

LETTER • OPEN ACCESS

The Chicago Center for Green Technology: life-cycle assessment of a brownfield redevelopment project^{*}

To cite this article: Thomas Brecheisen and Thomas Theis 2013 *Environ. Res. Lett.* **8** 015038

View the [article online](#) for updates and enhancements.

You may also like

- [The Impact of Participatory Planning Approach on the Quality Urban Design of Former Riverbank Brownfield Sites](#)
Zuzana Ladzianska, Vladimír Ondrejka, Silvia Ondrejikova et al.
- [How clean is clean: a review of the social science of environmental cleanups](#)
Keely Maxwell, Brittany Kiessling and Jenifer Buckley
- [Nature and city in sync: a study on the carbon sequestration potential of urban trees in a brownfield redevelopment in FTI Complex, Taguig City, Philippines](#)
J P M Guzman and N L Navarra



The Breath Biopsy[®] Guide
Fourth edition

FREE

DOWNLOAD THE FREE E-BOOK

BREATH BIOPSY

OWLSTONE MEDICAL

The Chicago Center for Green Technology: life-cycle assessment of a brownfield redevelopment project*

Thomas Brecheisen¹ and Thomas Theis

Department of Civil and Materials Engineering, Institute for Environmental Science and Policy,
University of Illinois at Chicago, 2121 West Taylor Street, Chicago, IL 60614, USA

E-mail: tbrech2@uic.edu

Received 3 December 2012

Accepted for publication 13 February 2013

Published 21 March 2013


Online at stacks.iop.org/ERL/8/015038

Abstract

The sustainable development of brownfields reflects a fundamental, yet logical, shift in thinking and policymaking regarding pollution prevention. Life-cycle assessment (LCA) is a tool that can be used to assist in determining the conformity of brownfield development projects to the sustainability paradigm. LCA was applied to the process of a real brownfield redevelopment project, now known as the Chicago Center for Green Technology, to determine the cumulative energy required to complete the following redevelopment stages:

(1) brownfield assessment and remediation, (2) building rehabilitation and site development and (3) ten years of operation. The results of the LCA have shown that operational energy is the dominant life-cycle stage after ten years of operation. The preservation and rehabilitation of the existing building, the installation of renewable energy systems (geothermal and photovoltaic) on-site and the use of more sustainable building products resulted in 72 terajoules (TJ) of avoided energy impacts, which would provide 14 years of operational energy for the site.

Keywords: sustainable brownfield development, life-cycle assessment, built environment, embodied energy, cumulative energy demand

 Online supplementary data available from stacks.iop.org/ERL/8/015038/mmedia

1. Introduction and purpose

The United States Environmental Protection Agency (USEPA) has defined a brownfield as 'real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a

hazardous substance, pollutant, or contaminant' (USEPA 2002). Many brownfield sites have the potential to become economically viable and host new businesses that create new jobs. However, some level of public assistance has often been required to achieve this potential, especially for sites that did not attract private redevelopers because the anticipated economic return on the investment did not justify the capital investment (Bartsch 1999).

Sustainable development of brownfields reflects a fundamental, yet logical, shift in thinking and policymaking regarding pollution prevention. Since it is believed that brownfields redevelopment is inherently more sustainable than conventional development, given the cleanup and reuse of land coupled with the creation of new economic



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](http://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

* Methodological note: data for this life-cycle assessment were obtained from project reports, construction blueprints and utility bills.

¹ Research assistance was provided by Kunal Dasai from the University of Illinois at Chicago.

opportunities, there is an increasing level of interest in designing brownfield projects that have sustainable characteristics. The conformance of various brownfield redevelopment practices to the sustainability paradigm is complicated by the many definitions of sustainability that have emerged since the Brundtland report. Given there is no universally accepted definition of sustainability, let alone a 'check list' of sustainable principles or practices, the evaluation of sustainability for complex brownfield redevelopment projects can approach the problem in an adaptive, relativistic manner through the comparison of redevelopment practices among multiple sites using a common set of indices in order to discern the *comparative directionality* (i.e. more or less sustainable) for alternative practices and outcomes.

