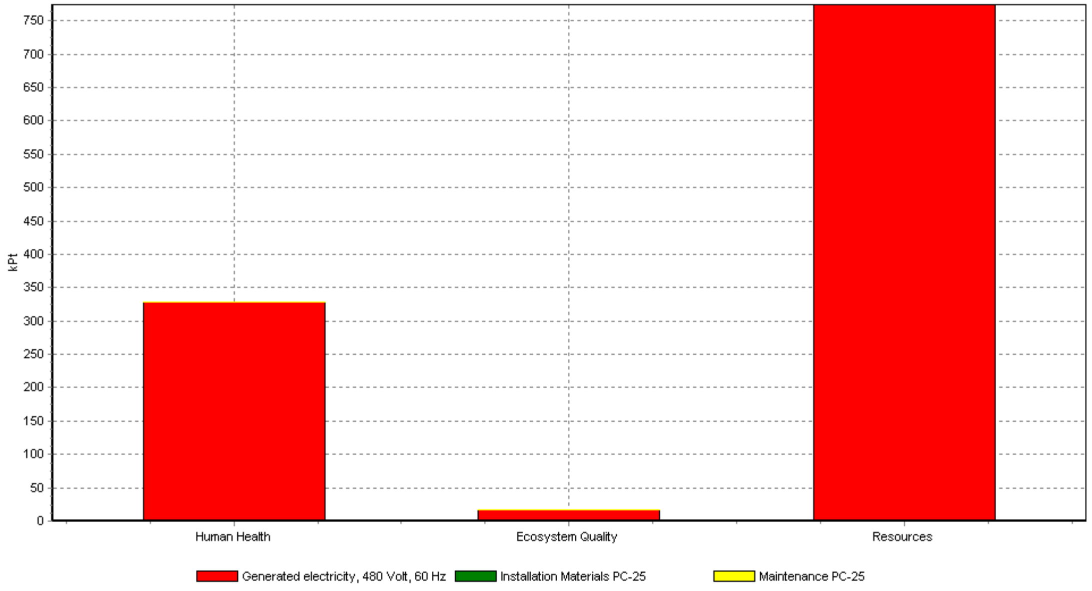


Figure 5-6: PureCell™ system use phase, weighted results for the damage categories

Due to the extremely high contribution of the use phase to the life cycle environmental impact, Figures 5-5 and 5-6 are almost identical in shape to Figures 5-1 and 5-2. A more direct view on the relative magnitude of the environmental impacts of PureCell™ system installation, maintenance and the generation of electricity is given is Figures 5-7 and 5-8.

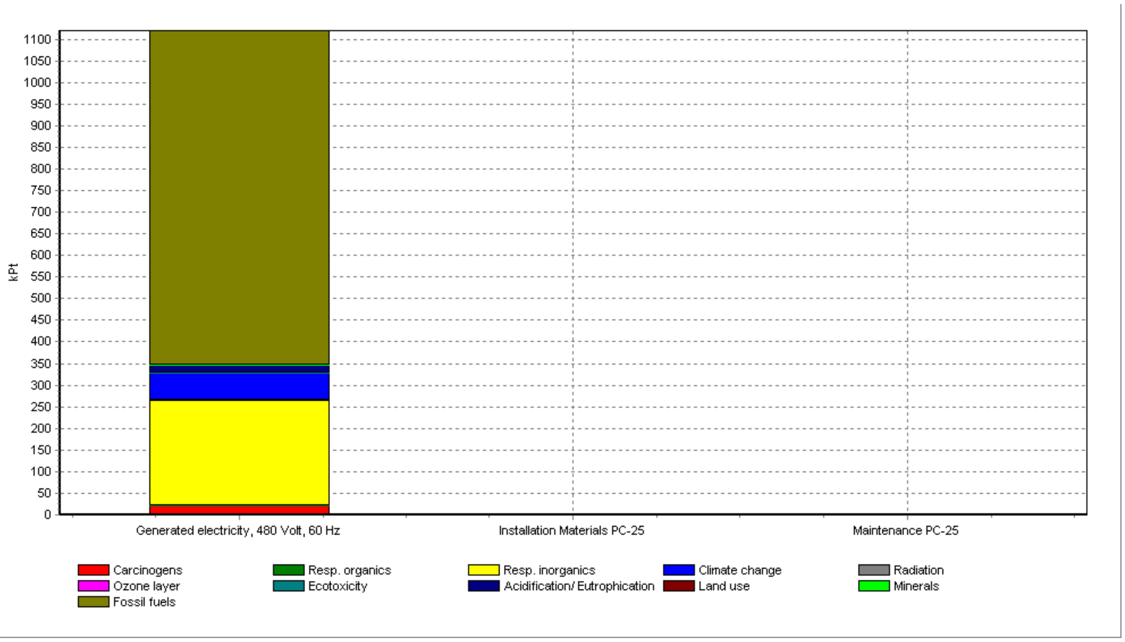


Figure 5-7: PureCell™ system use phase, single score results showing contribution of impact categories

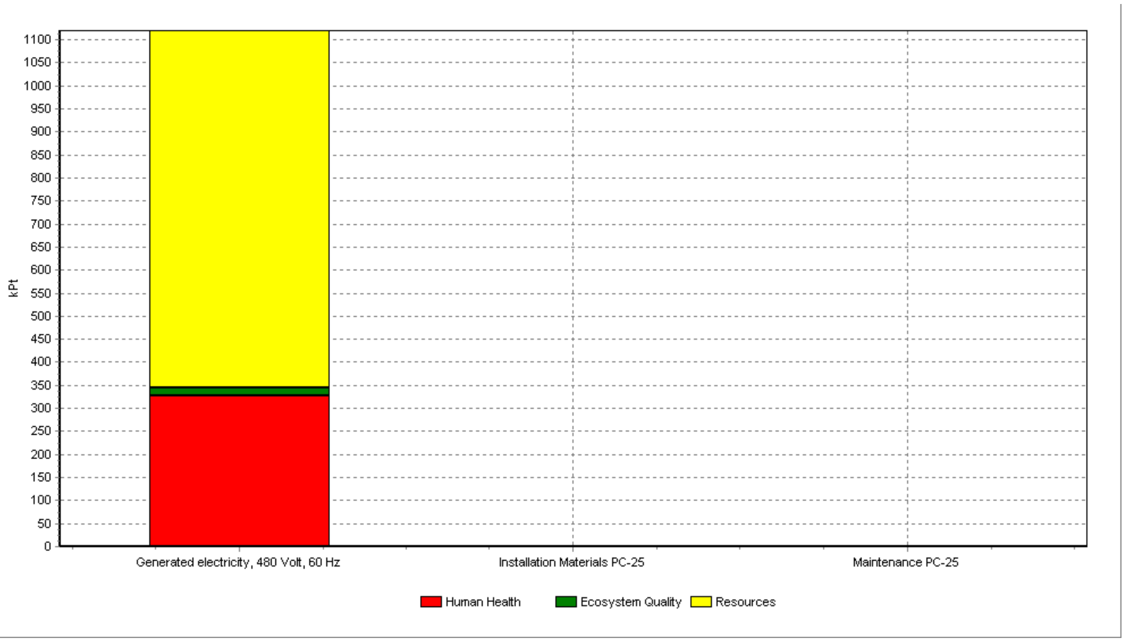


Figure 5-8: PureCell™ system use phase, single score results showing contribution of damage categories

It becomes clear that ‘Installation Materials PureCell™ system’ and ‘Maintenance PureCell™ system’ as they are modeled in SimaPro do not have a significant contribution to the environmental impact of the use phase, and therefore not to the environmental impact of the life cycle either. The ‘Generated Electricity, 400 Volt, 60 Hz’ process represents the input of natural gas to the fuel processing system and the emissions caused by the steam reforming process. Referring to Figure 5-7, the contributions of the impact categories ‘Fossil fuels’, ‘Respiratory inorganics’, ‘Carcinogens’ and ‘Acidification/Eutrophication’ to the total environmental impact of ‘Generated Electricity, 400 Volt, 60 Hz’ are almost entirely caused by the delivery of natural gas and its depletion as a resource. The contribution of the impact category ‘Climate change’ is caused by the emissions of the steam reforming process, particularly CO_2 emissions.

PureCell™ System Manufacturing Phase LCA Results

Although it is shown in Figure 5-3 and 5-4 that the manufacturing phase only has a small contribution to the environmental impact of the PureCell™ system life cycle, it is still valuable to assess the environmental impact of the manufacturing phase separately as well. Since the PureCell™ system is primarily an electricity-providing system using a non-renewable resource (natural gas) as a fuel, it is not surprising that the use phase has by far the highest environmental impact. One could argue that at present the steam reforming process is unavoidable for an economically feasible fuel cell system, and that therefore the environmental impact caused by the consumption of natural gas and the emissions of the steam reforming process is unavoidable, too.[4] If the use phase is seen as an unavoidable burden, the attention shifts to the PureCell™ system manufacturing and end-of-life phase. The LCA results for the manufacturing phase are analyzed in this section.

Figure 5-9 gives a visual representation of the manufacturing phase network as it is modeled in SimaPro. Not all assemblies and processes are included in the figure; only the biggest contributors are shown. The percentages in the boxes are percentages of the total environmental impact of the PureCell™ system manufacturing phase. It can be seen that the CSA is responsible for almost half of the total environmental impact. A separate analysis of the LCA results for the CSA will be given in the next section.

---

[4] LCA results for the hypothetical situation of a PC25 running on renewable hydrogen are given in chapter 6.

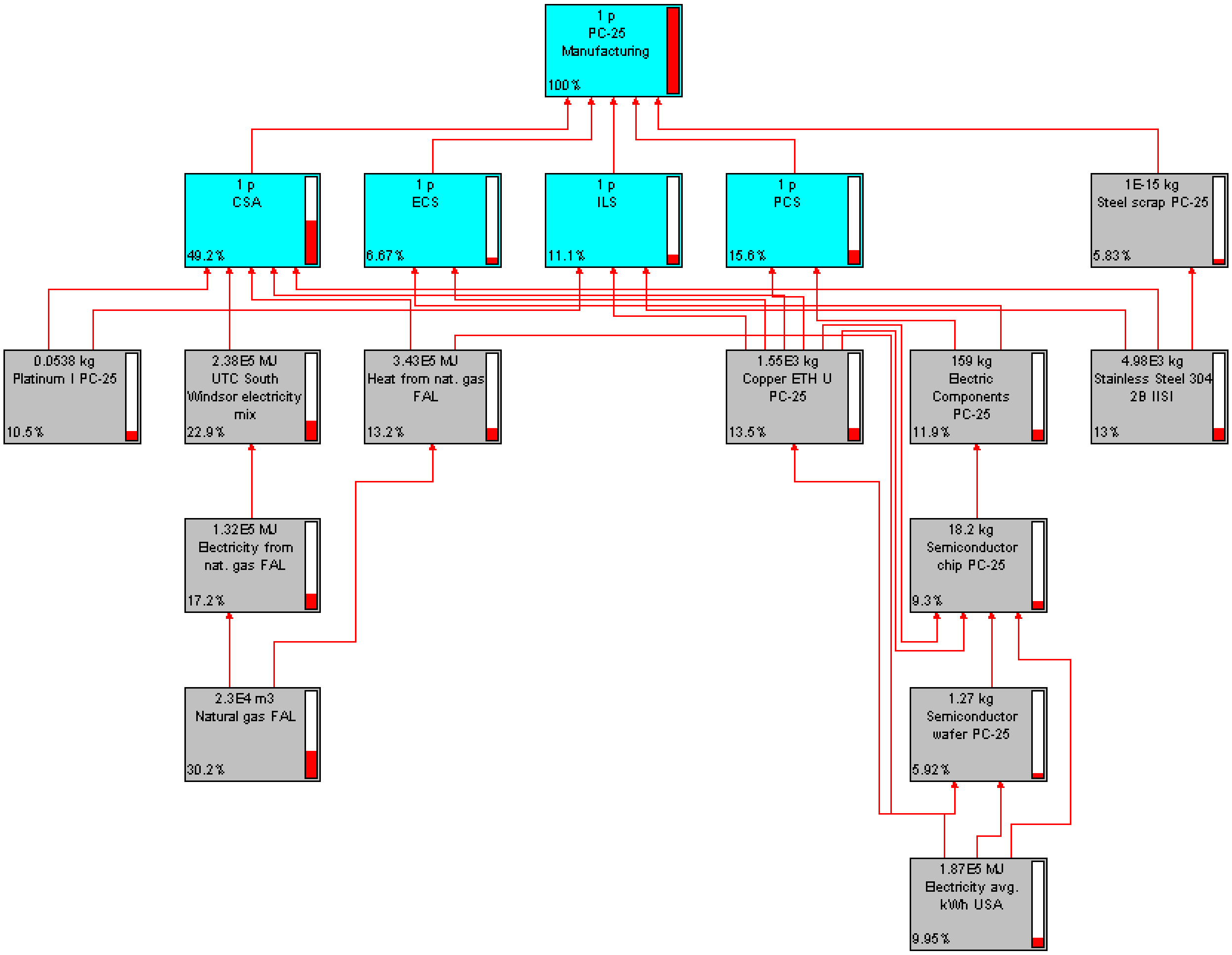


Figure 5-9: PureCell™ System manufacturing phase SimaPro network

This network figure is shown with the intention to clarify that a small number of subassemblies in the PureCell™ system make up a big part of the total environmental impact. Due to the high number of subassemblies in the PureCell™ system it is hard to put all the results in one transparent figure. Therefore only the subassemblies with the highest environmental impact are shown in the figures below. Together these seven subassemblies are responsible for 95% of the total environmental impact of the manufacturing phase. The subassemblies that are not shown in the figures each have a contribution of 0.9% or less.

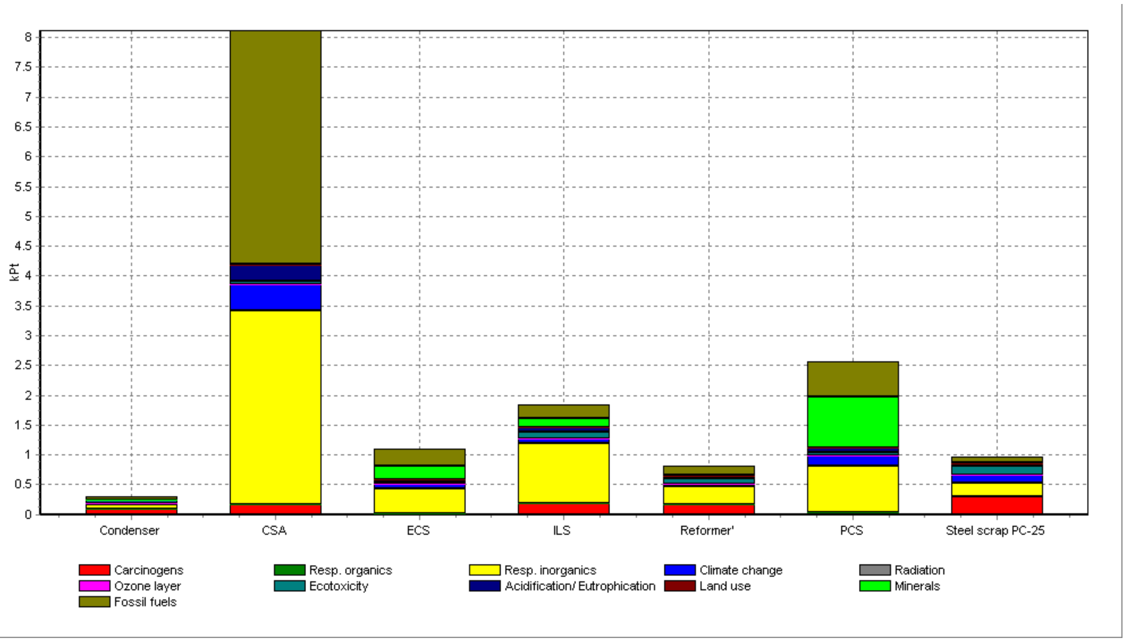


Figure 5-10: PureCell™ system manufacturing phase, single score results showing contribution of impact categories

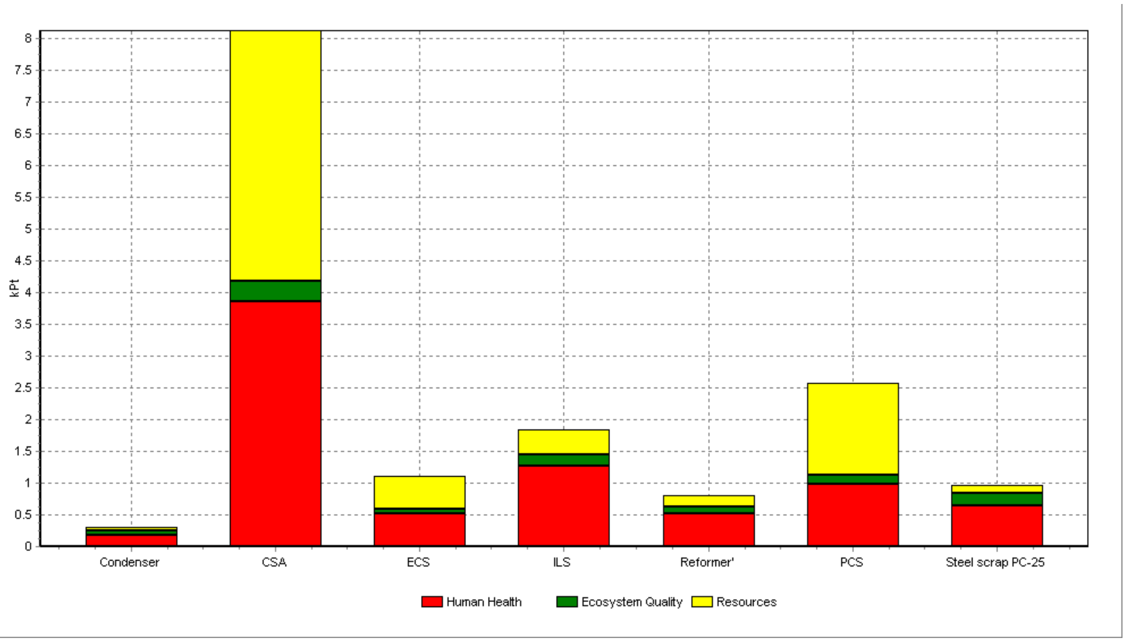


Figure 5-11: PureCell™ system manufacturing phase, single score results showing contribution of damage categories

Steel scrap is not a real subassembly but a process to include the steel scrap rate in the PureCell™ system subassembly production. It is included in Figures 5-10 and 5-11 in order to show its significant contribution.

From Figure 5-10 it becomes clear that the impact category ‘Respiratory inorganics’ has the biggest contribution to the total environmental impact of the manufacturing phase, while the other big contributor is the ‘Fossil fuels’ impact category. Other impact categories that have a significant contribution are ‘Minerals’, ‘Climate change’, ‘Carcinogens’, ‘Ecotoxicity’ and ‘Acidification/Eutrophication’.

Many processes contribute to the ‘Respiratory inorganics’ impact category. The biggest contributor is raw platinum with a 25% contribution. Use of natural gas is the biggest contributor (65%) to the ‘Fossil fuels’ category. The appearance of the ‘Minerals’ category is almost completely due to the use of copper (91%), whereas ‘Climate change’ is caused by many processes with carbon steel and stainless steel 304 as biggest contributors (19% and 15% respectively). Stainless steel 304 is also the biggest contributor to the ‘Ecotoxicity’ category (58%). The ‘Acidification/Eutrophication’ category is caused by many processes with raw platinum (18%) and natural gas (15%) as biggest contributors.

An aggregated overview of the environmental impact per material in the manufacturing phase is given in Figure 5-12. Surprisingly, natural gas comes out as the overall biggest contributor. This is mainly due to the natural gas used for the CSA manufacturing at UTC Power (89% of total natural gas impact).