Life-cycle assessment (LCA) is a tool that can be used to assist in determining the conformity of brownfield development projects to the sustainability paradigm. According to the Society of Environmental Toxicology and Chemistry (SETAC), the LCA is an objective process to evaluate the environmental burdens associated with a product, process, or activity. The LCA process is completed by identifying and quantifying energy and material usage, along with the associated environmental releases, in order to assess the impact of those energy and material uses and releases on the environment. The final stage of the LCA process is to evaluate and implement opportunities to effect environmental improvements. The LCA includes the entire life of the product, process, or activity, from the extraction and processing of raw materials; manufacturing, transportation and distribution; use, reuse, and maintenance; recycling; and final disposal (Bishop 2000). Generally speaking, LCA entails an iterative procedure that commences with initial scoping requirements that can be adapted later as more data become available (Goedkoop *et al* 2008).

The purpose of the LCA conducted for this brownfield redevelopment project was to determine the cumulative energy required to redevelop the brownfield, including all site preparation activities, environmental assessment and remediation activities, the rehabilitation of the existing building, and a full decade's worth of operational energy. Cumulative energy includes the sum of a building's operational energy and its embodied energy. Embodied energy is the sum of all energy required to produce a product (i.e. building product), including raw materials acquisition, processing and manufacturing, transportation and installation. The LCA conducted for this brownfield redevelopment project utilized acquired data, as opposed to theoretical or modeled data, and was intended to identify the most energy intensive life-cycle stage and estimate the avoided impacts associated with the preservation and reuse of the existing building in lieu of demolition and a newly constructed building.

2. Motivation

The world today is faced with serious environmental concerns over climate change, ozone depletion, waste accumulation and natural resource depletion. Of the many environmental

impacts of development, climate change has the highest profile. The emission of greenhouse gases (GHGs) is the result of the burning of fossil fuels, deforestation and land use changes. The largest contributor to greenhouse gas emissions is the built environment, which accounts for up to 50% of global carbon dioxide emissions and consumes 40% of the materials entering the global economy. Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for the production of various goods and services (Sharma *et al* 2011), including the construction, operation, demolition and disposal of buildings. LCA is a powerful tool for the evaluation of the environmental impacts of buildings and it has the potential to make a strong contribution to the goal of sustainable development (Khasreen *et al* 2009).

2.1. Prior LCA studies

Many LCAs have been conducted on residential and commercial buildings for a variety of purposes. Adalberth *et al* (2001) compared four multi-family buildings over a life-cycle of 50 years in order to determine which life-cycle stage had the highest environmental impact. The study found the occupation phase of the buildings' life-cycle accounted for 70–90% of the total environmental impact. Arpke and Hutzler (2005) used LCA to analyze the use of water in various multi-occupant residential and commercial buildings over a 25-year operational life-cycle. The results of this study found that the use of natural gas to heat the water would have resulted in an \$80 000 life-cycle savings over electricity. Scheuer *et al* (2003) performed a LCA on a six-story commercial building and found that the heating ventilation and cooling (HVAC) and electricity accounted for 94.4% of the primary energy consumption. Other studies have asserted that for conventional buildings in northern and central Europe, the life-cycle energy is distributed as 10–20% embodied energy for building products while 80–90% corresponds to energy consumption during the operational phase, and less than 1% is associated with end-of-life treatments and disposal (Kotaji *et al* 2003).

Sartori and Hestnes (2007) completed an analysis of 60 case studies from nine countries on buildings' life-cycle energy use. The study further evaluated the performance of 'low-energy' (i.e. energy efficient) buildings based on the definition of having an annual heating requirement less than 70 kWh m⁻² yr⁻¹. In all of the cases, the operating energy was the dominant life-cycle stage and a linear relationship between the operational energy and the total life-cycle energy existed. They pointed out that similar buildings in similar climates might also have very different characteristics in terms of primary energy because of the various energy carriers available for thermal purposes (i.e. natural gas versus electricity) or because of the various ways to produce electricity. For example, Norway uses 98% hydropower; Sweden relies on 49% nuclear and 44% hydropower. The United States uses approximately 50% coal, 19% natural gas, 19% nuclear, and 9% renewable energy (USEPA 2005).

Two studies that compared different versions of the same building (i.e. conventional versus low energy), showed that the amount of embodied energy used to construct a low-energy building was higher than the embodied energy required to construct a conventional building (Sartori and Hestnes 2007). One study (Winther and Hestnes 1999) analyzed six versions of a residential unit in Germany, while the other analyzed five versions of a residential unit in Norway (Feist 1996). However, only some of the buildings were actually built and several of the cases were hypothetical versions of the same buildings. Over a life-cycle of 80 years, it was estimated that with an incremental increase in initial embodied energy equivalent to about one year of operational energy, a low-energy building could be constructed that would result in a three-fold decrease in the total life-cycle energy. Therefore, it was concluded that the reduced operating energy demand was the most important aspect of designing buildings that are more energy efficient over their life-cycle (Sartori and Hestnes 2007).

By developing more energy efficient buildings, the percentage of life-cycle energy associated with building products is expected to increase (Kotaji *et al* 2003). The products required for buildings use great quantities of raw materials and also require large quantities of energy for processing. These materials selected for building construction also help determine the long-term energy consumption. Bribian *et al* (2011) evaluated the impacts of construction materials most commonly used in the building sector in comparison with different 'green' building materials based on the life-cycle assessment. The study highlighted some of the most energy intensive building products as steel, aluminum, copper, reinforced concrete, PVC and glass due to their high-energy consumption and raw materials in the numerous production processes that make up their life-cycle, especially aluminum, which has a higher electricity energy demand that increases its impact on the global warming potential. Wood products' primary embodied energy was mainly from biomass, which represented 69%–83% of the total primary energy demand since the processing energy for wood products is relatively low. The study concluded that it was important to harmonize existing inventory databases of construction materials to the characteristics of the construction industries in each country.

Jackson (2005) found that seven primary building components make up a building's embodied energy: wood, paint, asphalt, glass, stone and clay, iron and steel, and non-ferrous metals. Asif *et al* (2007) found that concrete accounted for 65% of the embodied energy for a residential building in Scotland. As improvements in the operational energy efficiency of buildings are made, the relative significance of embodied energy forms a higher proportion of the total energy over the life-cycle of the building (Yohanis and Norton 2002).

Peuportier (2001) developed a life-cycle simulation tool to compare three different single-family homes. Theoretical homes were compared on the basis of a LCA in terms of their overall energy consumption. The building materials data were based on published standards, and the energy consumption data were predicted using a thermal simulation tool. The

study indicated that many uncertainties and limitations were associated with data and indicators. The study suggested that the application of LCA to buildings was difficult and encouraged improvement of the assessment methodology.

2.2. Rationale for LCA research

Based on the cited literature, data availability has been an impediment in performing LCAs on buildings. There have been many impediments to the use of LCA for buildings and the main problems were the buildings themselves. The production process is complicated and the life-cycle is long with future phases based on numerous assumptions. Because there is little standardization within the building sector, there is a clear lack of data inventory. There is a need for the completion of a LCA based on actual as-built data such as construction blueprints and actual operational energy expenditures, as opposed to theoretical buildings based on published data and predicted energy consumption.

The United States Green Building Council (2009) in their post-occupancy study of LEED projects in Illinois concluded that 'a building's best benchmark is its own performance'. In that study, actual measured energy performances of buildings were compared to theoretical modeling results that were predicted according to ASHRAE 90.1 Standards. The study concluded that 'design models were not a reliable indicator of performance' (USGBC 2009). LCAs performed using actual building operational energy data would, at a minimum, narrow the level of uncertainty associated with LCAs based on theoretical energy modeling.

Among the cited literature, no studies could be compared directly because of differences in goal and scope, methodology, and data used. More studies have calculated the embodied impacts associated with building materials than the whole process of building construction and use and there is a need to conduct LCA studies to establish the effect of alternative materials on the energy performance of buildings. There is limited research published regarding complete LCA of buildings and there are no quantitative comprehensive LCA studies that included the assessment/remediation, construction, and operational phases of a brownfield redevelopment project.

3. Site history

The redeveloped brownfield site selected for analysis was the Chicago Center for Green Technology (CCGT), located at 445 N. Sacramento Boulevard in Chicago, Illinois. The site was an approximate 3.5-acre site improved with a rehabilitated two-story, 28 000 square foot (2600 square meter) building (the site) that received Chicago's first LEED (Leadership in Energy and Environmental Design) Platinum rating as a result of the efforts initiated by the Chicago Department of Environment. The CCGT is now renowned as an integrated model of energy efficiency and sustainable design (De Sousa and D'Souza 2012). The CCGT was a 'text-book' example of a brownfield as described in the following paragraph.



Figure 1. The undeveloped site (courtesy of city of Chicago).