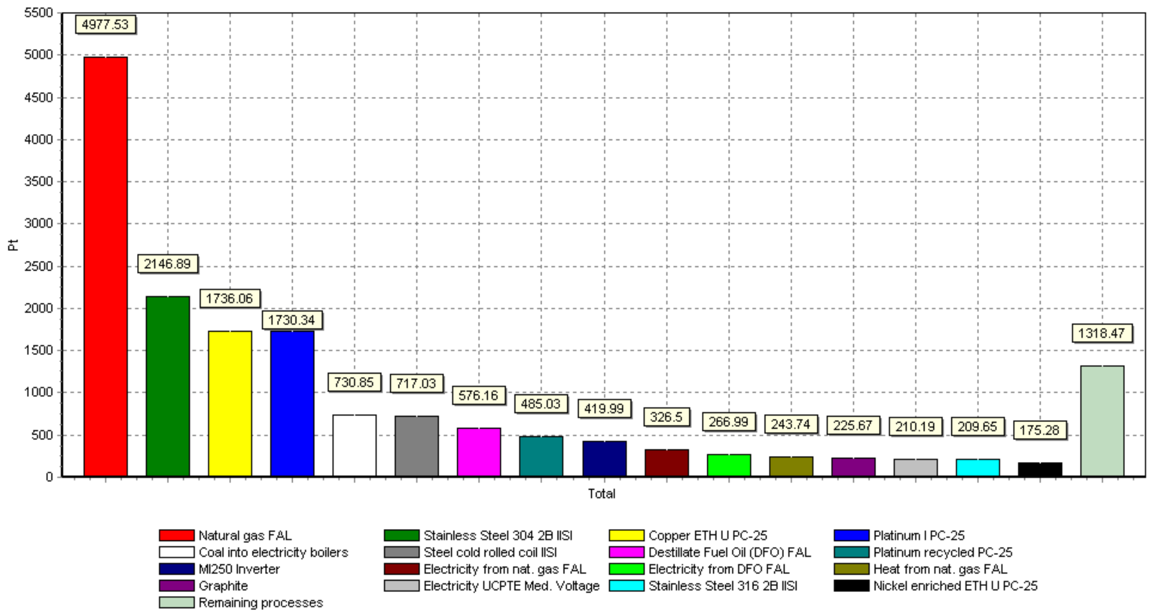


Figure 5-12: PureCell™ system manufacturing phase, overview of total environmental impact per material[5]

---

[5] ‘MI250 Inverter’ is a process used in SimaPro to model the electric components in the PCS and ECS.

In the next section the LCA results for the CSA alone are analyzed. There it will become clear why the contribution of natural gas is so high. The other big overall contributors to the environmental impact of the manufacturing phase are stainless steel 304, copper and raw platinum. Furthermore it can be seen that several processes representing electricity and heat needed for the material/component production processes also have a significant contribution. These processes will also receive more attention in the next section on LCA results for the CSA.

PureCell™ System CSA (Cell Stack Assembly) LCA Results

The LCA results for the CSA are analyzed separately here because in Figure 5-9 it is shown that the CSA is responsible for almost half of the total environmental impact of the manufacturing phase. Figure 5-13 is a similar network figure but this time for the CSA alone.

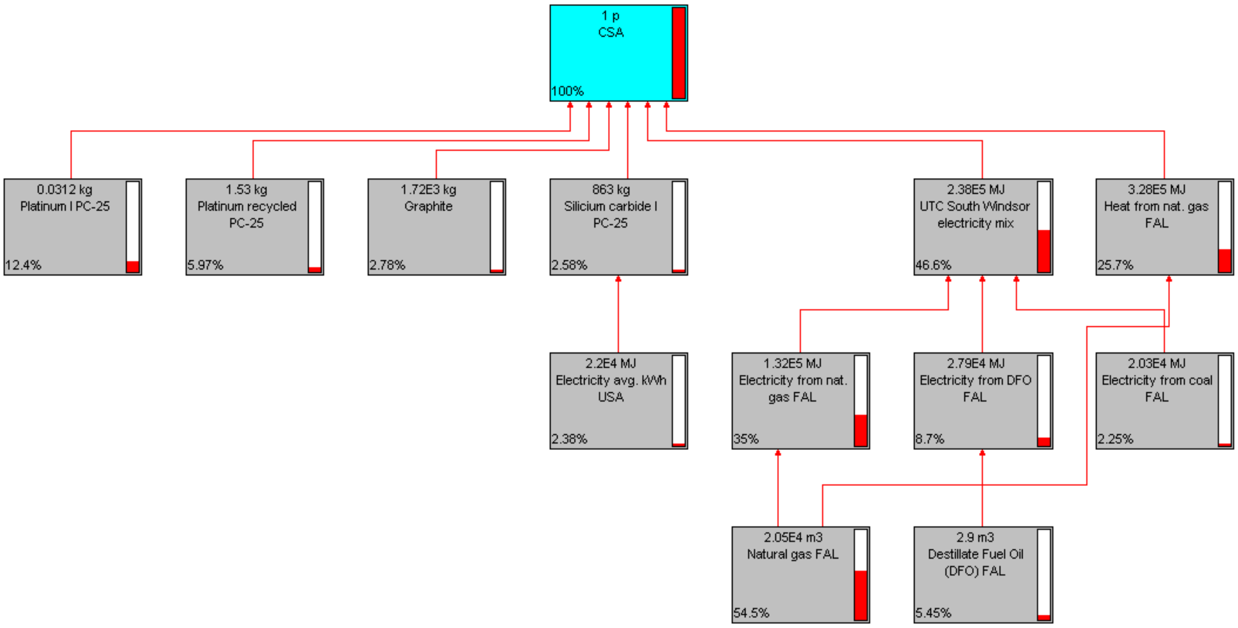


Figure 5-13: PureCell™ system CSA SimaPro network

As stated earlier the CSA is responsible for 89% of the total natural gas impact shown in Figure 5-12. In the network figure above it can directly be seen why so much natural gas is used in the CSA manufacturing process; it is both used as an input for the 'UTC South Windsor electricity mix' process (explained in Appendix F) and for the 'Heat from nat. gas FAL' process. These two processes have been modeled in SimaPro by using the allocation procedure described in Chapter 4 - Inventory Analysis. Figure 5-14 shows the PureCell™ system CSA weighted results for the impact categories and Figure 5-15 shows the weighted results for the damage categories.

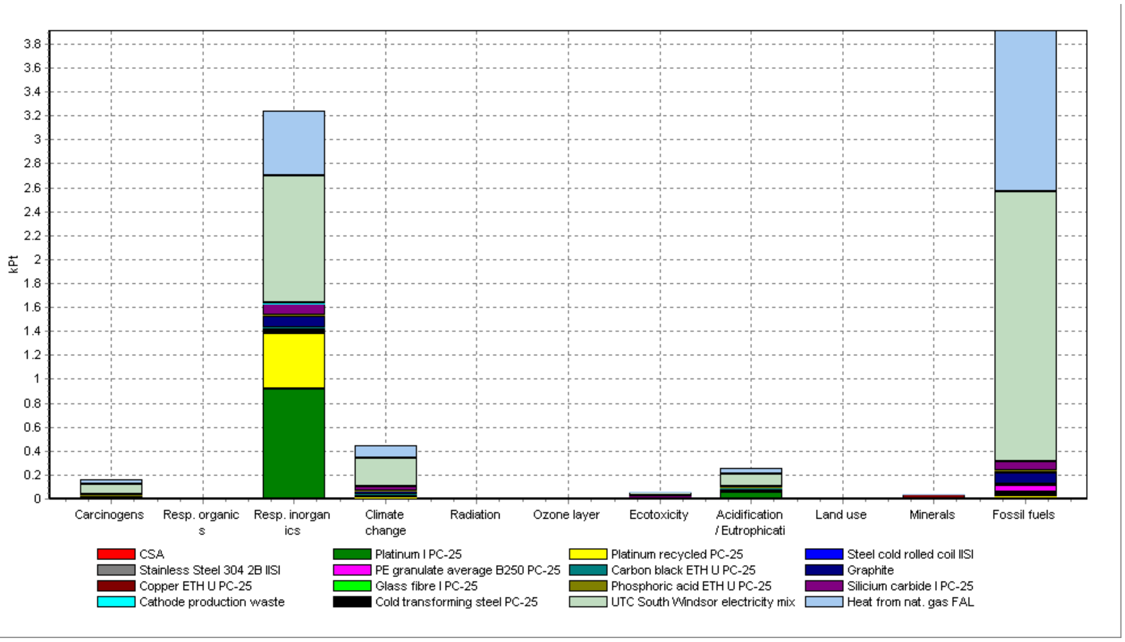


Figure 5-14: PureCell™ system CSA, weighted results for the impact categories

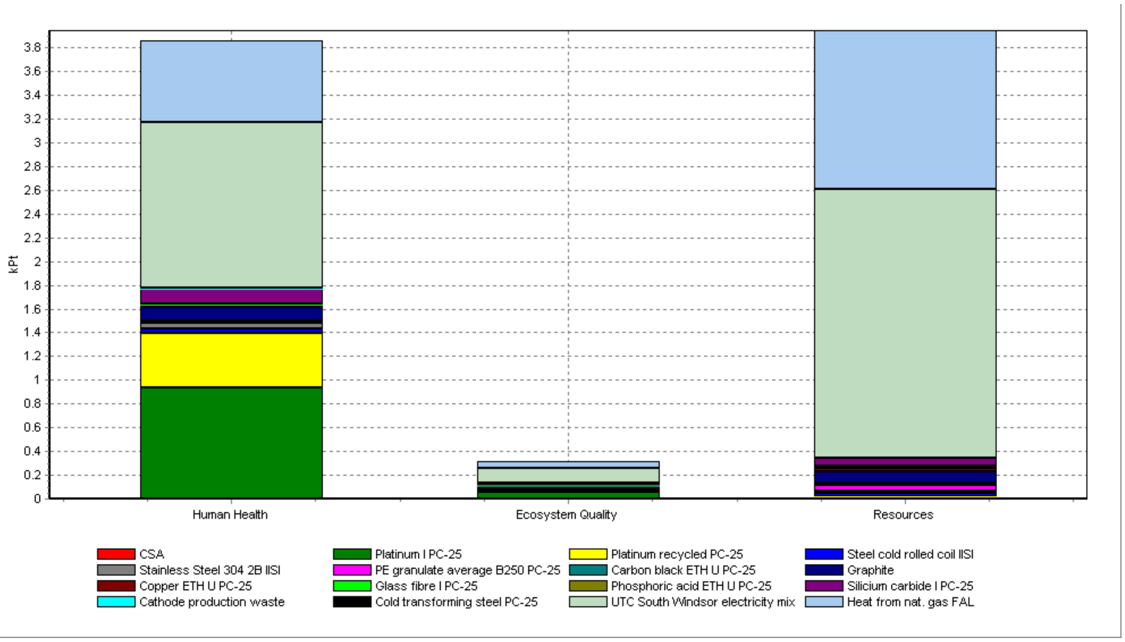


Figure 5-15: PureCell™ system CSA, weighted results for the damage categories

Figures 5-16 and 5-17 show the PureCell™ system CSA single score results for the impact and damage categories, respectively.

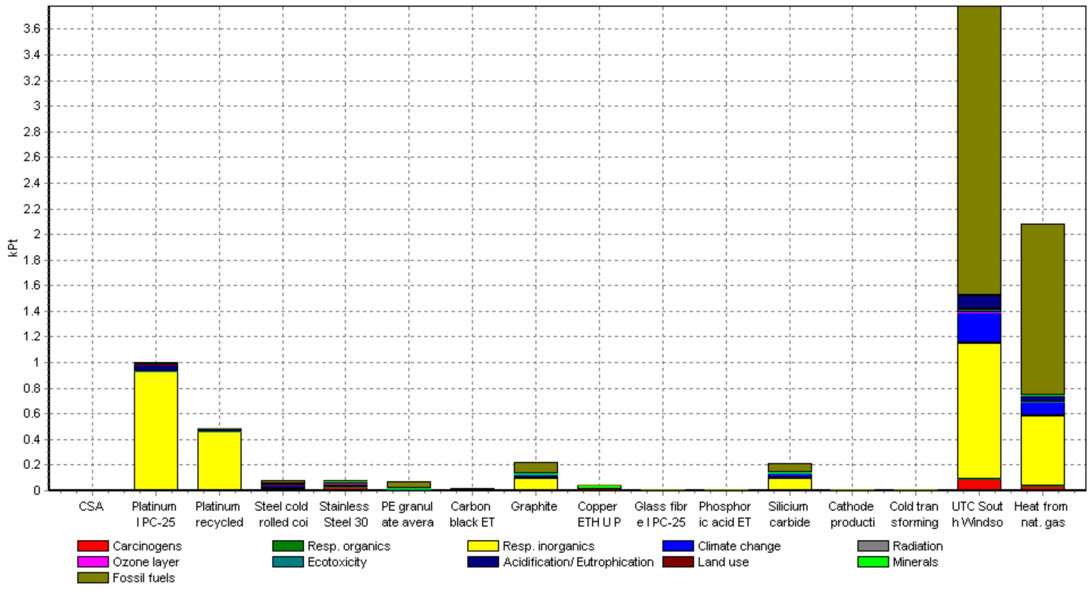


Figure 5-16: PureCell™ system CSA, single score results showing contribution of the impact categories

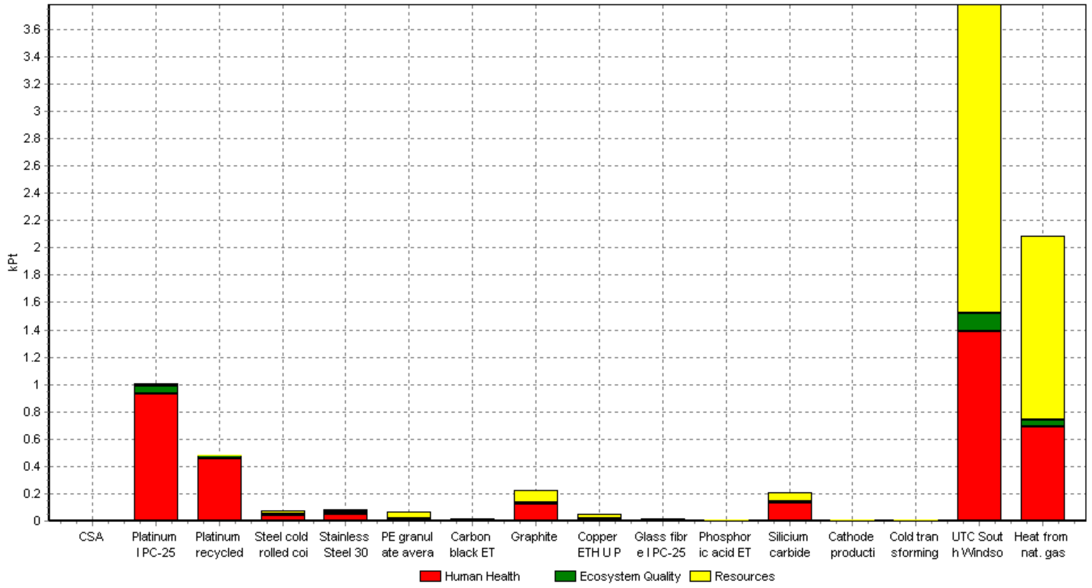


Figure 5-17: PureCell™ system CSA, single score results showing contribution of damage categories

The LCA results for the CSA are heavily influenced by the allocated electricity and heat from natural gas used at the UTC Power facility in South Windsor. Together they are responsible for 72% of the CSA total impact, whereas the CSA is responsible for 49% of the total impact of the manufacturing phase. This means that the contribution of the allocated electricity and heat from natural gas to the impact of the manufacturing phase is 35%. Unfortunately this affects the reliability of the LCA results, because the allocation is done by area which gives the results a high degree of uncertainty. Although the area allocation data are precise (obtained from AutoCAD drawings), the very procedure of area allocation is uncertain. The facility of UTC Power in South Windsor is not only aimed at producing power systems, but also at extensive R&D and performing experiments with fuel cell systems. Allocation by area is therefore far from ideal but also inevitable since only one number for the use of electricity and natural gas at the entire facility is available. Furthermore, the fact that only one number for the use of electricity and natural gas is available implies that all overhead (e.g., lighting and heating) included in this number is allocated to the CSA manufacturing process. Some of this overhead however should theoretically be allocated to PureCell™ system assembly, since both CSA manufacturing and PureCell™ system assembly occur at the UTC Power facility.

Furthermore, including overhead leads to an overestimation of the impact of the CSA because for all the other PureCell™ system subassemblies overhead is not included. No overhead data for these external facilities were available. Again, overhead for the CSA cannot be excluded since only one number for the total use of electricity and natural gas is available.

Figure 5-18 shows the aggregated overview of the environmental impact per material for the CSA. Natural gas is by far the most dominant contributor.

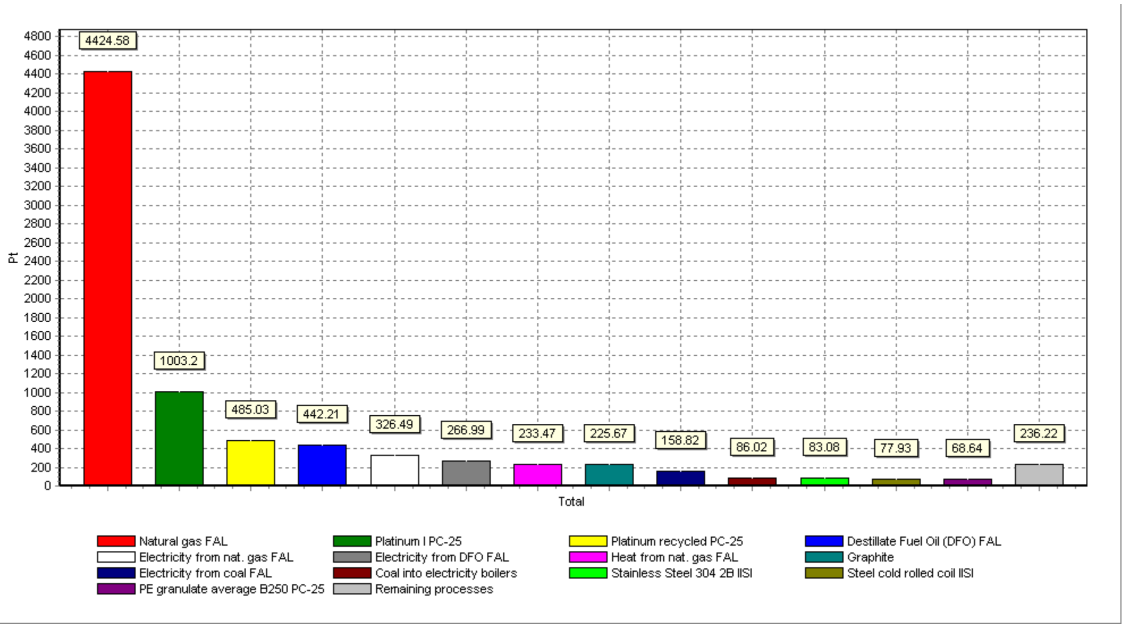


Figure 5-18: PureCell™ system CSA, overview of total environmental impact per material

The use of electricity and natural gas at the UTC Power facility is included in the LCA because it represents the energy use in the CSA manufacturing process. Energy used in the production processes for the other PureCell™ system subassemblies and components is also included where possible.

And although the modeled energy use for CSA production seems to be very high, it should be noted that fuel cell stack production is indeed an energy intensive process. Two previous fuel cell system LCAs both state that energy used in the cell stack production is of high significance in the LCA results, and that energy saving in the stack production is a primary focus in the cell stack life cycle improvement [28], [29].

Therefore it was decided that to get the closest approximation to a realistic situation the allocated energy for CSA production should be included. However, in order to give a transparent view on the significance of this decision, the next section gives LCA results for the CSA and for the manufacturing phase when the allocated energy use for CSA production is excluded.

PureCell™ System LCA Results without Allocated Energy Use for CSA Production

Figure 5-19 shows the SimaPro network for the CSA when the allocated electricity and heat from natural gas is excluded.

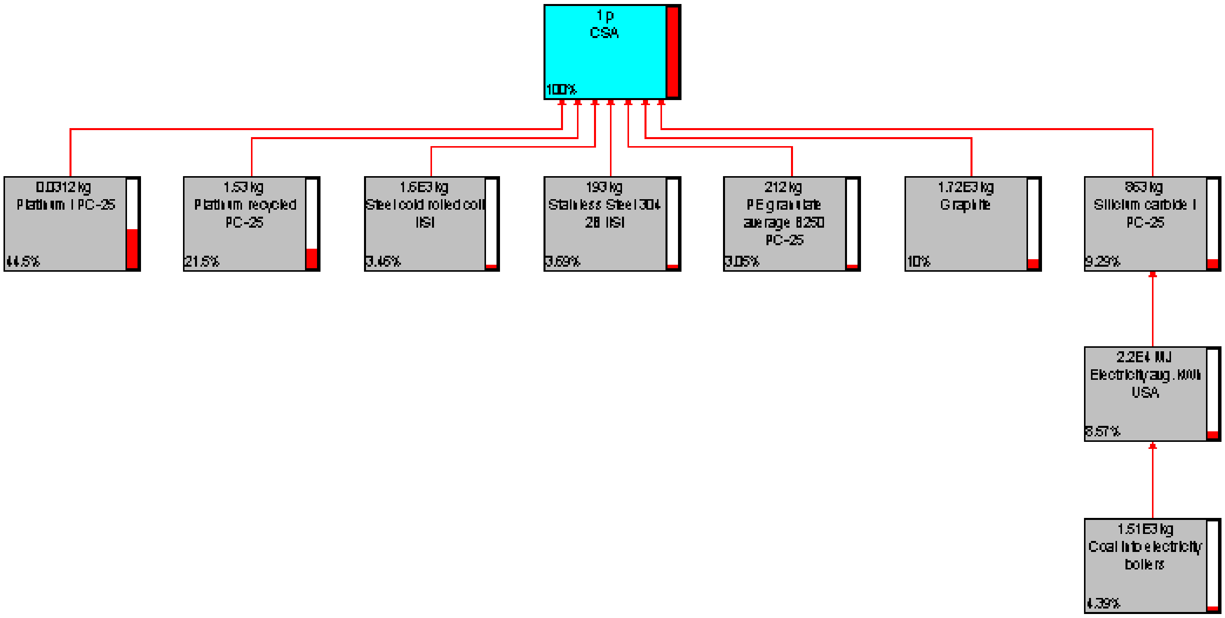


Figure 5-19: PureCell™ system CSA without allocated energy use, SimaPro network

It is obvious that the attention now shifts to the platinum, even though a 98% recycling rate is assumed. Figure 5-20 shows the impact per material for the CSA. The results for the materials physically present in the PureCell™ system remain the same. Natural gas and other processes related to electricity and heat production for the CSA manufacturing now have a much smaller contribution.

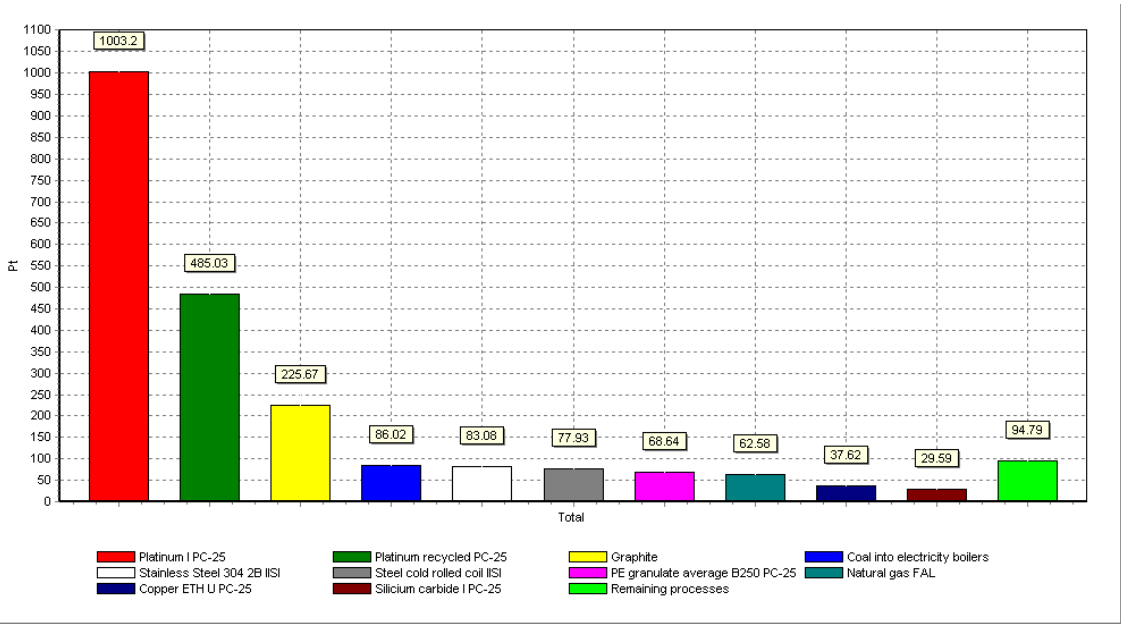


Figure 5-20: PureCell™ system CSA without allocated energy use, overview of total environmental impact per material

Given that the CSA was responsible for almost half of the total environmental impact of the manufacturing phase, it is also interesting to analyze the effect of excluding the allocated energy on the manufacturing phase LCA results. Figure 5-21 shows the SimaPro network for this situation.

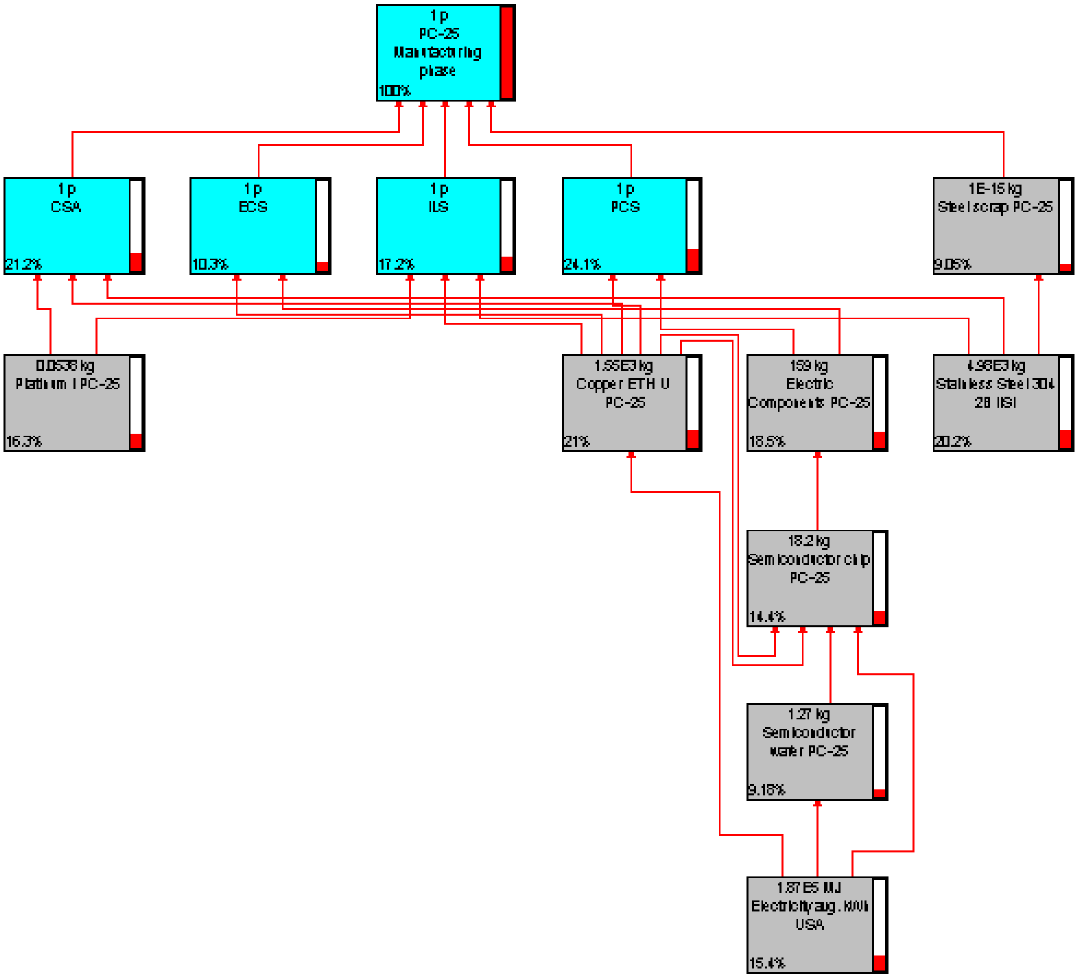


Figure 5-21: PureCell™ system manufacturing phase without allocated energy use for CSA production, SimaPro network

The contribution of the CSA has gone down from 49.2% to 21.2%. Furthermore, the PCS now has become the biggest contributor at 24.1%, for which mainly copper and electric components are responsible.

Figure 5-22 shows the impact per material for the manufacturing phase.

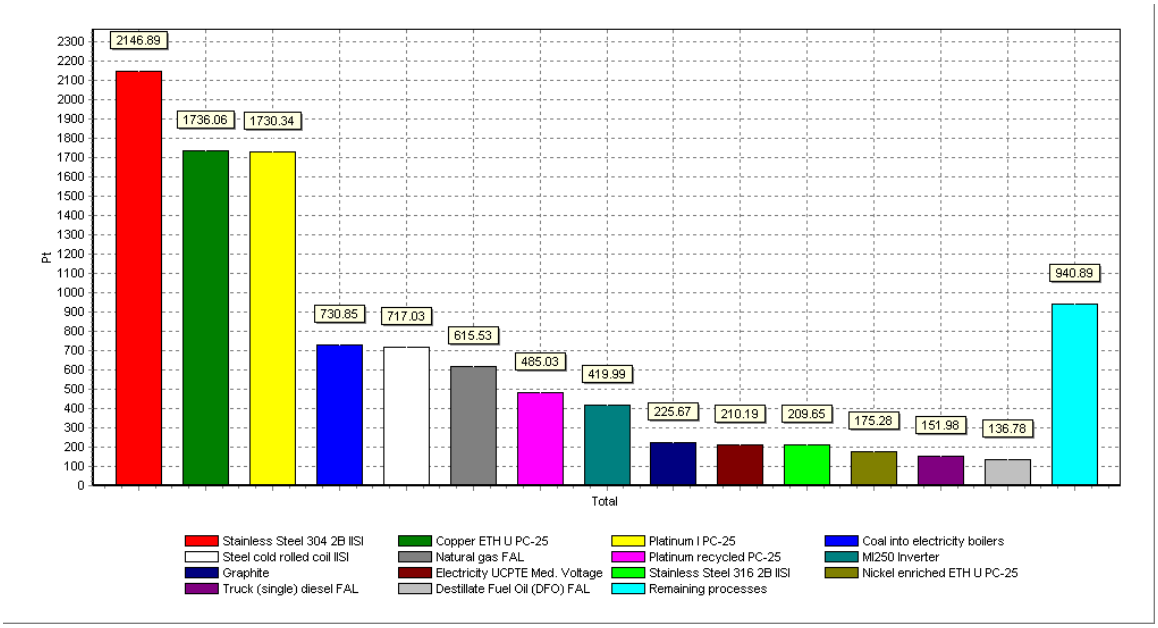


Figure 5-22: PureCell™ system manufacturing phase without allocated energy use for CSA production, overview of total environmental impact per material[6]

It can be seen that the contribution of natural gas has gone down drastically. The biggest contributor now is stainless steel 304, followed by copper and raw platinum.

Contribution and Sensitivity Analysis

Interpretation of LCA results for a one product alternative without uncertainty data includes performing contribution and sensitivity analyses. In a contribution analysis the results are decomposed into contributing elements. It is a way of testing results against what one would intuitively expect, and it also shows for which data it is important to have precise knowledge. In a sensitivity analysis (also known as perturbation or marginal analysis) inherently unstable elements are investigated. This is done by changing input data by 1% and determining how much this changes the result. The application-oriented purpose of a sensitivity analysis is to indicate the most promising opportunities for redesign and prevention strategies. The analysis-oriented purpose is to discover to which input data the LCA results are most sensitive; precise knowledge of these input data is most important for the LCA [30]. In this section both a contribution and a sensitivity analysis are performed. Also, the three different Eco-indicator 99 perspectives (egalitarian, hierarchist and individualist) are used to do what in the Eco-indicator 99 methodology is called a robustness analysis. Furthermore, changes in three major assumptions in the LCA model are applied in order to analyze how sensitive the results are to these assumptions.

---

[6] 'MI250 Inverter' is a process used in SimaPro to model the electric components in the PCS and ECS.

Contribution Analysis

The contribution analysis is performed at the single score level. Normalized values were multiplied by weighting factors and added to obtain a single score, representing the total environmental impact for all impact categories aggregated. The results are analyzed separately for each life cycle phase. Table 5-1 shows the life cycle contribution analysis per life cycle phase.

Unit	Score	%
Total	1.14E+06	100%
Manufacturing phase	1.65E+04	1.45%
Use phase	1.12E+06	98.2%
End-of-life phase	-421	-0.04%

Table 5-1: Contribution analysis per phase for PureCell™ system life cycle single score result

Table 5-2 shows the life cycle contribution analysis per material process. Only the ten biggest contributors are shown.

Material Process	Score	%
Total of all processes	1.14E+06	100%
Natural gas FAL	1.07E+06	94%
Generated electricity, 480 Volt, 60 Hz	5.25E+04	4.6%
Stainless Steel 304 2B IISI	2.17E+03	0.19%
Copper ETH U PureCell™ system	1.74E+03	0.15%
Platinum I PureCell™ system	1.73E+03	0.15%
Coal into electricity boilers	731	0.06%
Steel cold rolled coil IISI	720	0.06%
Electricity UCPTE Med. Voltage	580	0.05%
Destillate Fuel Oil (DFO) FAL	576	0.05%
Platinum recycled PureCell™ system	485	0.04%

Table 5-2: Contribution analysis per material process for PureCell™ system life cycle single score result

The process ‘Generated electricity, 480 Volt, 60 Hz’ represents the emissions caused by the steam reforming process. CO_2 emissions cause 99% of the 4.6% life cycle single score contribution of this process. The influence of the 85,000 hrs use phase is enormous when looking at the entire life cycle. Both the data for natural gas usage and PureCell™ system emissions (except CO_2) were obtained from a UTC Power PureCell™ system performance report, and can therefore be seen as precise and reliable. The calculations for the CO_2 emissions are shown in Chapter 4 - Inventory Analysis. For these calculations some assumptions had to be made which give the CO_2 emission data a degree of uncertainty.

Table 5-3 shows the manufacturing phase contribution analysis per material process.

Material Process	Score	%
Total of all processes	1.65E+04	100%
Natural gas FAL	4.98E+03	30%
Stainless Steel 304 2B IISI	2.15E+03	13%
Copper ETH U PureCell™ system	1.74E+03	11%
Platinum I PureCell™ system	1.73E+03	10%
Coal into electricity boilers	731	4.4%
Steel cold rolled coil IISI	717	4.3%
Destillate Fuel Oil (DFO) FAL	576	3.5%
Platinum recycled PureCell™ system	485	2.9%
MI250 Inverter	420	2.5%
Electricity from nat. gas FAL	327	1.9%

Table 5-3: Contribution analysis per material process for PureCell™ system manufacturing phase single score result

The single score results in this table are the same as pictured in Figure 5-12. As mentioned before, the contribution of natural gas and other processes related to electricity and heat is uncertain. However, no better data are available. The data for the materials physically present in the PureCell™ system come from a PureCell™ system weight breakdown sheet provided by UTC Power.

Table 5-4 shows the use phase contribution analysis per material process.

Material Process	Score	%
Total of all processes	1.12E+06	100%
Natural gas FAL	1.07E+06	95%
Generated electricity, 480 Volt, 60 Hz	5.25E+04	4.7%

Table 5-4: Contribution analysis per material process for PureCell™ system use phase single score result

Only the two biggest contributors are shown here. The other modeled processes for PureCell™ system installation and maintenance all have a contribution of less than 0.01%.

Table 5-5 shows the end-of-life phase contribution analysis per material process. Waste treatment processes from SimaPro databases are used to model the PureCell™ system end-of-life phase. The material processes appearing in Table 5-5 are therefore not input data but part of the SimaPro waste treatment processes.

Material Process	Total	%
Total of all processes	-421	100%
Electricity UCPTE Med. Voltage	390	-93%
Crude oil production onshore U	99.5	-24%
Crude oil production offshore U	80.3	-19%
Waste to special waste incinerator U	48.1	-11%
Zinc	-286	68%
Natural gas B	-285	68%
Crude coal B	-156	37%
Electricity UCPTE High Voltage	-97.5	23%
Sinter pellet	-54.6	13%
Coke S	-54.2	13%

Table 5-5: Contribution analysis per material process for PureCell™ system end-of-life phase single score result

Both positive and negative percentages appear in Table 5-5. This is because some processes in the end-of-life phase increase the environmental impact of the PureCell™ system, whereas other processes decrease the environmental impact. A decrease means that use of resources like natural gas and coal is avoided (e.g., by incineration with heat recovery) or that materials that are recycled in the end-of-life phase can be used as input for other processes, thereby avoiding the need for raw materials as input (e.g., recycling of steel). The positive percentages represent the energy used in or the emissions caused by the waste treatment processes in the end-of-life phase. Zinc appears in the table because for the 'Recycling Non-ferro' process it is assumed that the product from the recycling process is comparable with zinc from an environmental point of view. The recycling process of copper is therefore modeled as having a zinc output. This shows how limited the options are in SimaPro for modeling the end-of-life phase. In the 'Sensitivity Analysis for Assumptions' section in this chapter the metal recycling processes from SimaPro databases are replaced by processes that model a scrap metal output. In this way the 'Recycling Non-ferro' process containing poor data is avoided and it will be shown what the effect of this different approach is on the LCA results for the end-of-life phase.

Sensitivity Analysis

The sensitivity analysis is also performed at the single score level. Results of a sensitivity analysis are investigated for natural gas usage and CO_2 emissions in the use phase, and for allocated energy for CSA production, platinum and copper in the manufacturing phase.

First a 1% perturbation in natural gas use of the PureCell™ system is analyzed. This means that the natural gas input in the use phase in SimaPro is changed; the result of this perturbation is also evaluated by looking at the use phase single score result for the total environmental impact.

	input	single score result	multiplier
original	2050 cuft/hr	1.12E+06	n/a
1% perturbation	2070.5 cuft/hr	1.13E+06	0.89

Table 5-6: 1% Perturbation in natural gas usage, PureCell™ system use phase single score result

The multiplier shows the extent to which a perturbation of a certain input parameter propagates into a certain output result. For example, if an increase of 1% in an input parameter leads to an increase of 2% in an output result, the multiplier is 2 [30]. So, increasing the natural gas usage by 1% leads to an increase in the use phase single score result for the total environmental impact of 0.89%.

Table 5-7 shows the effect of a 1% perturbation in CO_2 emissions on the use phase total environmental impact.

	input	single score result	multiplier
original	112.2 kg/hr	1.12E+06	n/a
1% perturbation	113.322 kg/hr	1.12E+06	0

Table 5-7: 1% Perturbation in CO_2 emissions, PureCell™ system use phase single score result

As can be seen, a 1% perturbation in CO_2 emissions does not influence the three significant digits used in SimaPro to indicate the use phase total environmental impact.

Table 5-8 shows the effect of a 1% perturbation in both the allocated electricity and the allocated heat from natural gas for CSA production on the manufacturing phase single score result.

	input	single score result	multiplier
original	66180 kWh	1.65E+04	n/a
	311E+06 Btu		
1% perturbation	66841.8 kWh	1.66E+04	0.61
	314.11E+06 Btu		

Table 5-8: 1% Perturbation in allocated energy for CSA production, PureCell™ system manufacturing phase single score result

Increasing the allocated electricity and heat from natural gas by 1% leads to an increase in the manufacturing phase single score result for the total environmental impact of 0.61%.

Table 5-9 shows the effect of a 1% perturbation in the total platinum input (raw and recycled, CSA and ILS) on the manufacturing phase single score result.

	input	single score result	multiplier
original	31.18 g (raw, CSA)	1.65E+04	n/a
	1527.82 g (recycled, CSA)		
	22.6 g (raw, ILS)		
1% perturbation	31.4918 (raw, CSA)	1.65E+04	0
	1543.0982 g (recycled, CSA)		
	22.826 g (raw, ILS)		

Table 5-9: 1% Perturbation in total platinum input, PureCell™ system manufacturing phase single score result

Table 5-10 shows the effect of a 1% perturbation in the copper input for the PCS, ECS and Harnesses and Cables. These are the same copper inputs that are considered in the copper scrap process. The 1% perturbation is also applied to the copper input for the copper scrap process itself.

	input	single score result	multiplier
original	1800 lb (PCS)	1.65E+04	n/a
	300 lb (ECS)		
	100 lb (Harn. & Cabl.)		
	244 lb (Copper scrap)		
1% perturbation	1818 lb (PCS)	1.65E+04	0
	303 lb (ECS)		
	101 lb (Harn. & Cabl.)		
	246.44 lb (Copper scrap)		

Table 5-10: 1% Perturbation in copper input, PureCell™ system manufacturing phase single score result

A 1% perturbation in the platinum and copper input does not change the single score result of the manufacturing phase.

The results of the sensitivity analysis show that a decrease in the natural gas usage of the PureCell™ system will lead to the most significant environmental improvement in the PureCell™ system use phase. Maximizing the hydrogen output of the steam reforming process and increasing the efficiency of the electrochemical reaction in the fuel cell stack are the main opportunities for reducing the environmental impact of the PureCell™ system use phase. Regarding the manufacturing phase, the sensitivity analysis shows that reducing the energy used for CSA production has the most potential for reduction of environmental impact. One should keep in mind that these data have higher uncertainty than many others modeled in the LCA.