The CCGT site was occupied since at least 1896 by Griffin Wheel Co., which was a foundry that manufactured railroad wheels. The site was later occupied by the Sacramento Crushing Corp. (SCC), which served as a construction and demolition (C&D) debris recycling facility dating back to at least 1952. In March of 1996, after the Chicago Department of Environment (CDOE) received multiple complaints regarding particulate emissions and dust created by the SCC, the Illinois Environmental Protection Agency (Illinois EPA) held a pre-enforcement conference, which cited the SCC with violations of the Illinois Environmental Protection Act and City of Chicago ordinances, including the illegal operation of a solid waste management facility without the proper permits. The pre-enforcement conference was held to establish corrective action activities and deadlines needed to bring the site into compliance with the pertinent laws. After minimal progress toward these objectives, the SCC filed for bankruptcy in 1997, and vacated the site. The City of Chicago then obtained the property by placing an environmental lien on it and began the removal of approximately 382 500 cubic meters of stockpiled C&D debris (Patrick 1999a, 1999b). A view of the undeveloped site is pictured in figure 1.

4. Environmental assessment and remediation

The assessment and remediation of the brownfield site required several investigations and the completion of multiple reports in a systematic, step-wise fashion. Prior to the environmental assessment of the site, the removal of over 382 500 cubic meters of illegally stockpiled C&D debris was required. Once the site preparation activities were completed, the environmental site assessments were performed.

4.1. Phase I Environmental Site Assessment

In April 1999, a Phase I Environmental Site Assessment (Phase I ESA) was conducted at the site in order to provide CERCLA liability protection to the purchaser. The Phase I ESA constituted appropriate inquiry into the previous ownership and uses of the site with the purpose of identifying

recognized environmental conditions (RECs). Based on the current and historic uses of the site, RECs are the presence, or likely presence, of any hazardous substance and/or petroleum products at the site under conditions that indicate an existing release, a past release, or a material threat of a release of any hazardous substances and/or petroleum products into structures on the property or into the ground, groundwater, or surface water of the property (ASTM 2005).

The Phase I ESA identified the former site use as a foundry dating back until at least 1896 with a former gas plant located adjacent to the site. It was speculated that the foundry and the gas plant co-existed to generate and purify coke oven gas and generate by-products of environmental concern such as: cyanide, sulfur, iron and heavy-end petroleum products like oils and tars. Visual evidence of an Underground Storage Tank (UST) was observed at the site and five historical UST permits were documented for the site. Therefore, the Phase I ESA concluded that a Phase II ESA was warranted (Patrick 1999a).

4.2. Underground storage tank removal

In June 1999, the UST was removed from the site. The UST was found to be 10 000-gallons (44 049 l) in capacity and was used to store heating oil for consumptive use on the premises. Soil samples were collected from the excavation floor and sidewalls and analyzed for benzene, ethylbenzene, toluene, xylenes (BETX), polynuclear aromatic hydrocarbons (PNAs), and heavy metals. The laboratory analytical results confirmed that a release occurred from this UST and the Illinois Emergency Management Agency (IEMA) assigned Leaking Underground Storage Tank (LUST) Incident No. 991583 to the site (Patrick 1999b).

4.3. Phase II Environmental Site Assessment

In July 1999, a Phase II Environmental Site Assessment (Phase II ESA) was performed to evaluate the RECs identified in the Phase I ESA for the objective of obtaining information regarding the nature and extent of potential soil and groundwater impacts. The results of the Phase II ESA were used to assist in making informed business decisions regarding the site, such as potential cleanup costs, as well as providing the site owner with information needed to satisfy the innocent purchaser liability defense under CERCLA (ASTM 2002). The results of the Phase II ESA revealed that certain PNAs and arsenic were detected at levels exceeding the allowable levels for industrial/commercial land use; however, the vertical extent of impacts was largely limited to the uppermost three feet of soil. A supplemental investigation was completed in August 2000 to delineate the full nature and extent of soil impacts that exceeded the most stringent criteria for industrial/commercial land use (ESE 2000a, 2000b).

4.4. Remedial Action Plan

After the full nature and extent of soil impacts was defined, the Remedial Objectives Report/Remedial Action Plan (ROR/RAP) was developed to outline the necessary steps to remediate the site and ensure there was not an unacceptable risk to human health or the environment. The ROR/RAP included a risk assessment and a recommended remediation technology to address the impacted soil. The risk assessment quantified risk by considering the toxicities of the detected contaminants and the exposure pathways for the receptors (ESE 2000b). Illinois EPA guidelines imposed maximum allowable risks for both carcinogens and non-carcinogens. The ROR/RAP was designed to ensure that any soil impacts did not pose an unacceptable risk to human health or the environment based on the proposed remediation technology. The ROR/RAP was submitted to the Illinois EPA for review and approval prior to its implementation.