Eco-indicator 99 Robustness Analysis

Eco-indicator 99 provides the choice between three different perspectives on impact assessment. The default perspective is the hierarchist perspective in which LCA impact assessment is based on facts that are backed up by scientific and political bodies with sufficient recognition; for example, the IPCC (Intergovernmental Panel on Climate Change) provides widely accepted guidelines for climate change. The individualist perspective includes only proven cause-effect relations, and when relevant only the short-term perspective is used. The preference for proven relationships is the attitude of individualists to consider each limit as negotiable. For human health issues age-weighting is used, since in the individualist perspective a person is valued higher at the age between 20 and 40 years. The egalitarian perspective consistently uses the precautionary principle, in case of doubt, an environmental impact is included. Egalitarians do not accept guidance from internationally accepted scientific or political organizations. A very long term perspective is used as egalitarians do not accept that future problems can be avoided. This version is the most comprehensive version, but it also has the largest data uncertainties as sometimes data are included on which consensus is lacking [7]. This report does not debate the merits of each perspective. The LCA results are obtained using the default hierarchist perspective which works according to consensus building processes and a balanced view of long- and short-term perspectives, which is how most impact assessment models work [7]. The LCA results for all three perspectives are analyzed here in order to find out how important the influence of the choice of perspective is. It is therefore also a form of sensitivity analysis. Table 5-11 shows the life cycle single score results, both by life cycle phases and impact categories.

	Hierarchist	**Egalitarian**	**Individualist**
Total	1.14E+06	9.33E+05	6.96E+05
per life cycle phase			
Manufacturing phase	1.65E+04	1.58E+04	9.63E+04
Use phase	1.12E+06	9.19E+05	6.01E+05
End-of-life phase	-421	-1.76E+03	-1.43E+03
per impact category			
Carcinogens	2.16E+04	1.61E+04	2.84E+04
Resp. organics	1.40E+03	1.04E+03	3.32E+03
Resp. inorganics	2.50E+05	1.87E+05	4.14E+05
Climate change	6.35E+04	4.73E+04	1.55E+05
Radiation	0.484	0.361	0.0893
Ozone layer	1.2	0.891	2.47
Ecotoxicity	1.32E+03	1.65E+03	345
Acidification/Eutrophication	1.74E+04	2.18E+04	1.24E+04

Land use	51.3	64.1	36.5
Minerals	1.46E+03	2.08E+03	8.21E+04
Fossil fuels	7.80E+05	6.56E+05	n/a

Table 5-11: PureCell™ system life cycle single score results for three Eco-indicator 99 perspectives

The individualist perspective has the highest scores for all impact categories that are part of the human health damage category. Also the score for the minerals impact category is significantly higher. Still, it has the lowest total score because depletion of fossil fuels is not considered as an environmental impact in the individualist perspective. It is remarkable to see that the hierarchist score is higher than the egalitarian score. The biggest contribution to the difference in the two scores is caused by the fossil fuels impact category. This indicates that the use of natural gas as a non-renewable resource is weighted heavier in the hierarchist perspective than in the egalitarian perspective.

In general it can be concluded that for the PureCell™ system LCA results the choice of perspective has a serious influence on the total scores. As a result of this it can thus be concluded that the LCA results for the PureCell™ system are sensitive to assumptions of time frame, required level of proof and other assumptions that vary for the three different perspectives.

Sensitivity Analysis for Assumptions

The influence of four assumptions made for the PureCell™ system LCA model is investigated. It is therefore also a form of sensitivity analysis: the effect of the folowing changes in the assumptions on the LCA results will be analyzed:

- Reducing the recycling rate for platinum in the CSA from 98% to 95%.
- The steel scrap rate of 0.65 is changed to 0.5 (a 23% variation).
- A scenario where the PureCell™ system is transported from UTC Power in South Windsor to a client in Koln, Germany, is included in the LCA model.
- The metal recycling processes from SimaPro databases are replaced by processes modeling a scrap metal output.

Results from reducing the platinum recycling rate to 95% are shown in Table 5-12. The effect of the perturbation is analyzed for the PureCell™ system manufacturing phase single score result.

	single score result	**increase**
98% recycling	1.65E+04	n/a
95% recycling	1.80E+04	9.1%

Table 5-12: 95% Platinum recycling rate, PureCell™ system manufacturing phase single score result

A 3% decrease in the platinum recycling rate leads to a 9.1% increase in the environmental impact of the manufacturing phase. Figure 5-23 shows the aggregated overview of the environmental impact per material. Although natural gas is still the biggest contributor, platinum has a significantly more dominant impact than before.

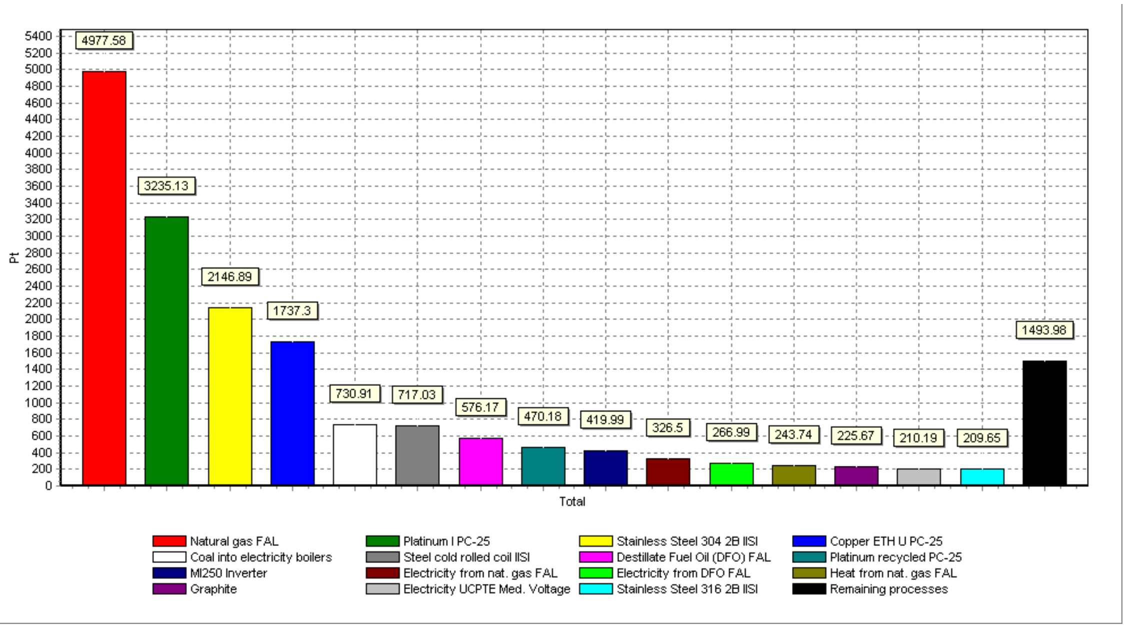


Figure 5-23: PureCell™ system manufacturing phase, overview of total environmental impact per material, 95% platinum recycling

Table 5-13 shows the results for a 0.5 steel scrap rate. A total of 28800 lb steel is used in the PureCell™ system; therefore now also 28800 lb of steel scrap is produced.

	input	amount (lb)	single score result	increase
0.65 steel scrap rate	Steel cold rolled coil IISI	11385	1.65E+04	n/a
	Stainless Steel 304 2B IISI	3845		
	Stainless Steel 316 2B IISI	275		
	Cold transforming steel PureCell™ system	15430		
	Rolling steel I PureCell™ system	7290		
0.5 steel scrap rate	Steel cold rolled coil IISI	21142	1.75E+04	6.1%
	Stainless Steel 304 2B IISI	7143		
	Stainless Steel 316 2B IISI	515		
	Cold transforming steel PureCell™ system	28660		
	Rolling steel I PureCell™ system	13500		

Table 5-13: 0.5 Steel scrap rate, PureCell™ system manufacturing phase single score result

Using a steel scrap rate of 0.5 (a 23% variation) leads to a 6.1% increase in the environmental impact of the manufacturing phase.

The influence of including a transport scenario to a client in Koln, Germany, is shown in Table 5-14. It can be debated whether transport from manufacturer to client should be included in the manufacturing or the use phase. For this analysis it is included in the manufacturing phase, and the effect of including the transport scenario is analyzed for the PureCell™ system manufacturing phase single score result. Due to the high relative impact of the use phase, including the transport scenario there will not change the use phase results. Therefore the significance of the PureCell™ system transport to a client can be better understood if it is included in the manufacturing phase.

	input	amount (tmi)	single score result	increase
without transport scenario	n/a	n/a	1.65E+04	n/a
with transport scenario	Truck (single) diesel FAL	1979	1.68E+04	1.82%
	Ocean freighter FAL	69267		
	Truck (single) diesel FAL	3166		

Table 5-14: Transport scenario to Koln, Germany, PureCell™ system manufacturing phase single score result

It is assumed that the PureCell™ system is shipped from Boston to Rotterdam. The total weight of the PureCell™ system is 39576 lb.

- The PureCell™ system is transported by truck from South Windsor to Boston. This is 100 miles, transporting 39576 lb, which is equal to 1979 tmi.
- The PureCell™ system is shipped from Boston to Rotterdam. This is approximately 3500 miles, transporting 39576 lb, which is equal to 69267 tmi.
- The PureCell™ system is transported by truck from Rotterdam to Koln. This is 160 miles, transporting 39576 lb, which is equal to 3166 tmi.

Including the transport scenario to a client in Koln, Germany, led to a 1.82% increase in the environmental impact of the manufacturing phase. Since the manufacturing phase is responsible for 1.45% of the life cycle environmental impact, including the transport scenario leads to a 0.03% increase in the life cycle environmental impact.

In the contribution analysis it was shown that the end-of-life phase results are heavily influenced by the metal recycling processes. The data used for these recycling processes are however of low quality. Therefore the effects of EoL changes on LCA results were analyzed. In this different approach the waste treatment of the PureCell™ system metals stops at the point where scrap metal is the output instead of complete recycling into ready-to-use materials, thereby avoiding the use of SimaPro recycling processes. Table 5-15 shows the changes in the PureCell™ system metal waste treatment as compared with Table 4-27.

Material	Waste treatment	Percentage
Steel cold rolled coil IISI	Iron scrap output	100%
Stainless Steel 304 2B IISI	Stainless steel scrap output	100%
Stainless Steel 316 2B IISI	Stainless steel scrap output	100%
Copper ETH U PureCell™ system	Copper scrap output	90%
Copper ETH U PureCell™ system	Copper (inert) to landfill	10%
Aluminum (primary) produced in the USA	Aluminum scrap output	90%
Aluminum (primary) produced in the USA	Landfill Aluminum B250 (1998)	10%
Aluminum 100% recycled ETH U PureCell™ system	Aluminum scrap output	90%
Aluminum 100% recycled ETH U PureCell™ system	Landfill Aluminum B250 (1998)	10%
Nickel enriched ETH U PureCell™ system	Nickel scrap output	90%
Nickel enriched ETH U PureCell™ system	Unspecified	10%

Table 5-15: PureCell™ system end-of-life phase, scrap metal output

The scrap output is modeled using the metal scrap processes in the IDEMAT database in SimaPro. In every scrap output process shown in Table 5-15 electricity is added for shredding and separating the scrap. The amounts of electricity used for shredding and separating scrap are 97 kJ/kg and 26 kJ/kg respectively, as given by [19]. This results in a total amount of electricity used of 123 kJ/kg.

Table 5-16 shows the end-of-life phase result when the metal waste treatment is modeled as scrap output.

	single score result	increase (in benefit)
Metal recycling processes	-421	n/a
Scrap metal output processes	-745	77%

Table 5-16: Scrap metal output, PureCell™ system end-of-life phase single score result

The scrap output approach in the end-of-life phase leads to an increase in the environmental benefit of 324 points, which is a 77% increase. If one however takes the aggregated moduli (i.e., the absolute values) of both positive and negative scores in the original end-of-life phase results, 651 points in positive values and 1072 in negative values resulting in an aggregated value of 1723 points, the 324 points increase in environmental benefit is equal to a 19% increase. With respect to the PureCell™ system life cycle, this increase of 324 points in environmental benefit leads to a -0.03% decrease in the life cycle environmental impact.

Conclusions

When the environmental impacts of the three life cycle phases (manufacturing, use and end-of-life phase) are shown relative to each other, it becomes clear that the use phase is by far the biggest contributor. The input of natural gas and the emission of CO_2 over the 85,000 hrs lifetime are the main causes for this contribution. A decrease in natural gas usage of the PureCell™ system while maintaining the same power output will therefore lead to the most significant environmental improvement in the PureCell™ system life cycle. As shown in the CO_2 calculations in Chapter 4 - Inventory Analysis, the input of natural gas is directly linked with the emission of CO_2. This means that maximizing the hydrogen output of the steam reforming process and increasing the efficiency of the electrochemical reaction in the fuel cell stack are the main opportunities for reducing the environmental impact of the PureCell™ system life cycle. One should realize here that the environmental impact of the use phase modeled in SimaPro is the environmental impact of producing 200 kW electricity for 85,000 hrs, or 17,000,000 kWh. The environmental impact is not expressed in burden per kWh[7]. Although increasing the PureCell™ system lifetime leads to a higher environmental impact of the PureCell™
□□□!□
hand to a lower environmental impact per kWh for the PureCell™ system life cycle.

If the manufacturing phase is analyzed separately it becomes clear that the CSA (Cell Stack Assembly) is responsible for almost half of the environmental impact. The main cause is the high amount of energy used in the CSA production process. Other big contributors are the PCS (Power Conditioning System) and the ILS (Integrated Low-temperature Shift converter). The end-of-life phase has a small environmental impact compared to the use and manufacturing phase.

In terms of ‘hotspots’ referred to in the description of the goal of the study, for the PureCell™ system life cycle these are the natural gas usage and, to a lesser extent, CO_2 emissions in the use phase. As described above, decreasing the natural gas input while maintaining the same power output has a beneficial effect on both of these hotspots. The impact of the CO_2 emissions can also be avoided through carbon sequestration. This means that CO_2 is not emitted but captured and stored. The procedure of capturing and storing CO_2 will however bring its own environmental impact, so a separate analysis and a trade-off are required to determine the benefit of carbon sequestration.

For the manufacturing phase the major hotspot is the energy used in the CSA production process. Other hotspots are platinum, stainless steel 304, copper and electric components. In case of platinum it is especially beneficial to increase the recycling rate

---

[7] In Appendix E the CO_2-equivalent emissions per kWh and the energy use per kWh are shown for the PC25 life cycle. The total amount of CO_2-equivalent emissions and energy use per life cycle phase is also shown.

(or at least achieve the assumed 98% recycling rate), since the environmental impact of recycled platinum is much smaller than that of raw platinum.

In Chapter 6 the LCA model will be used to analyze the environmental improvement effected by two different scenarios. First the effect of using renewable hydrogen from wind energy is shown. This means that no natural gas is required as input in the use phase, and also no steam reforming system is needed. Second the effect of a different end-of-life scenario is shown. In this scenario SimaPro is used to model reuse of certain components. Furthermore it is assumed in this scenario that the platinum and palladium in the ILS is also recycled with a recycling rate of 98%.

Chapter 6 - Opportunities and Implementation in LCA

This chapter consists of two parts. In the first part the opportunity of using renewable hydrogen from wind energy as a fuel for the PureCell™ system is described and data from a National Renewable Energy Lab (NREL) report on LCA of renewable hydrogen production via wind/electrolysis are implemented in the SimaPro model. Changes in the PureCell™ system inventory tables are explained and the new LCA results are analyzed and compared with results obtained by using the original model based on steam reforming of natural gas.

The second part describes the opportunity of improving the end-of-life scenario from an environmental perspective. SimaPro is used to model a hypothetical scenario of reusing the steam ejector, steam drum, frame, enclosure, PCS and ECS subassemblies. The steam drum is part of the thermal management system (TMS). The improved end-of-life scenario also includes a 98% recycling rate for the platinum and palladium in the ILS. This means that the ILS platinum and palladium are modeled in SimaPro in the same way as the CSA platinum. Palladium is a platinum group metal (PGM). PGMs have similar physical and chemical properties and tend to occur together in the same mineral deposits; therefore the 98% recycling rate is applied to platinum as well as palladium.

Renewable Hydrogen from Wind Energy

The benefits of using renewable hydrogen compared to the present PureCell™ system are that no natural gas is required as input in the use phase and that emissions caused by the steam reforming process are avoided. Of course the system required to produce hydrogen from wind energy also has negative impacts on the environment. Data from an LCA done by NREL [31] for a wind/electrolysis system are used here to model these impacts The wind/electrolysis system considered in the NREL LCA replaces the steam reforming system and the use phase input and emissions of the current PureCell™ system.

System Description

The system that is modeled in SimaPro is the same as the system examined in the NREL report. This system is shown in Figure 6-1. Using a wind/electrolysis system in combination with stationary fuel cells results in a constant source of energy supply and it can therefore compensate for increased shares of fluctuating renewable energy sources.

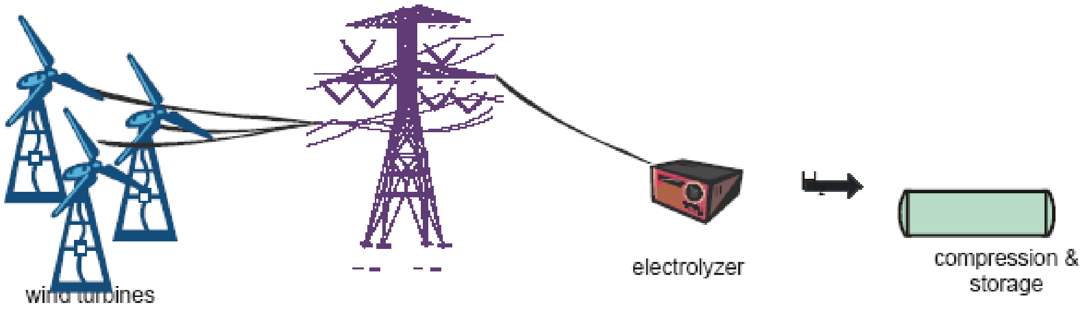


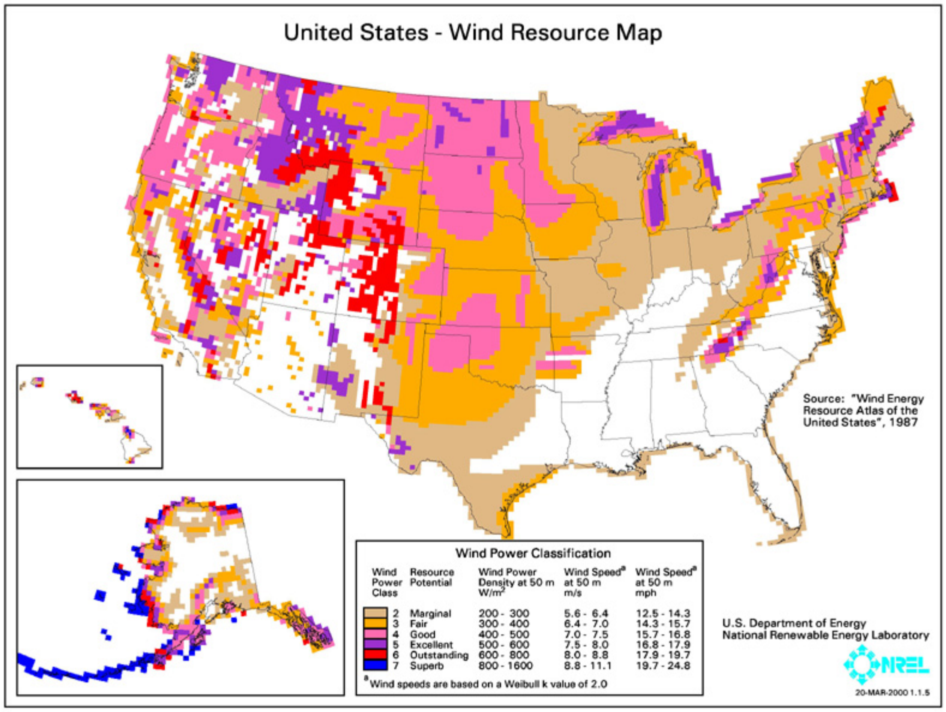
Figure 6-1: Wind/electrolysis system as used in NREL study [31]

Material requirements and design data for this system were taken from electrolyzer and wind turbine manufacturers. For the LCI data the material production processes required to construct the wind turbines, electrolyzer and hydrogen storage tanks were taken into account. The electricity grid as shown in Figure 6-1 transports the electricity from the wind turbine site to the electrolyzer where it is converted into hydrogen with an efficiency of 85% (based on HHV). The electricity grid as a capital good is not taken into account in the LCA.

The system operation was determined using class 5 wind data from the upper Midwest region of the United States. The system has a fixed lifetime, and the LCI data for resource consumption, emissions and energy requirement of the system are expressed in g/kg H_2 or MJ/kg H_2. This means that these LCI data can easily be implemented in the PureCell™ system in order to model the required hydrogen production. Several electrical losses were subtracted from the gross amount of electricity produced by the wind turbines. These losses include transmission losses of the grid, electricity required to pump the deionized water in the electrolyzer and electricity required to compress the hydrogen.

Hydrogen transport from the electrolyzer site to the PureCell™ system sites is not included in the NREL system. This will therefore be added separately in the form of transport by trailer. In the NREL system the hydrogen is compressed to a pressure of 20 MPa (or 197 atm). Hydrogen can be transported both in compressed (at present up to 200 atm [32]) and liquefied form. Liquefied hydrogen has the advantage of having a much higher energy density than compressed hydrogen, and is thus more efficient to transport, but at the same time it has the disadvantage that hydrogen liquefaction is a very energy intensive process. Using today's technology, liquefaction consumes 30% or more of the energy content of the hydrogen, dependent on the size of the liquefaction facility [32]. In a very small liquefaction plant (less than $5kg_{LH_2}/hr$) the energy needed to liquefy hydrogen may even exceed the HHV energy of hydrogen [33]. Moreover, some of the stored and transported liquefied hydrogen will be lost through evaporation, dependent on the surface-to-volume ratio of the storage tank. Due to the complexity of the hydrogen liquefaction process and of the transport of liquefied hydrogen, it is considered outside the scope of this research to analyze the environmental impact of this option. Transport of compressed hydrogen at 200 atm is included in the LCA model in addition to the LCI data from the NREL system. Assessing the environmental impact of liquefied hydrogen transport as part of the PureCell™ system using renewable hydrogen from wind energy is recommended for further research.

The compressed hydrogen transport by truck is based on the assumption that, if renewable hydrogen from wind energy would at present be used as a fuel for the PureCell™ system, the hydrogen would be produced at the wind turbine site and thereafter be transported by truck to its destination. As mentioned before, the system operation was determined using class 5 wind data. Figure 6-2 shows a U.S. wind resource map with the wind power classifications.



Wind Power Classification

	Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
🟫	2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
🟧	3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
🟪	4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
🟪	5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
🟥	6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
🟦	7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

Figure 6-2: United States wind resource map

Based on this map it is assumed that when 1000 miles of hydrogen transport is taken into account any place in the United States can be supplied with hydrogen from class 5 wind energy. On the other hand, not all PureCell™ system locations will be at a 1000 miles distance from a class 5 wind turbine site. Therefore two hydrogen transport scenarios are analyzed, one for a 100 miles transport distance and one for 1000 miles.

Inventory Tables

Regarding the inventory, first of all the use phase data are changed. The input of natural gas and the emissions of the steam reforming process are replaced by an input of renewable hydrogen. Transport of hydrogen is also included. The PureCell™ system installation and maintenance processes remain the same. In the manufacturing phase the subassemblies that make up the fuel processing system are removed from the SimaPro model because their function is now superfluous. The removed subassemblies are the reformer, the ILS and the steam ejector. The rest of the PureCell™ system is assumed to remain the same.

As mentioned before, the LCI data for the wind/electrolysis system are expressed in g/kg H_2 or MJ/kg H_2. In SimaPro the production of renewable hydrogen is therefore modeled for 1 kg of hydrogen.

The inventory data for the production of renewable hydrogen from wind energy are shown in Table 6-1.

Products	Amount	Unit
Hydrogen from wind energy NREL	1	kg
Resources		
coal FAL	0.2147	kg
iron (ore)	0.2122	kg
scrap, external	0.1742	kg
limestone	0.3666	kg
natural gas FAL	0.0162	kg
crude oil FAL	0.0483	kg
water	26.7	kg
energy (undef.)	0.65	MJ
Emissions to air		
CO2	0.95	kg
CO	0.9	g
methane	0.3	g
NOx	4.7	g
N2O	0.05	g
non-methane hydrocarbon (NMHC)	4.4	g
particulates (unspecified)	28.7	g
SOx	6.1	g
Final waste flows		
solid waste	223	g

Table 6-1: Renewable hydrogen from wind energy NREL inventory data

Now it needs to be calculated how much hydrogen the PureCell™ system uses per hour, or in other words, how much hydrogen does the PureCell™ system require to produce 200 kWh of electricity. Detailed calculations showing how this number was obtained can be found in Appendix G. In the SimaPro model of the PureCell™ system using renewable hydrogen the hydrogen consumption rate of $15.035 kg / hr$ is used, as shown in Table 6-2.

Products	Amount	Unit
Generated electricity, 480 Volt, 60 Hz, Renewable H2	200	kWh
Produced heat at 140 F, Renewable H2	271.025	kWh
Materials/fuels		
Hydrogen from wind energy NREL	15.035	kg

Table 6-2: 200 kWh electricity generation inventory data, renewable hydrogen

Table 6-3 shows the inventory data for the 85,000 hrs life cycle. Compressed hydrogen transport by truck is also included in this table.

Products	Amount	Unit
Generated electricity, 480 Volt, 60 Hz, Renewable H2	17000000	kWh
Produced heat at 140 F, Renewable H2	23037125	kWh
Materials/fuels		
Hydrogen from wind energy NREL	1277975	kg
Processes		
Trailer diesel FAL [100 miles scenario]	9158500	tmi
Trailer diesel FAL [1000 miles scenario]	91585000	tmi

Table 6-3:17,000,000 kWh electricity generation inventory data, renewable hydrogen

If the compressed hydrogen transport is calculated by multiplying payload and distance (as is common in SimaPro), then this results in 1277975 kg = 1409 short ton times 100 miles is 140900 tmi, or, in case of the 1000 miles scenario, 1409000 tmi. However, compressed hydrogen transport is limited by pressure and volume. At present, a 40-ton trailer truck can only deliver 400 kg of hydrogen (compressed to 200 bar) to the customer, as opposed to 26 tons of gasoline [34]. This is a direct consequence of the low density of hydrogen, as well as the weight of the pressure vessels and safety armatures.

The transport processes in the Franklin database in SimaPro are based on an average payload per truck and are thus not representative for the special case of hydrogen transport. To solve this problem the weight ratio for transported hydrogen versus gasoline in a 40-ton trailer truck as mentioned above is used to obtain a tmi value that represents hydrogen transport, under the assumption that the Franklin transport processes indeed *are* representative for gasoline transport. This means that, if 1277975 kg of gasoline were to be transported, 1409000 tmi would be included in the LCA model. For compressed hydrogen transport, this tmi value is multiplied by the gasoline/hydrogen weight ratio for transport in a 40-ton trailer truck, which is $\frac{26000kg}{400kg} = 65$.

For the 100 miles scenario, this then results in $140900tmi * 65 = 9158500tmi$. For the 1000 miles scenario this results in $1409000tmi * 65 = 91585000tmi$. The transport process is modeled in SimaPro as 'Trailer diesel FAL' because the transport of compressed hydrogen is comparable to the transport of gasoline in a trailer truck. The compressed hydrogen pressure as an NREL system output is 20 MPa which is equal to the 200 bar assumed for transport.

The removal of the reformer, ILS and steam ejector subassemblies also causes a change in the steel scrap process. Less steel is used in the PureCell™ system production and therefore less steel scrap is produced. Revised inventory data for this process are shown in Table 6-4.
For the copper scrap process only the PCS, ECS and Harnesses and Cables subassemblies were taken into account, so this process doesn't change.

Materials	Amount	Unit
Steel cold rolled coil IISI	10255	lb
Stainless Steel 304 2B IISI	1000	lb
Stainless Steel 316 2B IISI	275	lb
Total	11530	lb
Processes		
Cold transforming steel PureCell™ system	11472	lb
Rolling steel I PureCell™ system	5419	lb
Waste to treatment		
Steel scrap to Recycling Ferro metals	11530	lb

Table 6-4: Steel scrap inventory data, renewable hydrogen

The amount of steel in the final PureCell™ system without the fuel processing system is:

- Steel cold rolled coil IISI: 19047 lb
- Stainless Steel 304 2B IISI: 1854 lb
- Stainless Steel 316 2B IISI: 515 lb
- Aggregated this is 21416 lb steel.

With a scrap rate of 0.35, this means that a total amount of 11530 lb steel scrap is produced, from which:

- 10255 lb is Steel cold rolled coil IISI
- 1000 lb is Stainless Steel 304 2B IISI
- 275 lb is Stainless Steel 316 2B IISI.

And for the manufacturing processes:

- 0.995 * 11530 lb = 11472 lb 'Cold transforming steel PureCell™ system'
- 0.47 * 11530 lb = 5419 lb 'Rolling steel I PureCell™ system'.

Results

The SimaPro results for the PureCell™ system using renewable hydrogen from wind energy instead of natural gas will be shown for both the use phase and the total life cycle, and for both the 100 miles and 1000 miles transport scenario.

100 Miles Transport Scenario

Figure 6-3 shows the SimaPro network for the use phase with renewable hydrogen when 100 miles of compressed hydrogen transport are modeled.

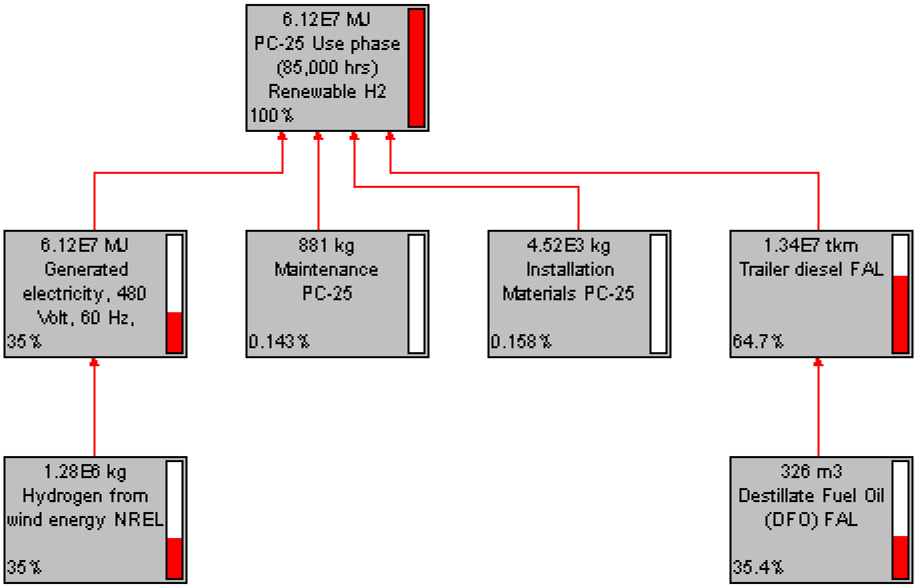


Figure 6-3: PureCell™ system use phase renewable hydrogen SimaPro network, 100 miles scenario

The use phase environmental impact is mainly due to hydrogen transport (64.7%) and hydrogen production (35%). The impact of the PureCell™ system installation and maintenance processes is relatively small, responsible for only 0.31% of the impact of the use phase.

Table 6-5 compares the use phase single score results for the current PureCell™ system with the results for the PureCell™ system using renewable hydrogen. The last column shows the percentages of the scores for the PureCell™ system using renewable hydrogen relative to the scores of the current PureCell™ system.

Impact category	**Current PureCell™ system single score result**	**Renewable H2 PureCell™ system single score result**	**Percentage of current system**
Total	1.12E+06	1.40E+05	13%
Carcinogens	2.08E+04	1.93E+02	0.9%

Resp. organics	1.41E+03	1.23E+02	8.7%
Resp. inorganics	2.44E+05	5.97E+04	24%
Climate change	6.29E+04	1.23E+04	20%
Radiation	0.0234	0.0234	100%
Ozone layer	0.314	0.0526	17%
Ecotoxicity	697	54.9	7.9%
Acidification/ Eutrophication	1.69E+04	7.32E+03	43%
Land use	5.85	5.85	100%
Minerals	0.418	188	4.5E+04%
Fossil fuels	7.74E+05	6.03E+04	7.8%

Table 6-5: PureCell™ system use phase, steam reforming vs. renewable hydrogen single score results, 100 miles scenario

The total single score results show that the environmental impact of the PureCell™ system use phase is decreased by a factor 8 when renewable hydrogen is used as a fuel for the PureCell™ system. The results per impact category show that the impact categories 'Fossil fuels', 'Respiratory inorganics' and 'Climate change' have the most significant absolute decrease in impact. The only impact category that shows an increased impact is the 'Minerals' impact category, due to the resources that are required to manufacture the wind/electrolysis system.

Figure 6-4 shows the SimaPro network for the PureCell™ system life cycle with renewable hydrogen when 100 miles of compressed hydrogen transport are modeled.

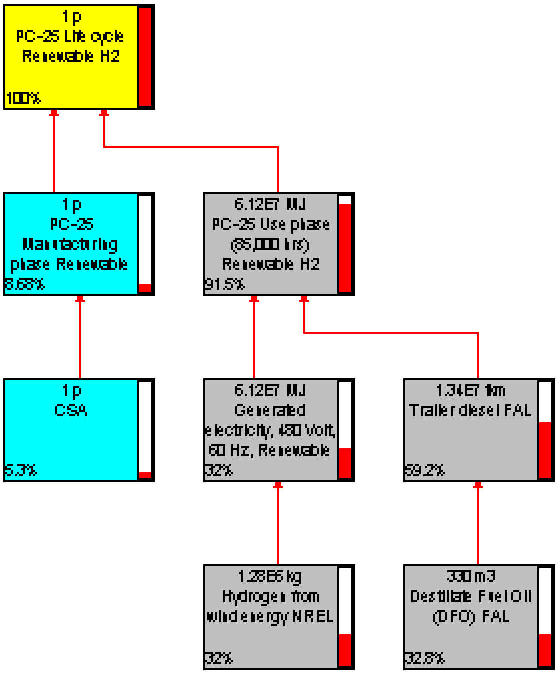


Figure 6-4: PureCell™ system life cycle renewable hydrogen SimaPro network, 100 miles scenario

The network shows that the use phase is still the biggest contributor to the life cycle environmental impact. However, the relative contribution of the use phase has gone down from 98.6% to 91.5%, and the relative contribution of the manufacturing phase has gone up from 1.45% to 8.68%.

In Table 6-6 the life cycle single score results for the current PureCell™ system are compared with the results for the PureCell™ system using renewable hydrogen. The last column shows the percentages of the scores for the PureCell™ system using renewable hydrogen relative to the scores of the current PureCell™ system.

Impact category	Current PureCell™ system single score result	Renewable H2 PureCell™ system single score result	Percentage of current system
Total	1.14E+06	1.53E+05	13%
Carcinogens	2.16E+04	3.93E+02	1.8%
Resp. organics	1.40E+03	117	8.4%
Resp. inorganics	2.50E+05	6.45E+04	26%
Climate change	6.40E+04	1.32E+04	21%
Radiation	0.484	0.437	90%
Ozone layer	1.2	0.776	65%
Ecotoxicity	1.32E+03	352	27%
Acidification/ Eutrophication	1.74E+04	7.73E+03	44%
Land use	51.7	36.8	71%
Minerals	1.46E+03	1.46E+03	100%
Fossil fuels	7.80E+05	6.54E+04	8.4%

Table 6-6: PureCell™ system life cycle, steam reforming vs. renewable hydrogen single score results, 100 miles scenario

The total single score results show that the environmental impact of the PureCell™ system life cycle is decreased by a factor 7 when renewable hydrogen is used as a fuel for the PureCell™ system and a 100 miles transport scenario is assumed.

1000 Miles Transport Scenario

Figure 6-5 shows the SimaPro network for the use phase with renewable hydrogen when 1000 miles of compressed hydrogen transport are modeled.

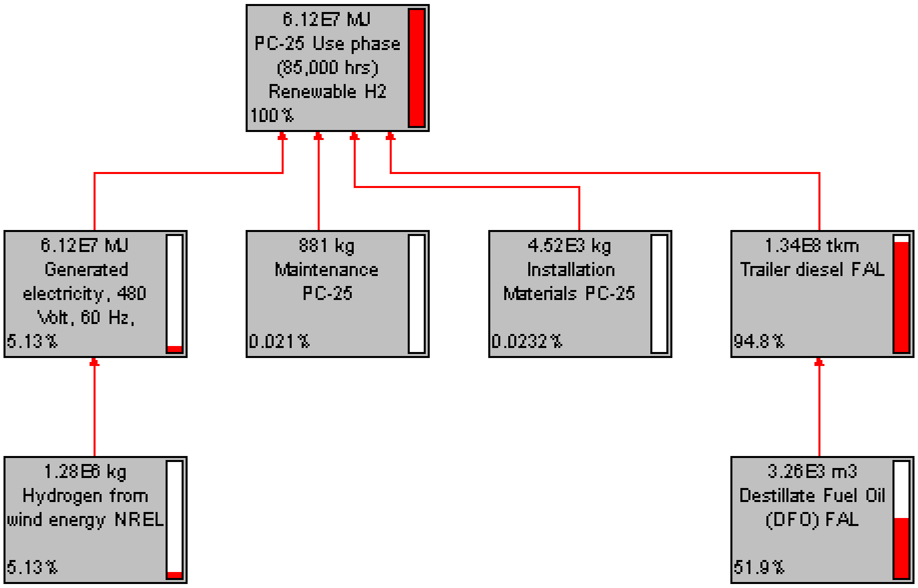


Figure 6-5: -25 Use phase renewable hydrogen SimaPro network, 1000 miles scenario

The network shows that in the 1000 miles transport scenario the use phase environmental impact is mainly due to hydrogen transport (94.8%). Hydrogen production only accounts for 5.13%. PureCell™ system installation and maintenance are together responsible for 0.04% of the total environmental impact of the use phase.

In Table 6-7 the use phase single score results for the current PureCell™ system are compared with the results for the PureCell™ system using renewable hydrogen. The last column shows the percentages of the scores for the PureCell™ system using renewable hydrogen relative to the scores of the current PureCell™ system.

Impact category	Current PureCell™ system single score result	Renewable H2 PureCell™ system single score result	Percentage of current system
Total	1.12E+06	9.56E+05	85%
Carcinogens	2.08E+04	1.66E+03	8.0%
Resp. organics	1.41E+03	1.23E+03	87%
Resp. inorganics	2.44E+05	3.70E+05	152%
Climate change	6.29E+04	6.13E+04	97%
Radiation	0.0234	0.0234	100%

Ozone layer	0.314	0.272	87%
Ecotoxicity	697	478	69%
Acidification/ Eutrophication	1.69E+04	4.33E+04	256%
Land use	5.85	5.85	100%
Minerals	0.418	188	4.5E+04%
Fossil fuels	7.74E+05	4.78E+05	62%

Table 6-7: PureCell™ system use phase, steam reforming vs. renewable hydrogen single score results, 1000 miles scenario

The total single score results show that the environmental impact of the PureCell™ system use phase is decreased by a factor 1.2 when renewable hydrogen is used as a fuel for the PureCell™ system. The results per impact category show that the 'Fossil fuels' and 'Carcinogens' impact categories have the most significant absolute decrease in impact. The most significant absolute increase in impact occurs in the 'Respiratory inorganics' and the 'Acidification/Eutrophication' impact categories.

Figure 6-6 shows the SimaPro network for the PureCell™ system life cycle with renewable hydrogen when 1000 miles of compressed hydrogen transport are modeled.

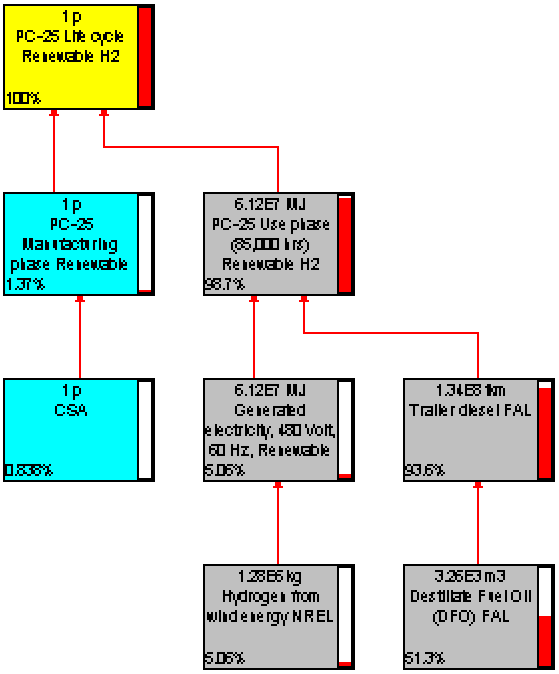


Figure 6-6: PureCell™ system life cycle renewable hydrogen SimaPro network, 1000 miles scenario

The network shows that in the life cycle of a PureCell™ system running on renewable hydrogen with a 1000 miles transport scenario the use phase is still the biggest contributor to the life cycle environmental impact. Due to the removal of the reformer, ILS and steam ejector subassemblies in the manufacturing phase (thereby reducing the impact of the manufacturing phase), the relative contribution of the use phase has gone up from 98.6% to 98.7%, although the impact of the use phase has decreased by a factor 1.2. Relative contribution of the manufacturing phase dropped from 1.45% to 1.37%.