4.5. Remedial action completion

Once the ROR/RAP was approved, the site remediation activities were executed. The remediation consisted of limited excavation and disposal of soil and the replacement with clean fill in the most severely impacted area of the site. Because the soil impacts were limited to relatively low levels of PNAs and metals, the majority of residual soil impacts at the site were managed in-place by construction an *in situ* cap, also known as an engineered barrier. The engineered barrier consisted of impermeable surfaces, such as the building foundation and the paved parking lots, and served to mitigate human exposure to the residual underlying impacts. A risk assessment was performed for the areas of the site that were not capped with impermeable surfaces, such as green spaces and a stormwater retention swale. The results of the risk assessment indicated the probability of cancer risk to humans from the residual soil impacts at the site was less than one in a million; thus, the excavation and disposal of these soils was not required.

The results of the remedial activities were compiled in a Remedial Action Completion Report (RACR). The RACR documented the volume of soil that was excavated and disposed from the site, or safely managed in-place. A Site Base Map was provided in the RACR to illustrate the location(s) of the impacted soil safely managed in-place, and the locations of engineered barriers required to mitigate human exposure to residual subsurface impacts (Harding ESE 2002). Upon review and approval of the RACR, the Illinois EPA issued the Comprehensive NFR Letter for the site, with an industrial/commercial land use restriction. The Comprehensive NFR Letter signified a release of further responsibilities of the Illinois Environmental Protection Act and was considered *prima facie* evidence that the site did not constitute a threat to human health and the environment.

5. Brownfield redevelopment and operation

Once the brownfield remedial action activities were completed, the site redevelopment activities began. Part of the

redevelopment involved the preservation and reuse of the existing building on the site. The building rehabilitation activities involved the improvement of the building envelope, the building interior, including new walls, new ceilings, floors, doors, paint, etc. A geothermal heating and cooling system, consisting of 28 vertical wells drilled to a depth of 200 ft and six high-efficiency heat pumps (45 ton cooling capacity (160 kW)), was constructed to provide 100% of the cooling and 90% of the heating requirements (IBC Engineering 2010). An approximate 970 square meter photovoltaic system was constructed, which was designed to provide approximately 136 500 kWh (490 000 MJ (megajoules)) of electricity annually (Building Green 2010). A 230 m² extensive green roof of low growing sedum was constructed to reduce the urban heat island effect (Zvenyach and Littman 2006). Four rainwater cisterns were installed to provide 12 000-gallons (53 900 l) of rainwater storage that was used to irrigate a 1-acre (4047 m²) stormwater retention swale and reduce runoff from the site (Farr 2000).

The site was redeveloped it into Chicago's first LEED-Platinum site. The CCGT site now serves as a government office building, training facility and resource center. The CCGT offers training and continuing education opportunities for architects and engineers as a certified provider for the Illinois Department of Regulation, and reports continuing education units (CEUs) to registered attendees of various seminars and courses. The redeveloped brownfield site became operational in June 2002. The building was serviced by renewable energy sources. A natural gas-fired furnace supplemented the geothermal heating and cooling system, and conventional electricity supplemented the photovoltaic system. The energy delivered by the geothermal and photovoltaic systems was not monitored; however, the natural gas and electricity purchased to supplement these systems was known.

6. Life-cycle assessment methodology

6.1. Scope and boundary

The LCA was performed on the site to estimate the CED required to perform the brownfield remediation activities, the building rehabilitation activities, and to operate the redeveloped site. Three primary life-cycle stages were analyzed: (1) brownfield assessment and remediation, (2) building rehabilitation and site redevelopment, and (3) the energy consumed during the operation of the site. The LCA boundary for the brownfield redevelopment project is shown on figure 2.