In Table 6-8 the life cycle single score results for the current PureCell™ system are compared with the results for the PureCell™ system using renewable hydrogen. The last column shows the percentages of the scores for the PureCell™ system using renewable hydrogen relative to the scores of the current PureCell™ system.

Impact category	Current PureCell™ system single score result	Renewable H2 PureCell™ system single score result	Percentage of current system
Total	1.14E+06	9.69E+05	85%
Carcinogens	2.16E+04	1.86E+03	8.6%
Resp. organics	1.40E+03	1.22E+03	87%
Resp. inorganics	2.50E+05	3.75E+05	150%
Climate change	6.40E+04	6.22E+04	97%
Radiation	0.484	0.437	90%
Ozone layer	1.2	0.995	83%
Ecotoxicity	1.32E+03	775	59%
Acidification/ Eutrophication	1.74E+04	4.37E+04	251%
Land use	51.7	36.8	71%
Minerals	1.46E+03	1.46E+03	100%
Fossil fuels	7.80E+05	4.83E+05	62%

Table 6-8: PureCell™ system life cycle, steam reforming vs. renewable hydrogen single score results, 1000 miles scenario

The total single score results show that the environmental impact of the PureCell™ system life cycle is decreased by a factor 1.2 when renewable hydrogen is used as a fuel for the PureCell™ system and a 1000 miles transport scenario is assumed.

Conclusions

The SimaPro results show that the environmental impact of using renewable hydrogen from wind energy as a fuel for the PureCell™ system is highly dependent on the compressed hydrogen transport scenario. If a 100 miles transport scenario is assumed, a decrease in the environmental impact of the PureCell™ system use phase by a factor 8 relative to the current PureCell™ system's use phase is reached. Likewise, the environmental impact of the PureCell™ system life cycle decreases by a factor 7. However, if a 1000 miles transport scenario is assumed, the environmental impact of the PureCell™ system use phase decreases only by a factor 1.2 relative to the current PureCell™ system's use phase. The environmental impact of the PureCell™ system life cycle also decreases by a factor 1.2, due to the extremely high contribution of the use phase to the life cycle environmental impact in the 1000 miles transport scenario. In both scenarios the use phase remains the biggest contributor. Compared to the current

PureCell™ system, the relative contribution of the use phase to the total life cycle impact decreases from 98.6% to 91.5% for the 100 miles transport scenario, but it increases from 98.6% to 98.7% for the 1000 miles transport scenario. Compressed hydrogen transport is responsible for 64.7% of the use phase impact in the 100 miles transport scenario, and for 94.8% of the use phase impact in the 1000 miles transport scenario.

Alternative End-of-Life Scenario

In this section, improvement of the environmental performance of the PureCell™ system through reuse of certain PureCell™ system subassemblies and through maximizing platinum recycling is analyzed. Some of the PureCell™ system subassemblies have an indefinite lifetime and can possibly be reused. If for instance a subassembly is reused once then its environmental impact in the manufacturing phase is shared by two PureCell™ systems. Even though only 22.6 g platinum and 8.8 g palladium are used in the ILS it may still be worthwhile to recycle these materials due to the extremely high environmental impact per kg for PGMs (platinum group metals). Likewise as for the CSA platinum, a 98% recycling rate is assumed and implemented in the SimaPro model.

Regarding reuse, there are however some difficulties involved which have to be kept in mind. First of all there are technological difficulties. For example, in case of frame subassembly reuse, parts of the frame where the nuts and bolts are attached can rust and break, making the frame useless. In case of reuse these kinds of technological difficulties should therefore be taken into account in the design and manufacturing stage to ensure an increased lifetime. Second, there are also economical difficulties. In some (or even many) cases it may not be economically worthwhile to reuse subassemblies or components. In case of the enclosure subassembly, for example, this will need to be shipped, stripped, cleaned and re-painted before reuse, which will be more expensive than manufacturing a new enclosure. Finally, reuse also raises the question of liability. Within a conventional supplier/buyer system, the buyer will never want to buy a product in which not all components are new. This is because the liability shifts to the buyer whenever the product is bought. Ways to get around this are providing a guaranteed product lifetime or using a leasing contract. This issue will be further addressed in the conclusion of this section.

This alternative end-of-life scenario is intended to show the significance of the opportunities of reusing subassemblies and maximizing platinum recycling when looking at the environmental impact of the PureCell™ system. SimaPro is used to develop a preliminary model. A more detailed assessment is required to explore this strategy further.

Changes in SimaPro Model

The subassemblies that are reused in this alternative scenario are the steam ejector, steam drum subassembly (part of the TMS), frame, enclosure, PCS and ECS. The decision to include reuse of these subassemblies in the SimaPro model is based on discussions on reuse opportunities with people at UTC Power. The PCS is taken as an example in order to show how the subassembly reuse is modeled in SimaPro. Table 6-9 shows the PCS waste scenario as it is modeled in SimaPro.

PCS waste scenario	1	kg
Separated waste		
Recycling Ferro metals	Steel cold rolled coil IISI	100%
Landfill Ferro metals	Steel cold rolled coil IISI	0%
Recycling Non-ferro	Copper ETH U PureCell™ system	90%
Copper (inert) to landfill U	Copper ETH U PureCell™ system	10%
Remaining waste		
Unspecified		100%

Table 6-9: PCS SimaPro waste scenario

In the original PureCell™ system LCA model the PCS was fully 'sent' to this waste scenario in the PureCell™ system end-of-life phase. The recycling rates correlate with those mentioned in Chapter 4 - Inventory Analysis, and the unspecified remaining waste represents the electric components in the PCS. In the alternative end-of-life scenario the PCS is for 50% sent to the waste scenario shown above and for 50% sent to PCS reuse, as shown in Table 6-10. This means that the PCS will be reused once, and half of the PCS environmental impact in the manufacturing phase is now subtracted (thus being an environmental benefit) from the environmental impact of the end-of-life phase. In this way the environmental impact of both the PCS manufacturing and the PCS disposal are evenly divided between a current PureCell™ system and a hypothetical PureCell™ system in the future. Note that the benefit of reuse appears in the end-of-life phase and not in the manufacturing phase.

Assembly	Amount	Unit
PCS	1	p
Waste scenarios	Percentage	
PCS waste scenario	50%	
Reuses	Percentage	
PCS reuse	50%	

Table 6-10: PureCell™ system PCS disposal scenario including reuse

Figure 6-7 shows the SimaPro network for the PureCell™ system end-of-life phase including reuse. Only the subassemblies and processes with the biggest contribution to the end-of-life phase environmental impact are exposed. The light blue boxes show that SimaPro models reuse by subtracting half of the environmental impact of the subassembly in the manufacturing phase from the end-of-life phase environmental impact.

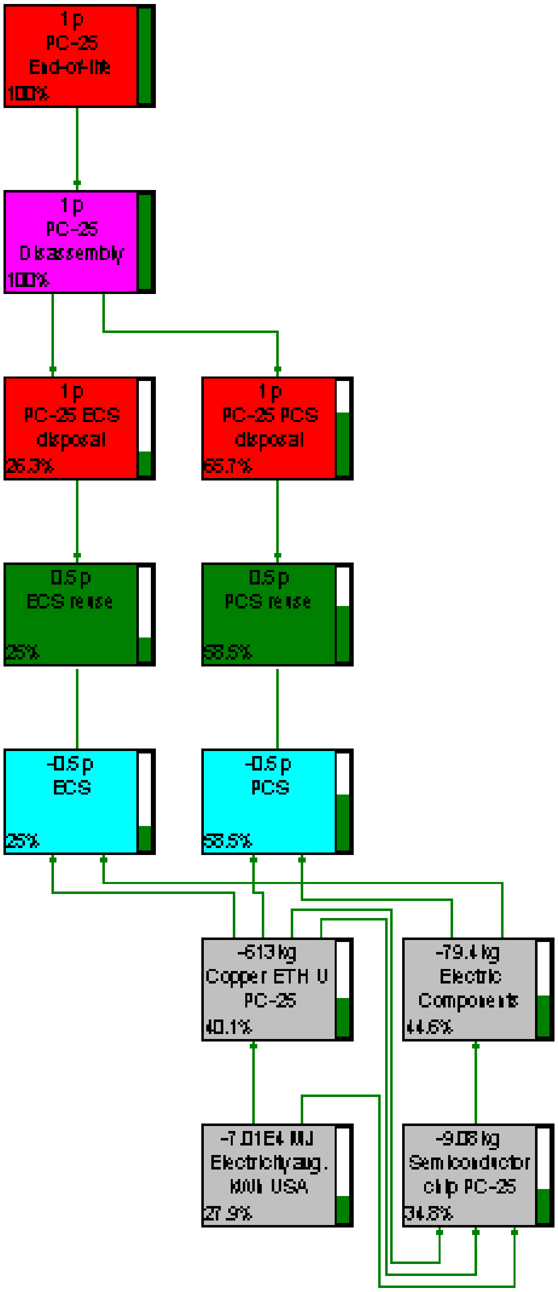


Figure 6-7: PureCell™ system end-of-life phase including reuse SimaPro network

Figure 6-7 shows that, in particular, the reuse of the PCS and ECS has a big influence on the end-of-life phase environmental impact. Results will be analyzed in more detail in the 'Results' paragraph.

The 98% recycling of ILS platinum and palladium in the alternative end-of-life scenario also requires changes in the SimaPro model. Table 6-11 shows the LCI data for the ILS platinum and palladium when 98% is recycled.

	current ILS	**98% recycling**
Platinum I PureCell™ system	22.6 g	0.452 g
Palladium I PureCell™ system	8.8 g	0.176 g
Platinum recycled PureCell™ system	0 g	22.148 g
Palladium recycled PureCell™ system	0 g	8.624 g

Table 6-11: ILS Platinum and palladium data 98% recycling

The recycled platinum is modeled in SimaPro with LCI data from [13]. The process inventory is specified in Appendix D. For the palladium recycling process the same data are used as for the platinum recycling, as both materials are PGMs and have similar physical and chemical properties.

Results

Results of the alternative end-of-life scenario are shown for the end-of-life phase, the manufacturing phase and for the end-of-life and manufacturing phase aggregated. The benefit of subassembly reuse is shown in the end-of-life phase results, whereas the benefit of 98% ILS platinum and palladium recycling is shown in the manufacturing phase results.

Table 6-12 shows a comparison of end-of-life phase results for the original LCA model versus the LCA model with the alternative end-of-life scenario. The last column shows the percentages of the scores for the PureCell™ system with reuse scenario relative to the scores of the current PureCell™ system without reuse scenario. The percentages represent the increase or decrease in the absolute value of the scores, thereby considering negative scores as positive environmental benefits and positive scores as positive environmental impacts.

Impact category	**Without reuse single score result**	**With reuse single score result**	**Percentage of current system**
Total	-421	-2.20E+03	523%
Carcinogens	-221	-145	66%
Resp. organics	-13.7	-11.3	82%
Resp. inorganics	-44.9	-671	1.5E+03%
Climate change	-2.44	-154	6.3E+03%
Radiation	0.083	-0.0441	n/a
Ozone layer	0.187	0.0573	31%
Ecotoxicity	-6.06	-60.9	1.0E+03%

Acidification/ Eutrophication	-2.99	-63.4	2.1E+03%
Land use	21.6	16.1	75%
Minerals	-18.6	-562	3.0E+03%
Fossil fuels	-134	-551	411%

Table 6-12: PureCell™ system end-of-life phase, without vs. with reuse single score results

The environmental benefit as a result of end-of-life treatment of the PureCell™ system increases from -421 to -2200 (environmental benefit being a negative environmental impact). This is an increase in environmental benefit by a factor 5.23. The most significant increase in environmental benefit due to subassembly reuse is found in the 'Respiratory inorganics' and 'Minerals' impact categories. This is mainly due to the reuse of copper and electric components in the PCS and ECS.

Table 6-13 shows a comparison of manufacturing phase results for the original LCA model versus the LCA model with the alternative end-of-life scenario. As a result of the way in which the ILS platinum and palladium recycling is modeled in SimaPro, the environmental benefit appears in the manufacturing phase. The last column shows the percentages of the scores for the PureCell™ system with 98% recycling of ILS platinum and palladium relative to the scores of the current PureCell™ system.

Impact category	Current PureCell™ system single score result	With ILS Pt & Pd 98% recycling	Percentage of current system
Total	1.65E+04	1.57E+04	95%
Carcinogens	956	953	100%
Resp. organics	2.18	2.17	100%
Resp. inorganics	6.27E+03	5.54E+03	88%
Climate change	1.08E+03	1.08E+03	100%
Radiation	0.377	0.377	100%
Ozone layer	0.695	0.691	99%
Ecotoxicity	628	627	100%
Acidification/ Eutrophication	519	477	92%
Land use	24.2	24.2	100%
Minerals	1.48E+03	1.48E+03	100%
Fossil fuels	5.56E+03	5.55E+03	100%

Table 6-13: PureCell™ system manufacturing phase, current PureCell™ system vs. ILS Pt & Pd 98% recycling single score results

98% Recycling of platinum and palladium in the ILS leads to a decrease in the total environmental impact of the manufacturing phase from 16500 to 15700. This is a decrease of 4.8%. The decrease in the environmental impact of the 'Respiratory inorganics' impact category is mainly responsible for this, which is in turn due to the decrease in input of raw platinum and palladium.

Table 6-14 shows a comparison of aggregated manufacturing and end-of-life phase results for the original end-of-life scenario with the alternative end-of-life scenario. The use phase environmental impact is left out in order to show the significance of the implementation of the alternative end-of-life scenario.

Impact category	Original end-of-life scenario	Alternative end-of-life scenario	Percentage of current system
Total	1.61E+04	1.35E+04	84%
Carcinogens	735	808	110%
Resp. organics	-11.6	-9.09	78%
Resp. inorganics	6.23E+03	4.87E+03	78%
Climate change	1.08E+03	922	85%
Radiation	0.46	0.333	72%
Ozone layer	0.881	0.748	85%
Ecotoxicity	621	566	91%
Acidification/ Eutrophication	516	413	80%
Land use	45.8	40.4	88%
Minerals	1.46E+03	917	63%
Fossil fuels	5.43E+03	5.00E+03	92%

Table 6-14: Original vs. alternative end-of-life scenario, PureCell™ system manufacturing phase and end-of-life phase single score results aggregated

The alternative end-of-life scenario leads to a decrease in this aggregated environmental impact from 16100 to 13500. This is a decrease of 16%.

Conclusions

Implementation of the alternative end-of-life scenario described above results in a 16% decrease in the environmental impact of the PureCell™ system manufacturing and end-of-life phase aggregated. Reuse of the steam ejector, steam drum, frame, enclosure, PCS and ECS subassemblies is responsible for an 11% decrease, and 98% recycling of the platinum and palladium in the ILS is responsible for a 5% decrease. However, if one looks at the effect of the alternative end-of-life scenario on the environmental impact of the PureCell™ system life cycle (i.e., if the use phase is included) then the decrease is only 0.23% due to the high contribution of the use phase to the life cycle environmental impact.

As mentioned before, liability issues make the option of reuse more than just a technological problem. A buyer will never want to buy a product in which not all components are new unless the product has a guaranteed period of functioning. One way to solve this problem is to sell PureCell™ system's with a guaranteed lifetime. Another way is to use a leasing system, where the client leases a PureCell™ system for an agreed price while leaving the liability for the system to function to UTC Power. In this way UTC Power determines which subassemblies or components can be reused, while at the same time product reliability and customer satisfaction are maintained. For complex products that consist of many different components with different lifetimes, leasing can be a solution that enhances subassembly or component reuse and thus reduces the product’s environmental impact.

Chapter 7 - Final Conclusions

In this research an LCA was performed on the PureCell™ power system. The PureCell™ system is a phosphoric acid fuel cell system manufactured by UTC Power, located in South Windsor, Connecticut. Data for the LCA were collected in collaboration with UTC Power, and the LCA was modeled using SimaPro software.

The objective of this project was to provide a guide for environmental improvement of the PureCell™ power system. The approach to accomplish this objective was divided into two steps. In the first step the 'hotspots' that contribute to the present environmental profile of the product were identified by using LCA to model the product life cycle. An analysis of the targeted hotspots was given in the Chapter 5 - Impact Assessment and Interpretation.

Looking at the LCA results for the PureCell™ system life cycle, it became clear that the 85,000 hrs use phase has an extremely high environmental impact relative to the manufacturing and end-of-life phase. In fact, the use phase is responsible for 98% of the PureCell™ system life cycle's total environmental impact. This is mainly due to the use of natural gas as a fuel (and its depletion as a resource) and the emissions caused by the steam reforming process.

When the PureCell™ system manufacturing phase was analyzed separately it was shown that the CSA (Cell Stack Assembly) is responsible for 49% of the total environmental impact of the manufacturing phase. The CSA is followed by the PCS (Power Conditioning System, 16%) and the ILS (Integrated Low-temperature Shift converter, 11%). If one looks at the energy fuel and material level instead of the subassembly level, natural gas turns out to be by far the biggest contributor to the manufacturing phase impact. This is mainly due to the natural gas used for CSA manufacturing at UTC Power. Materials with a big contribution to the environmental impact of the manufacturing phase are stainless steel 304, copper and raw platinum.

LCA results for the CSA were also analyzed separately because the CSA is responsible for 49% of the total environmental impact of the manufacturing phase. The electricity and natural gas used for CSA manufacturing are the main contributors to this 49%. Together they are responsible for 72% of the CSA total impact. Thus, the contribution of electricity and natural gas to the impact of the manufacturing phase is 35%. It should however be kept in mind that due to the allocation procedure these electricity and natural gas data have a high degree of uncertainty, as described in Chapter 5.

To accomplish the second project objective, opportunities for improving the environmental footprint were explored. Based on the results shown in Chapter 5 - Impact Assessment and Interpretation, two feasible opportunities within the scope of this research were modeled in SimaPro. These two opportunities were: using renewable hydrogen from wind power and improving the end-of-life scenario from an environmental perspective by reusing components and maximizing platinum recycling.

The goal of this part of the research was to quantify the potential environmental improvement for both opportunities relative to the current PureCell™ system.
Data from an LCA done by NREL for a wind/electrolysis system were used to model the opportunity for using renewable hydrogen from wind power. The wind/electrolysis system considered in the NREL LCA replaced the steam reforming system and the use phase input and emissions of the current PureCell™ system. The hydrogen was assumed to be transported by truck and in compressed form to the PureCell™ system locations. Both a 100 mile and a 1000 miles transport scenario were implemented in the LCA model. SimaPro results show that using renewable hydrogen from wind energy as a fuel for the PureCell™ system instead of natural gas provides a decrease in the environmental impact of the PureCell™ system life cycle by a factor 7 for the 100 miles transport scenario and a decrease by a factor 1.2 for the 1000 miles transport scenario. In the renewable hydrogen use phase, compressed hydrogen transport is responsible for 64.7% of the use phase impact in the 100 miles transport scenario, and for 94.8% of the use phase impact in the 1000 miles transport scenario. The distance over which the hydrogen has to be transported is therefore an important factor for the environmental impact of a PureCell™ system using renewable hydrogen from wind energy.

In the alternative end-of-life scenario the steam ejector, steam drum (part of the TMS), frame, enclosure, PCS and ECS subassemblies were assumed to be reused. Furthermore, a 98% recycling rate was assumed for the platinum and palladium in the ILS. Results show that implementation of this alternative end-of-life scenario results in a 16% decrease in the environmental impact of the PureCell™ system manufacturing and end-of-life phase aggregated. Reuse is responsible for an 11% decrease and ILS platinum and palladium recycling is responsible for a 5% decrease. The effect of the alternative end-of-life scenario on the environmental impact of the PureCell™ system life cycle is however only a decrease of 0.23%.

Based on the overall results of this study, a number of recommendations for environmental improvement of the PureCell™ system can be made to UTC Power. The biggest possibilities for improving the environmental performance of the PureCell™ system clearly lie in the use phase. The biggest impacts in the use phase occur due to the steam reforming of natural gas. Within the current PureCell™ system, increasing the efficiency of the steam reforming process and increasing the electrical efficiency of the fuel cell stack will both lead to a decrease in natural gas usage and therefore also to a decrease in the emissions caused by the steam reforming process, thereby significantly reducing the PureCell™ system life cycle's environmental impact.

A second option is to use hydrogen from renewable energy, as it is described in this report for the case of hydrogen from wind energy.

A third option to improve the PureCell™ system's environmental performance in the use phase is carbon sequestration. Although this option is not analyzed in this report, the LCA results show that emissions caused by the steam reforming process are responsible for 4.6% of the life cycle environmental impact of the PureCell™ system. 99% of this overall impact of the steam reforming process is caused by CO_2 emissions. Therefore carbon sequestration can theoretically lead to a maximum decrease of 4.6% in the environmental impact of the PureCell™ system life cycle, dependent on the environmental impact of the carbon sequestration system.

Regarding the manufacturing phase, platinum deserves the most attention. A decrease in the amount of platinum used in the PureCell™ system leads to a significant decrease in the environmental impact of the manufacturing phase. The platinum recycling rate also has a big influence on the environmental impact, and maximizing the platinum recycling rate is therefore a major opportunity for improvement. Furthermore the LCA results show that the CSA manufacturing process is very energy intensive. It therefore appears to be worthwhile to make the CSA manufacturing process more energy efficient. However, this conclusion is based on data with a high degree of uncertainty.

Finally, reuse of certain subassemblies looks promising from an environmental point of view. Although many difficulties are involved with the option of reuse, it is worth considering.

References

1. Energy Information Administration (EIA), *Annual Energy Review 2004: World Primary Energy Production, 1970-2003*. 2004, http://www.eia.doe.gov.
2. Pehnt, M., *Life Cycle Analysis of Fuel Cell System Components.* Handbook of Fuel Cells - Fundamentals, Technology and Applications, 2003. **4**(13): p. 1293-1317.
3. UTC Power, *A United Technologies Company*. 2006, www.utcpower.com.
4. ISO, *Environmental management - Life cycle assessment - Principles and framework*. 1997, International Organization for Standardization: Geneva.
5. PRe Consultants, *Life cycle tools to improve environmental performance*. 2006, www.pre.nl.
6. National Renewable Energy Laboratory (NREL), *Life-Cycle Inventory Database*. 2006, http://www.nrel.gov/lci/database/.
7. Goedkoop, M. and R. Spriensma, *The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment, Methodology Report*. 2001, PRé Consultants B.V.: Amersfoort, NL.
8. Aboussouan, L. and S. Malm, *IISI LCA data*. 2006, International Iron and Steel Institute.
9. Fujii, H., et al., *How to quantify the environmental profile of stainless steel*, in *SETAC North America 26th Annual Meeting*. 2005.
10. UTC Power, *PureCell 200TM Commercial Fuel Cell Power System*. 2003.
11. ABB Motors A/S, *Environmental Product Declaration for Electric Motor Type 90S 4 Pole*, E. Just, Editor. 1999, http://library.abb.com/global.
12. The Aluminum Association Inc. 2006, www.aluminum.org.
13. AEA Technology, *Platinum and hydrogen for fuel cell vehicles*, U.K. Department for Transport, Editor. 2006.
14. U.S. Environmental Protection Agency, *Perfluorooctanoic Acid (PFOA) and Fluorinated Telomers*. 2006, http://www.epa.gov/opptintr/pfoa/.
15. Carnegie Mellon Green Design Institute, *Economic Input-Output Life Cycle Assessment*. 2006, http://www.eiolca.net/.
16. Lewis, G.M., et al., *PV-BILD: A Life Cycle Environmental and Economic Assessment Tool for Building-Integrated Photovoltaic Installations*. 1999, National Science Foundation / Lucent Technologies Industrial Ecology Grant.
17. Williams, E.D., R.U. Ayres, and M. Heller, *The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices.* Environmental Science & Technology, 2002. **36**(24): p. 5504-5510.
18. MWS Wire Industries, *Insulation Specification Cross Reference Table*. 2006, http://www.mwswire.com/insspec.htm.
19. Keoleian, G.A., et al., *Industrial Ecology of the Automobile: A Life Cycle Perspective*. 1997, Society of Automotive Engineers: Warrendale, PA.
20. TIFAC, *Activated Carbon Production Plant*. 2006, www.tifac.org.in.
21. UTC Power, *PC25 200 kW Fuel Cell Power Plant, Major Systems and Components Description*. 2006.
22. Union Gas, *Chemical Composition of Natural Gas*. 2006, www.uniongas.com.

23. Steel Recycling Institute, *Steel: Driving Auto Recycling Success*. 2006, http://www.recycle-steel.org/cars.html: Pittsburgh.
24. U.S. Environmental Protection Agency, *Municipal Solid Waste: Automotive Parts*. 2006, http://www.epa.gov/garbage/auto.htm.
25. Handley, C., N.P. Brandon, and R. van der Vorst, *Impact of the European Union vehicle waste directive on end-of-life options for polymer electrolyte fuel cells.* Journal of Power Sources, 2002. **106**: p. 344-352.
26. Heijungs, R., *Advanced Course on LCA*. 2005, CML: Leiden.
27. Department of the Environment and Transport and the Regions, *Winter Smog Summer Smog*. 1998, http://www.defra.gov.uk/environment/airquality/smog/index.htm.
28. Pehnt, M., *Life Cycle Assessment of Fuel Cell Stacks.* International Journal of Hydrogen, 2001. **26**: p. 91-101.
29. Lunghi, P. and R. Bove, *Life Cycle Assessment of a Molten Carbonate Fuel Cell Stack*. 2003, Universita degli Studi di Perugia.
30. Heijungs, R., *UNEP LCA Training Kit, Module F: Interpretation*. 2005, CML: Leiden.
31. Spath, P.L. and M.K. Mann, *Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis*. 2004, NREL: Golden.
32. U.S. Department of Energy, E.E.a.R.E., *Hydrogen, Fuel Cells & Infrastructure Technologies Program*. 2006, http://www.eere.energy.gov/hydrogenandfuelcells/delivery/current_technology.html#trucks.
33. Bossel, U., B. Eliasson, and G. Taylor, *The Future of the Hydrogen Economy: Bright or Bleak?* 2003, http://www.oilcrash.com/articles/h2_eco.htm.
34. Bossel, U. and B. Eliasson, *Energy and the Hydrogen Economy*. 2003.
35. Larminie, J. and A. Dicks, *Fuel Cell Systems Explained*. 2nd ed. 2003.

Appendices

Appendix A: PureCell™ System Manufacturing Phase Aggregated Inventory Table

Table 0-1 below gives the aggregated weights of the PureCell™ system input materials in the manufacturing phase. The databases from which these processes are selected are also mentioned. The database PureCell™ system consists of data that do not come from a generic SimaPro database; these processes were imported in SimaPro especially for this research project and are specified in Appendix D. The processes that come from generic SimaPro databases but have 'PC25' added to their description are adapted to the geographical location of UTC Power if this was considered to be relevant. An example is adapting the electricity input in a material production process to the U.S. average electricity mix.

Materials/Assemblies	**Amount (kg)**	**SimaPro database**
Steel cold rolled coil IISI	1.48E+04	PC25
Recycling Ferro metals (recycling steel scrap)	7.03E+03	Data Archive
Stainless Steel 304 2B IISI	4.98E+03	PC25
Graphite	1.72E+03	PC25
Copper ETH U PureCell™ system	1.15E+03	ETH-ESU 96
Silicium carbide I PureCell™ system	863	IDEMAT 2001
Zinc oxide PureCell™ system	566	PC25
Zinc I PureCell™ system	453	IDEMAT 2001
Glass fiber I PureCell™ system	418	IDEMAT 2001
Stainless Steel 316 2B IISI	358	PC25
Aluminum oxide PureCell™ system	215	BUWAL250
PE granulate average B250 PureCell™ system	212	BUWAL250
Electric Components PureCell™ system	159	PC25
Zeolite ETH U PureCell™ system	148	ETH-ESU 96
Phosphoric acid ETH U PureCell™ system	114	ETH-ESU 96
Recycling Non-ferro (recycling copper scrap)	111	Data Archive
Carbon black ETH U	81.6	ETH-ESU 96
Electric motor PureCell™ system	81.6	PC25
Nickel enriched ETH U PureCell™ system	38.8	ETH-ESU 96
PET ETH U PureCell™ system	38.6	ETH-ESU 96
Aluminum (primary) produced in the USA	20.7	PC25
Aluminum 100% recycled ETH U PureCell™ system	20.7	ETH-ESU 96
PP granulate average B250	20.4	BUWAL250
Paint ETH U PureCell™ system	6.8	ETH-ESU 96
Lanthanum PureCell™ system	2.22	Raw material
Platinum recycled PureCell™ system	1.53	PC25
Platinum I PureCell™ system	0.0538	IDEMAT 2001
Palladium I PureCell™ system	0.0088	IDEMAT 2001
Total	3.40E+04	
Processes		

Cold transforming steel PureCell™ system	1.99E+04	Data Archive
Rolling steel I PureCell™ system	9.44E+03	IDEMAT 2001
Copper wire PureCell™ system	1.11E+03	Data Archive
Turning steel PureCell™ system	159	Data Archive
Cast work, non-ferro PureCell™ system	68	Data Archive
Injection molding PureCell™ system	43.1	IDEMAT 2001
Forging steel PureCell™ system	43.1	Data Archive
Turning aluminum I PureCell™ system	15.9	IDEMAT 2001
Cold transforming Al I PureCell™ system	15.9	IDEMAT 2001
Electric welding steel 5 PureCell™ system	150 m	Data Archive
Electric welding steel 3 PureCell™ system	37 m	Data Archive
Heat from nat. gas FAL	3.28E+05 MJ	Franklin USA 98
UTC South Windsor electricity mix	2.38E+05 MJ	PC25
Truck (single) diesel FAL (Franklin)	1.18E+04 tkm	Franklin USA 98

Table 0-1: PureCell™ system manufacturing phase aggregated inventory table

Appendix B: PureCell™ System Use Phase Inventory Tables

Materials	**Amount (lb)**	**SimaPro database**
Steel cold rolled coil IISI	132	PC25
Stainless Steel 304 2B IISI	114	PC25
Propylene glycol ETH U PureCell™ system	476	ETH-ESU 96
Activated carbon PureCell™ system	60	PC25
Concrete PureCell™ system	7940	IDEMAT 2001
Water decarbonized ETH U	992	ETH-ESU
Nitrogen	185	Raw material
Total	9899	
Processes		
Cold transforming steel PureCell™ system	132	Data Archive
Cold transforming steel PureCell™ system	114	Data Archive

Table 0-2: PureCell™ system installation inventory data

Products	**Amount**	**SimaPro database**
Generated electricity, 480 Volt, 60 Hz	17000000 kWh	PC25
Produced heat at 140 F	23037125 kWh	PC25
Materials/fuels		
Natural gas FAL (Franklin)	174250000 cuft	Franklin USA 98
Emissions to air		
NOx	272 lb	Airborne emission
CO	391 lb	Airborne emission
CO2	9537000 kg	Airborne emission
non-methane hydrocarbon (NMHC)	6.12 lb	Airborne emission

Table 0-3: 17,000,000 kWh electricity generation inventory data

Materials	**Amount**	**Waste treatment**	**SimaPro database**
Activated carbon PureCell™ system	1852.5 lb		PC25
Total	1852.5 lb		
Waste to treatment			
inorganic general	1852.5 lb	Landfill Compostables	Data Archive
chromium compounds	570 kg	LT waste to chemical landfill	ETH-ESU 96
chromium compounds	570 kg	Waste to chemical landfill	ETH-ESU 96

Table 0-4: PureCell™ system maintenance inventory data

Appendix C: PureCell™ System End-of-Life Phase Inventory Table

Material	Waste treatment	SimaPro database	%
Steel cold rolled coil IISI	Recycling Ferro metals	Data Archive	100%
Stainless Steel 304 2B IISI	Recycling Ferro metals	Data Archive	100%
Stainless Steel 316 2B IISI	Recycling Ferro metals	Data Archive	100%
Copper ETH U PureCell™ system	Recycling Non-ferro	Data Archive	90%
Copper ETH U PureCell™ system	Copper (inert) to landfill	ETH-ESU 96	10%
Aluminum (primary) produced in the USA	Recycling aluminum B250	BUWAL 250	90%
Aluminum (primary) produced in the USA	Landfill Aluminum B250 (1998)	BUWAL 250	10%
Aluminum 100% recycled ETH U PureCell™ system	Recycling aluminum B250	BUWAL 250	90%
Aluminum 100% recycled ETH U PureCell™ system	Landfill Aluminum B250 (1998)	BUWAL 250	10%
Nickel enriched ETH U PureCell™ system	Recycling Non-ferro	Data Archive	90%
Nickel enriched ETH U PureCell™ system	Unspecified	BUWAL 250	10%
Graphite PureCell™ system	Waste to special waste incinerator	ETH-ESU 96	100%
Carbon black ETH U PureCell™ system	Waste to special waste incinerator	ETH-ESU 96	100%
PTFE (Teflon®)	Waste to special waste incinerator	ETH-ESU 96	100%
Glass fiber I PureCell™ system	Landfill Glass B250 (1998)	BUWAL 250	100%
Zeolite ETH U PureCell™ system	Zeolite (inert) to landfill	ETH-ESU 96	100%
PP granulate average B250 PureCell™ system	Landfill PP B250 (1998)	BUWAL 250	100%
PET ETH U PureCell™ system	Landfill PET B250	BUWAL 250	100%

Electric Components PureCell™ system	Unspecified	BUWAL 250	100%
Other materials	Unspecified	BUWAL 250	100%

Table 0-5: PureCell™ system end-of-life phase, materials to waste treatment

Appendix D: PureCell™ System Processes Imported in SimaPro

This appendix contains the input data of the processes that were imported in SimaPro especially for the PureCell™ system research project.

Steel cold rolled coil IISI [8]

Products		
Steel cold rolled coil IISI	1	kg
Resources		
coal FAL	0.747546	kg
dolomite	0.028108	kg
iron (in ore)	1.85785	kg
natural gas FAL	0.041579	kg
crude oil FAL	0.039205	kg
scrap, external	0.102475	kg
water	20.5351	kg
energy from hydro power	0.321558	MJ
energy (undef.)	4.4966	MJ
Emissions to air		
Cd	6.63E-05	g
CO2 (fossil)	2.43815	kg
CO	30.4184	g
Cr	0.0038	g
dioxin (TEQ)	2.04E-08	g
HCl	0.072779	g
H2S	0.081512	g
Pb	0.003689	g
Hg	6.61E-05	g
Methane	0.731735	g
NOx (as NO2)	3.01092	g
N2O	0.127983	g
particulates (unspecified)	1.893079	g
SOx (as SO2)	2.86906	g
VOC	0.145793	g
Zn	0.003553	g
Emissions to water		

NH4+	0.043917	g
NH3 (as N)	0.04	g
Cd	7.25E-05	g
Cr	0.000107	g
COD	0.27784	g
Fe	0.037039	g
Pb	2.32E-05	g
Ni	0.000228	g
Nitrogen	0.023711	g
P	0.003154	g
suspended substances	0.230015	g
Zn	0.002066	g
Final waste flows		
solid waste	1.69622	kg

Table 0-6: Steel cold rolled coil IISI

Stainless Steel 304 2B IISI [8]

Products		
Stainless Steel 304 2B IISI	1000	kg
Resources		
chromium (ore)	175.2	kg
coal FAL	1129.6	kg
dolomite	49.4	kg
iron (ore)	277	kg
lignite	58.7	kg
limestone	210.7	kg
manganese (ore)	19.1	kg
molybdenum (ore)	1.1	kg
natural gas FAL	266.8	kg
nickel (ore)	57.9	kg
crude oil FAL	217.3	kg
steel scrap	774	kg
water (process)	62846.6	kg
water	17700.7	kg
energy from hydro power	2038.6	MJ
Emissions to air		
CO2 (fossil)	6100000	g
CO	10047.6	g
Cr	91.9	g
Cr (VI)	0.1	g
dioxin (TEQ)	0.000009	g

Mo	5.4	g
Ni	77.9	g
NOx (as NO2)	14209.1	g
particulates (unspecified)	6936.5	g
SOx (as SO2)	46415.1	g
silicates	362.5	g
Emissions to water		
Acid as H+	83.5	g
Al	22.7	g
NH4+	54	g
NH3 (as N)	50	g
Cd	0.2	g
Cl-	6884.4	g
Cr	11.2	g
Cr (VI)	8.1	g
COD	1756.8	g
Cu	0.6	g
fluoride ions	125.6	g
hydrocarbons (misc)	65.5	g
Fe	147	g
Pb	1.9	g
Mn	6.7	g
Mo	2.5	g
Ni	8.5	g
nitrate	3261.4	g
nitrogen	3984.9	g
P	4.7	g
S	1498.2	g
Sn	0.3	g
Zn	3.5	g
Final waste flows		
solid waste	3356.4	kg
steel waste	169.1	kg

Table 0-7: Stainless Steel 304 2B IISI

Stainless Steel 316 2B IISI [8]

Products		
Stainless Steel 316 2B IISI	1000	kg
Resources		
chromium (ore)	170.4	kg
coal FAL	1187	kg
dolomite	51.9	kg
iron (ore)	274.8	kg
lignite	52.3	kg
limestone	269.8	kg
manganese (ore)	19.5	kg
molybdenum (ore)	29.5	kg
natural gas FAL	325.1	kg
nickel (ore)	97.7	kg
crude oil FAL	277.1	kg
steel scrap	769.2	kg
water (process)	110808.3	kg
water	15563.9	kg
energy from hydro power	3452.2	MJ
energy (undef.)	155.4	MJ
Emissions to air		
CO2 (fossil)	6500000	g
CO	11628.9	g
Cr	108.1	g
Cr (VI)	0.1	g
dioxin (TEQ)	0.000018	g
Mo	14.2	g
Ni	129.3	g
NOx (as NO2)	16468.5	g
particulates (unspecified)	9548.9	g
SOx (as SO2)	70939.6	g
silicates	399.2	g
Emissions to water		
Acid as H+	83.1	g
Al	28.8	g
NH4+	53.5	g
NH3 (as N)	50	g
Cd	0.1	g
Cl-	7366.4	g
Cr	8.9	g
Cr (VI)	10.6	g
COD	1871.9	g
Cu	0.7	g
fluoride ions	114.1	g

hydrocarbons (misc)	78.5	g
Fe	123.6	g
Pb	2.7	g
Mn	8.4	g
Mo	5.9	g
Ni	11.6	g
nitrate	2805.7	g
nitrogen	10036.6	g
P	2.4	g
S	1623.1	g
Sn	0.3	g
Zn	3	g
Final waste flows		
solid waste	14461	kg
steel waste	158.9	kg

Table 0-8: Stainless Steel 316 2B IISI

Graphite PureCell™ system [15]

Products		
Graphite	3784	lb
Resources		
energy from hydro power	0.0144	TJ
energy from coal	0.019	TJ
energy from natural gas	0.02	TJ
energy from fossil	0.005	TJ
energy from oil	0.006	TJ
Emissions to air		
CO2 (fossil)	5.01	ton
CO	0.487	ton
SO2	0.018	ton
NOx	0.013	ton
VOC	0.029	ton
particulates (PM10)	0.004	ton
Final waste flows		
toxic waste	3.07	kg

Table 0-9: Graphite PureCell™ system

Electric Components PureCell™ system [16]

Products		
Electric Components PureCell™ system	1.679	kg
Materials/fuels		
MI250 Inverter	1.487	kg
Semiconductor chip PureCell™ system	192	g

Table 0-10: Electric Components PureCell™ system

MI250 Inverter [16]