It should be noted that the recycling/disposal (of the building) life-cycle stage was not included in the scope because the building is still operational. Furthermore, the system boundary included the transportation of building materials to the site as well as the transportation of waste materials away from the site. The system boundary did not extend beyond the transportation of waste materials to their destination. For example, although a significant amount of the C&D materials removed from the site were recycled (De Sousa and D'Souza 2012), the scope of this LCA included

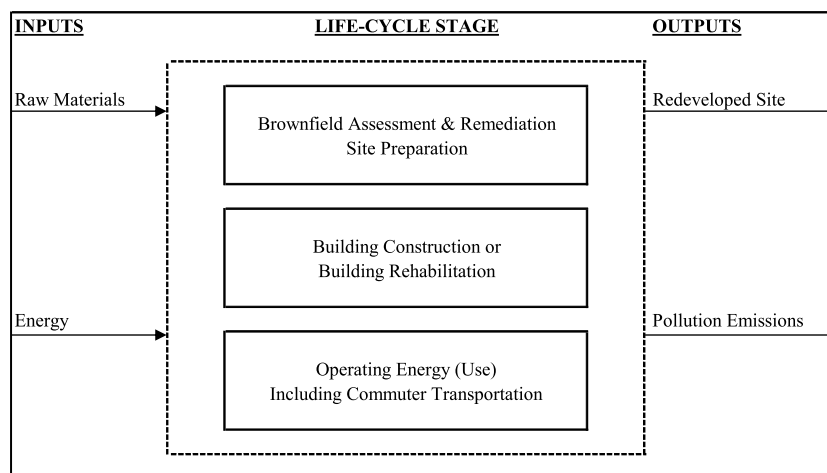


Figure 2. LCA system boundary.

only the removal of the C&D materials (excavation and trucking) from the site.

6.2. Tools

The SimaPro software package, Version 7.3.3 (Product Ecology Consultants 2012), was used to perform the CED calculations for the LCA. SimaPro included several databases; however, only the Ecoinvent and United States Input–Output (US IO) databases were used. The Ecoinvent database includes over 4000 datasets based on life-cycle assessment research in the following fields: energy, building products, chemicals, wood, metals, packaging and graphical paper, detergents, waste treatment services, transportation services, agricultural production systems, biofuels, electric and electronic equipment, pure chemicals, renewable materials, petrochemical solvents and metals processing (Frischknecht *et al* 2007).

The US IO database consists of a commodity matrix from 1998, supplemented with data for capital goods. The IO commodity matrix is linked to a large environmental intervention matrix. Environmental data have been compiled using several data sources: Toxic Releases Inventory 98 (TRI), Air Quality Planning and Standard (AIRS) data of the US EPA, Energy Information Administration (EIA) data of the US Department of Energy, Bureau of Economic Analysis (BEA) data of the US Department of Commerce (DOC), National Center for Food and Agricultural Policy (NCFAP) and the World Resource Institute (WRI) (Kellenberger *et al* 2007). Default materials and processes included within SimaPro’s databases were utilized as much as practical. Materials or processes that were not included within the SimaPro databases, such as a green roof, were created manually using data from alternate sources.

6.3. Data

6.3.1. Brownfield assessment and remediation data. Environmental brownfield assessment and remediation data

were collected manually through the review of technical environmental reports. The technical environmental reports described the activities that were completed in order to assess and clean up the site. The reports that were reviewed for the site included the aforementioned Phase I ESA, Phase II ESAs, ROR/RAP and RACR. These technical environmental reports were obtained from the Illinois EPA through a Freedom of Information Act (FOIA) request.

6.3.2. Building rehabilitation data. The City of Chicago provided the architect’s construction blueprints for the project. The construction blueprints were used to determine quantities of building materials needed for the rehabilitation of the site building. Typical information obtained from the review of construction blueprints included: the amount of steel framing, drywall, and drywall insulation needed to construct the interior walls, the square footage of glass needed for the interior and exterior windows, the number of new steel and wooden doors and the associated door frames, the square footage of various floor and ceiling finishes, the amount of paint needed to paint the interior walls, the external building finishes of brick or metal siding, external roof details, and other components. In addition, the origins of the building materials were provided thus enabling the transportation of the building materials to the site to be included in the analysis.

6.3.3. Operational energy data. The source of long-term building operational energy consumption was actual utility expenditures for natural gas and electricity, which were also provided by the City of Chicago. The City provided energy consumption data from July 2002, when the site became operational, through June 2012. Based on actual energy consumption data, the electricity and natural gas consumption for the site were known. The site’s long-term operational energy also included the commuter transportation impacts for the site building’s occupants.

The commuter transportation data were generated through the administration of a commuter transportation

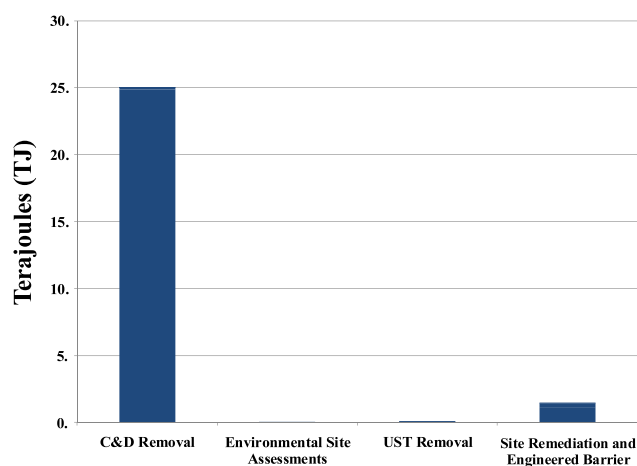


Figure 3. Energies required for brownfield remediation activities.

survey, which ascertained the number of trips an employee commutes to and from the site over the course of a typical year, the distance traveled to and from the building daily, and the mode of transportation used (i.e. driving alone, carpooling, bus, light rail, commuter rail, bicycle, walk) to commute to and from the building (USGBC 2011).

7. Life-cycle assessment results

7.1. Brownfield assessment and remediation

Based on a review of the environmental reports obtained for the site, the following activities were quantified.

- The excavation and removal of 382 500 cubic meters of C&D debris.
- The performance of the Phase I and Phase II environmental site assessments.
- The removal of one 10 000-gallon (44 409 l) heating oil UST.

- The excavation and disposal of 2450 cubic meters of soil, replacement with clean fill, and the construction of an engineered barrier and vegetated bioswale.

The collected data have been summarized in table A.1. The energies required for the brownfield assessment and remediation activities are illustrated in figure 3.

The cumulative energy demand associated with these activities was calculated to be 26.5 TJ (terajoules) and was distributed as shown above. Ninety-four per cent of the energy was required for the removal of the 382 500 cubic meters of C&D debris. The site remediation and engineered barrier construction accounted for 5% of required energy while the combined UST removal and site assessment activities required less than 1% of the energy for this life-cycle stage.

7.2. Building rehabilitation

Based on a review of the contractor's construction blueprints, the following activities were quantified.

- The rehabilitation of a 2600 square meter (28 000 square foot) two-story brick building.
- The construction of a 45 ton (160 kW) geothermal heating and cooling system.
- The installation of 1108 solar panels (970 square meters) to construct a photovoltaic system, which was designed to deliver 136 500 kWh (490 000 MJ) annually.
- The construction of a 2500 square foot (230 square meters) green roof.

The collected data have been summarized in table A.2 and the energies required for the brownfield assessment and remediation activities are shown in figure 4.

The cumulative energy demand associated with these activities was calculated to be 12.0 TJ and was distributed among several components of the rehabilitation activities as illustrated above. The external windows (and their associated wooden frames), the geothermal heating and cooling system,

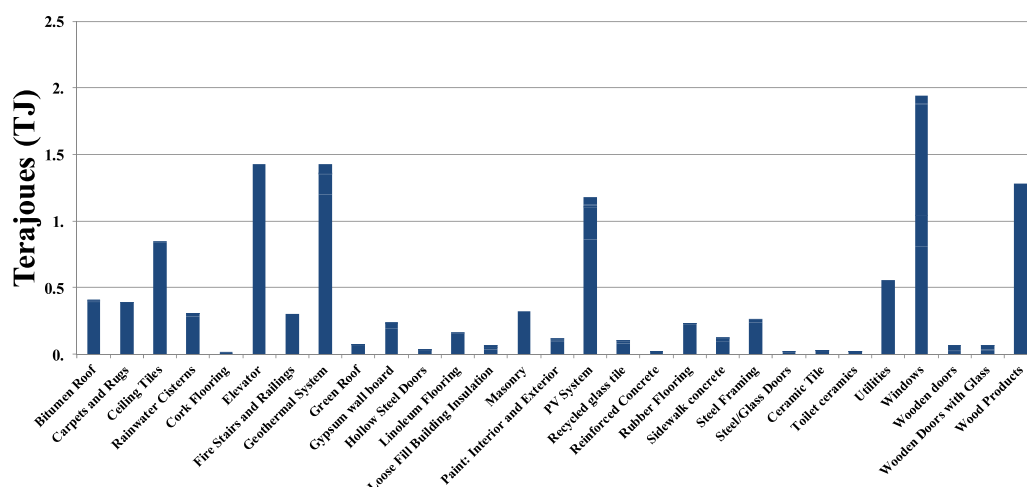


Figure 4. Embodied energies associated with building rehabilitation activities.