Products		
MI250 Inverter	1.487	kg
Resources		
baryte	0.036971	kg
bauxite	4.30173	kg
bentonite	0.010128	kg
calcium sulphate	3.44E-07	kg
chromium (ore)	1.31E-10	kg
clay	0.039825	kg
coal (in ground)	11.1275	kg
copper (ore)	9.84205	kg
dolomite	0.005539	kg
feldspar	0.00285	kg
fluorspar	0.120356	kg
iron (ore)	0.189974	kg
lead (ore)	2.07E-10	kg
lignite	7.4134	kg
limestone	1.63218	kg
manganese (ore)	7.61E-11	kg
natural gas (in ground)	7.0385	kg
nickel (ore)	4.42E-11	kg
oil (in ground)	8.67516	kg
silica	0.019358	kg
sand	0.202245	kg
silver (in ore)	3.29E-12	kg
NaCl	2.25355	kg
sulphur	0.112488	kg
uranium (ore)	0.000926	kg
zinc (ore)	4.83E-12	kg
calciumfluoride	0.028717	kg

glass cullet	0.007194	kg
scrap, external	3.22E-06	kg
water	1125	kg
wood	0.260316	kg
SO2	0.022159	kg
Materials/fuels		
Gravel ETH U PureCell™ system	4.70E-05	kg
Kaolin B250	0.018211	kg
Iron sulfate ETH U	5.21647	kg
Iron	0.65073	g
Explosives ETH U	9.61E-06	kg
Glass fibre I PureCell™ system	0.01	kg
Epoxy resin I	0.1	kg
Emissions to air		
acetaldehyde	5.50E-05	g
acetic acid	0.000222	g
acetone	5.50E-05	g
ethyne	2.82E-07	g
aldehydes	0.00145	g
alkanes	3.22454	g
alkenes	1.14E-05	g
Al	5.47E-06	g
ammonia	0.230425	g
Sb	1.19E-09	g
Aromatic HC	0.062011	g
As	0.001778	g
Ba	9.82E-05	g
benzaldehyde	2.00E-13	g
benzene	0.1816	g
benzo(a)pyrene	1.29E-08	g
Be	2.09E-06	g
B	5.37E-07	g
Br	1.05E-07	g
butane	0.001559	g
butene	1.81E-05	g
Cd	0.000319	g
Ca	3.22E-05	g
CO2 (fossil)	74535.6	g
CO	95.5524	g
CxHy halogenated	0.45223	g
Cl2	8.26E-06	g
Cr (III)	6.18E-06	g
Cr	1.24E-08	g
cobalt	1.27E-05	g
Cu	0.140897	g
cyanides	1.95E-09	g

dioxin (TEQ)	9.99E-12	g
ethane	0.038142	g
ethanol	0.00011	g
ethylbenzene	1.81E-05	g
ethylene	0.04406	g
fluoride	0.931602	g
formaldehyde	0.000167	g
CxHy halogenated	5.94E-20	g
HALON-1301	0.002857	g
heptane	0.00018	g
hexane	0.000361	g
hydrocarbons (misc)	116.1	g
H2	2.62581	g
HCl	6.05563	g
HF	0.675021	g
H2S	0.14532	g
I	2.68E-08	g
Fe	0.294527	g
La	1.71E-09	g
Pb	0.158428	g
Mg	1.94E-06	g
Mn	0.000353	g
mercaptans	6.42E-08	g
Hg	0.000121	g
metals	0.312141	g
methane	168.104	g
methanol	0.000187	g
Mo	6.17E-06	g
Ni	0.009713	g
NOx (as NO2)	190.1	g
N2O	1.36447	g
organic substances	2.68641	g
particulates (unspecified)	178.283	g
pentane	0.00092	g
phenol	1.53E-12	g
P	4.86E-08	g
P2O5	3.25E-11	g
PAH's	0.04511	g
K	9.98E-07	g
propane	0.003224	g
propionaldehyde	5.50E-13	g
propionic acid	6.89E-10	g
propylene	3.64E-05	g
Sc	5.80E-10	g
Se	4.66E-06	g
Si	1.32646	g
Na	0.000289	g
Sr	1.06E-07	g
SOx (as SO2)	1627.35	g

tar	4.32E-11	g
Tl	5.31E-10	g
Th	1.09E-09	g
Sn	3.42E-10	g
Ti	1.90E-07	g
toluene	0.000124	g
U	1.30E-06	g
V	0.001685	g
xylene	7.23E-05	g
Zn	1.34101	g
Zr	8.13E-10	g
Emissions to water		
Acid as H+	47.9719	g
alkanes	0.000129	g
alkenes	1.19E-05	g
Al	15.4362	g
NH3 (as N)	0.575399	g
AOX	0.001236	g
hydrocarbons (misc)	0.061227	g
As	0.292035	g
Ba	2.20988	g
baryte	7.001	g
benzene	0.041318	g
BOD	3.2684	g
B	1.61E-05	g
Cd	0.000223	g
calcium ions	24.7978	g
Cs	2.29E-07	g
Cl-	464.332	g
CxHy chloro	2.10E-11	g
Cr (III)	9.10E-08	g
Cr	0.028041	g
Cr (VI)	1.85E-05	g
Co	5.62E-09	g
COD	20.7878	g
Cu	0.075887	g
cyanide	0.004744	g
dissolved substances	7.40714	g
DOC	0.088207	g
ethyl benzene	2.37E-05	g
fluoride ions	0.104275	g
formaldehyde	2.66E-13	g
hexachloroethane	3.70E-17	g
hydrocarbons (misc)	9.75E-06	g
inorganic general	37.4785	g
I	9.89E-05	g
Fe	16.3057	g
Pb	0.088786	g

Mg	10.4668	g
Mn	5.42E-05	g
Hg	0.001074	g
metallic ions	1.41459	g
dichloromethane	6.00E-08	g
Mo	4.11E-07	g
Ni	0.014022	g
nitrate	2.99091	g
nitrite	0.019485	g
N-tot	0.07837	g
oil	7.9478	g
dissolved organics	0.001922	g
other organics	0.099081	g
phenol	0.000129	g
phenol	0.049571	g
phenols	6.97E-05	g
phosphate	1.0088	g
P	4.11E-06	g
P2O5	9.69E-10	g
PAH's	0.02025	g
K	5.15672	g
salts	25.5652	g
fats/oils	1.56528	g
Se	4.11E-07	g
SiO2	2.15E-08	g
Ag	5.93E-07	g
Na	143.741	g
Sr	2.00006	g
sulphates	147.378	g
sulphide	0.010452	g
SO3	0.010718	g
S	5.58E-10	g
H2SO4	0.930463	g
SO3	1.03E-10	g
suspended substances	49.1142	g
tetrachloroethene	9.03E-14	g
Ti	2.26E-07	g
TOC	9.09628	g
toluene	0.00853	g
1,1,1-trichloroethane	2.04E-13	g
trichloroethene	5.60E-12	g
triethylene glycol	6.91E-06	g
V	4.11E-07	g
VOC as C	0.000346	g
waste water (vol)	3.51	l
xylene	0.00093	g
Zn	0.164672	g
Emissions to soil		

Al (ind.)	0.502462	g
As (ind.)	0.000201	g
Cd	7.31E-06	g
Ca (ind.)	2.00591	g
C (ind.)	1.54376	g
Cr (VI) (ind.)	4.34E-08	g
Cr (ind.)	0.002507	g
Co	8.37E-06	g
Cu	4.18E-05	g
Fe	1.00295	g
Pb	0.000191	g
Mn (ind.)	0.020059	g
Hg	1.30E-06	g
Ni	6.27E-05	g
N	1.36E-10	g
oil (ind.)	0.272936	g
phosphor (ind.)	0.026352	g
S (ind.)	0.301869	g
Zn	0.007955	g
Final waste flows		
aluminium scrap	0.013567	kg
waste	0.0457	kg
waste in incineration	0.000536	kg
process waste	0.112202	kg
Municipal solid waste	0.059539	kg
unspecified	1.15264	kg
low,med. act. nucl. waste	6.03E-06	l
mineral waste	1.84594	kg
waste	0.265036	kg
chemical waste	3.18E-09	kg
radioactive waste (kg)	1.74E-06	kg
slags/ash	0.109157	kg
Non material emission		
land use II-III	4.35E-05	m2a
land use II-IV	5.84E-06	m2a
land use III-IV	2.06E-06	m2a
Pb210 to air	2.42E-08	kBq
Po210 to air	4.37E-08	kBq
K40 to air	6.68E-09	kBq
radioactive substance to air	1.97E-10	kBq
Ra226 to air	6.17E-09	kBq
Ra228 to air	3.34E-09	kBq
Rn220 to air	7.77E-11	kBq
Rn222 to air	1.80E-07	kBq
Th228 to air	2.83E-09	kBq
Th232 to air	1.80E-09	kBq
U238 to air	5.14E-09	kBq

radioactive substance to water	1.82E-12	kBq
Ra224 to water	4.95E-05	kBq
Ra226 to water	9.89E-05	kBq
Ra228 to water	9.89E-05	kBq
Th228 to water	0.000198	kBq

Table 0-11: MI250 Inverter

Semiconductor chip PureCell™ system [17]

Products		
Semiconductor chip PureCell™ system	2	g
Materials/fuels		
Semiconductor wafer PureCell™ system	0.14	g
Copper ETH U PureCell™ system	1.2	g
Epoxy resin I	0.7	g
Copper ETH U PureCell™ system[8]	29	g
Epoxy resin I	17	g
Electricity/heat		
Electricity avg. kWh USA	0.54	kWh
Waste to treatment		
copper waste	29	g
plastic production waste	17	g

Table 0-12: Semiconductor chip PureCell™ system

Semiconductor wafer PureCell™ system [17]

Products		
Semiconductor wafer PureCell™ system	0.088	g
Resources		
water (process)	20	kg

---

[8] Semiconductor chip packaging: copper input resulting in scrap

Materials/fuels		
Silicon wafer PureCell™ system	0.16	g
Chemicals inorganic ETH U PureCell™ system	0.0093	g
Ammonia ETH U	0.012	g
Chlorine ETH U	0.0048	g
HCl ETH U	0.005	g
HF ETH U	0.00095	g
Chemicals inorganic ETH U PureCell™ system	0.20725	g
HF ETH U	2.84	g
Phosphoric acid ETH U PureCell™ system	2.07	g
HF ETH U	0.13	g
Nitric acid ETH U	0.83	g
Sulphuric acid B250	7.5	g
HCl ETH U	0.91	g
Ammonia ETH U	0.22	g
NaOH ETH U, PureCell™ system	0.33	g
Chemicals inorganic ETH U PureCell™ system	14.2	g
NaOH ETH U, PureCell™ system	7.6	g
Electricity/heat		
Electricity avg. kWh USA	1.5	kWh
Heat from nat. gas FAL	1	MJ
Emissions to air		
HF	2.97	g
HCl	0.91	g
phosphoric acid	2.07	g
ammonia	0.23	g
Cl2	0.0048	g
HNO3	0.83	g
H2SO4	7.5	g
Emissions to water		
inorganic general	14.4	g
Final waste flows		
water	17	kg
solid waste	7.8	kg

Table 0-13: Semiconductor wafer PureCell™ system

Silicon wafer PureCell™ system [17]

Products		
Silicon wafer PureCell™ system	1	kg
Materials/fuels		
Silicon I, PureCell™ system	9.4	kg
Electricity/heat		
Electricity avg. kWh USA	2100	kWh

Table 0-14: Silicon wafer PureCell™ system

Electric motor PureCell™ system [11]

Products		
Electric motor PureCell™ system[9]	8.31	kg
Resources		
resin glue	0.02	kg
Materials/fuels		
Steel cold rolled coil IISI	5.35	kg
Aluminum (primary) produced in the USA	0.14	kg
Aluminium 100% recycled ETH U PureCell™ system	0.14	kg
G-AlSi8Cu3 (380) I	1.45	kg
Copper ETH U PureCell™ system	1.13	kg
Wood board ETH U PureCell™ system	0.07	kg
Paint ETH U, PureCell™ system	0.01	kg
Electricity/heat		
Electricity avg. kWh USA	456	MJ

Table 0-15: Electric motor PureCell™ system

---

[9] Data for production of a 1 hp motor.

Aluminum (primary) produced in the USA [6]

Products		
Aluminum (primary) produced in the USA	1000	lb
Resources		
bauxite	5274	lb
crude oil FAL	507	lb
Materials/fuels		
Soda ETH U, adapted to USA	143	lb
Lime B250, adapted to USA	88.2	kg
Coal FAL	16.6	lb
Coal cokes U, adapted to USA	0.033	MJ
Gasoline FAL	0.2	gal*
Destillate Fuel Oil (DFO) FAL	2.98	gal*
Natural gas FAL	8606	cuft
LPG FAL	0.84	gal*
Residual Fuel Oil (RFO) FAL	26.8	gal*
Electricity/heat		
Electricity bauxite prod. FAL	0.83	kWh
Electricity alumina prod. FAL	95.5	kWh
Electricity anode production USA	53.9	kWh
Electricity alum. smelting FAL	699	kWh
Electricity alum. smelting FAL	95.8	kWh
Ocean freighter FAL	1754	tmi*
Diesel locomotive FAL	218	tmi*
Ocean freighter FAL	1755	tmi*
Diesel locomotive FAL	304	tmi*
Emissions to air		
CO2	1698	lb
CO	67.8	lb
CFC-11	0.121	lb
Cl2	0.0176	lb
fluoride	0.0192	lb
HCN	0.0368	lb
HF	0.645	lb
Pb	9.37E-06	lb
Hg	0.00004	lb
metals	1.45E-05	lb
methane	0.0622	lb
N2O	0.00196	lb
non-methane hydrocarbon (NMHC)	1.11	lb
organic substances	0.0111	lb
PAH's	0.151	lb

particulates (unspecified)	17.5	lb
perfluorpropane	0.382	lb
SOx	18.5	lb
COS	1.12	lb
Emissions to water		
acids (unspecified)	0.12	lb
NH4+	0.001	lb
BOD	0.057	lb
calcium ions	0.011	lb
Cl-	0.031	lb
COD	0.46	lb
cyanide	0.00021	lb
detergent/oil	0.00061	lb
chlorinated solvents (unspec.)	0.00021	lb
dissolved organics	0.014	lb
dissolved solids	0.28	lb
fluoride ions	0.061	lb
hydrocarbons (misc)	0.000014	lb
Fe	0.0033	lb
Pb	7.8E-06	lb
Mg	0.0021	lb
Hg	1.6E-06	lb
metallic ions	0.15	lb
nitrate	0.00096	lb
oil	0.039	lb
nitrogen	0.000013	lb
phenol	0.00018	lb
phosphate	0.000011	lb
Na	3.79	lb
sulphate	0.01	lb
S	0.00057	lb
suspended solids	0.4	lb
Final waste flows		
solid waste	2885	lb

Table 0-16: Aluminum (primary) produced in the USA

Platinum recycled PureCell™ system [13]

Products		
Platinum recycled PureCell™ system[10]	0.98	kg
Resources		
energy (undef.)	43700	MJ
Emissions to air		
SO2	0.207	ton

Table 0-17: Platinum recycled PureCell™ system

Activated carbon PureCell™ system [20]

Products		
Activated carbon PureCell™ system	650	ton
Resources		
coconuts	2000	ton
water	1800	ton
Materials/fuels		
Electricity avg. kWh USA	792	MJ
Nat. gas into industr. boilers	19069917	cuft

Table 0-18: Activated carbon PureCell™ system

---

[10] This process represents the energy used and SO2 emitted in the platinum recycling process. In this way platinum becomes a 98% 'lease' material rather than an input material.

Appendix E: PureCell™ System Life Cycle CO_2-equivalent Emissions and Energy Use

A disadvantage of the Eco-indicator 99 impact assessment method is that the midpoint results of the characterization step are hidden. The CO_2-equivalent emissions are therefore calculated using the PureCell™ system inventory data. For the CO_2-equivalent emissions only CO_2 and methane are taken into account. This assumption was validated by using other SimaPro impact assessment methods, which showed that CO_2-equivalent emissions for the PureCell™ system are practically entirely made up of CO_2 and methane emissions. The GWP (Global Warming Potential) characterization factor used dNote_Jaap.enl" path="H:\EndNote_Jaap.enl">EndNote_Jaap.enl<co-indicator 99 method.

Table 0-19 shows the CO_2-equivalent emissions (total as well as per kWh) for the PureCell™ system life cycle and for the three life cycle phases. The emissions per kWh are calculated by dividing the total emissions by 17,000,000. This is the number of kWh produced by the PureCell™ system over an 85,000 hrs lifetime.

	Total (kg)	**per kWh (g/kWh)**
Life cycle	11,610,992	683
Manufacturing phase	197,658	11.6
Use phase	11,412,900	671
End-of-life phase	434	0.03

Table 0-19: PureCell™ system CO_2-equivalent emissions

The energy use over the PureCell™ system life cycle is also hidden in the Eco-indicator 99 method. The three impact assessment methods in SimaPro that do show the energy use are Eco-indicator 95, CML 1992 and Ecopoints 97. All three methods show the exact same numbers for PureCell™ system energy use and they are therefore assumed to be consistent with the Eco-indicator 99 method as well.

Table 0-20 shows the energy use (total as well as per kWh) for the PureCell™ system life cycle and for the three life cycle phases. MJ LHV means that the energy use is calculated with the lower heating values of the fuels used.

	Total (MJ LHV)	**per kWh (MJ LHV)**
Life cycle	2.21E+08	13.0
Manufacturing phase	2.70E+07	0.16
Use phase	2.18E+08	12.8
End-of-life phase	-6.22E+05	-0.04

Table 0-20: PureCell™ system energy use

Appendix F: UTC Power South Windsor Electricity Mix

The electricity used at the UTC Power facility in South Windsor, Connecticut, is modeled in SimaPro as 'UTC South Windsor electricity mix'. The electric utility in Connecticut is NPCC, Northeast Power Coordinating Council. The grid electricity mix modeled in SimaPro is based on the Figure 0-1 below, showing the prospect for the grid in 2010.

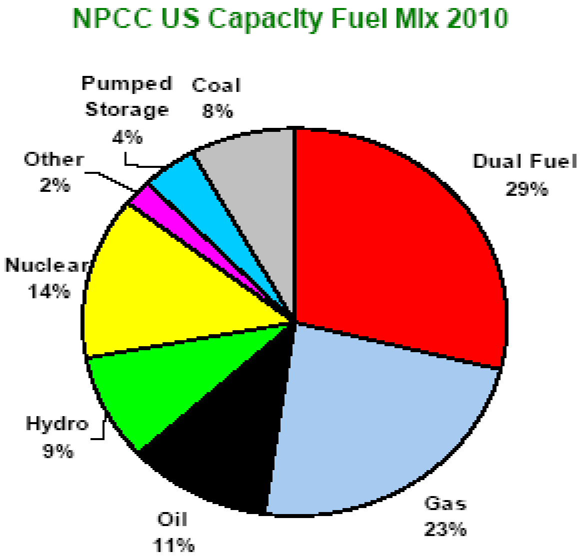


Figure 0-1: NPCC US projected capacity fuel mix – summer 2010

The percentage described as dual fuel is assumed to come from natural gas, since Connecticut (and other states in New England) relies primarily on natural gas.

Appendix G: Calculations for the PureCell™ System Hydrogen Consumption

In this appendix it is calculated how much hydrogen the PureCell™ system uses per hour, or in other words, how much hydrogen the PureCell™ system requires producing 200 kWh of electricity. The calculations are based on the electrical efficiency of the PureCell™ system, which is 40% [21]. The definition of electrical efficiency is:

$$\eta_{el.} = \frac{\text{electrical energy produced per mole of fuel}}{-\Delta \bar{\mathrm{h}}_f} \text{ [35],}$$

where $-\Delta \bar{h}_f$ is the enthalpy of formation, which is in this case the LHV (lower heating value) of hydrogen. The electrical efficiency is based on the LHV of hydrogen. The LHV of hydrogen is $-241.83\,kJ/mol$ [35]. With an electrical efficiency of 40% and a hydrogen LHV of $-241.83\,kJ/mol$, it can be calculated that the electrical energy produced per mole of hydrogen is

$$0.4 * 241.83kJ/mol = 96.732kJ/mol\,.$$

With this number the required moles of hydrogen per hour can be calculated:

$$\frac{200kW}{\left(\frac{96.732}{3600}\right)kWh\!\!\left/\!mol\right.} = 7443.2mol/hr\,.$$

Given that the molar mass of hydrogen (H_2) is 2.02 u this is equal to $7443.2mol/hr * 2.02u = 15.035kg/hr$. This number is used in SimaPro to model the hourly hydrogen consumption of the PureCell™ system.

Another way to determine the consumption of hydrogen is to use stoichiometric calculations. In this way the hydrogen output of the steam reforming process can be calculated. In Chapter 4 - Inventory Analysis the steam reforming and low shift reactions were used to calculate the CO_2 emission rate. The steam reforming and low shift reactions are:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \text{(steam reforming)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{(shift reaction)}$$

And this results in the following overall reaction:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

Based on the assumption that natural gas is 100% CH_4 it was calculated that the current PureCell™ system consumes $40.75kg/hr$ natural gas. This number was used to calculate a CO_2 emission rate of $112.2kg/hr$. The overall steam reforming reaction shows that four moles of H_2 are produced for every mole of CO_2. Given that the molar mass of CO_2 is 44 u and the molar mass of H_2 is 2 u it can be calculated that

$$\left(\frac{4*2}{44}\right)*112.2kg/hr = 20.4kg/hr$$

of hydrogen is produced by steam reforming of natural gas in the PureCell™ system. If this number is used to check the number obtained from the calculations based on the electrical efficiency of the fuel cell it becomes clear that the latter is significantly lower ($15.035kg/hr$). The main cause for this is most probably the assumption that natural gas is $100\% CH_4$. In reality, natural gas also contains small amounts of nitrogen and CO_2, which means that less hydrogen can be formed per kg of natural gas than is assumed here. Another cause for the deficit between the numbers calculated above is the idealized assumption that four moles of H_2 are formed for every mole of CH_4. The shift reaction as given above however is an equilibrium reaction which is never shifted completely to the right, which means that there is never a 100% overall reaction as shown above. In other words, the assumption that all carbon is emitted as CO_2 leads to an overestimation of the amount of produced hydrogen. Due to the fact that the shift reaction is never completely shifted to the right, a small amount of carbon will be emitted as CO. This also means that less hydrogen can be formed per kg of natural gas than is assumed here.

The calculations for the hydrogen production rate of the steam reforming process and for the hydrogen consumption rate of the fuel cell stack can be used to calculate the efficiency of the steam reforming process:

$$\eta_{SMR} = \frac{15.035}{20.4} = 73.7\%$$

In the SimaPro model of the PureCell™ system using renewable hydrogen the hydrogen consumption rate of $15.035kg/hr$ is used, as shown in Table 6-2.