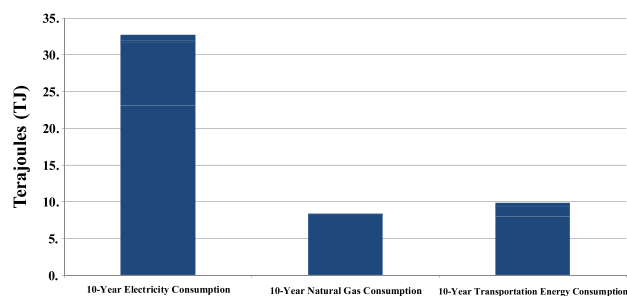


Figure 5. Energy required for 10 years of operation.

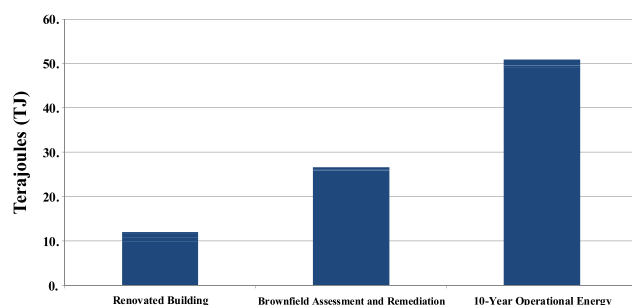


Figure 6. Life-cycle energy distribution.

the elevator, wood products, and the photovoltaic system accounted for approximately 60% of the embodied energy.

7.3. Operating energy

Based on a review of the energy consumption records and the data generated from the commuter transportation survey, the following activities were quantified.

- 10 yr electricity consumption.
- 10 yr natural gas consumption.
- 10 yr commuter transportation energy consumption.

The operating energy data have been summarized in table A.3. The cumulative energy demand associated with these activities was calculated to be 50.9 TJ and was distributed as shown on figure 5. Electricity consumption accounted for approximately 65% of the operational energy. Commuter transportation and natural gas consumption contributed 19% and 16%, respectively.

7.4. Comparison of life-cycle stages

An illustration of the energies required for each life-cycle stage is provided in figure 6.

The cumulative energy, including embodied energy and operational energy, for the brownfield redevelopment project totaled approximately 89.4 TJ after redevelopment and ten years of operation. After ten years of operation, the operating energy life-cycle stage contributed approximately 57% of the life-cycle energy for the brownfield redevelopment

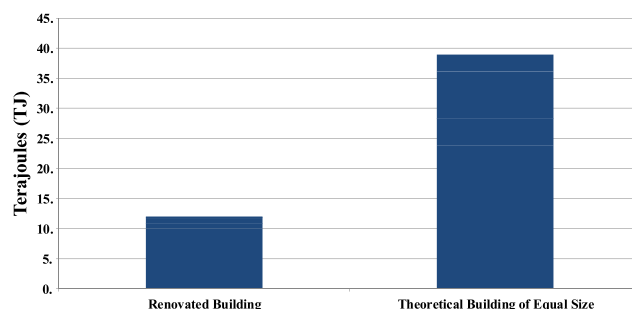


Figure 7. Comparison of renovated building to a theoretical new building.

project. This percentage will continue to increase with time and is expected to contribute 80–90% of the overall life-cycle energy at the end of the building's operational life (Kotaji *et al* 2003).

8. Discussion

8.1. Normalization

When normalizing the annual energy consumption on a square meter basis to determine the energy use intensity (EUI), the CCGT consumes approximately $601 \text{ MJ m}^{-2} \text{ yr}^{-1}$ ($53 \text{ kBTU ft}^{-2} \text{ year}^{-1}$). According to prior studies, the median energy consumption for commercial buildings in the Midwest is $1124 \text{ MJ m}^{-2} \text{ yr}^{-1}$ ($99 \text{ kBTU ft}^{-2} \text{ year}^{-1}$), and the median energy consumption from seventeen LEED certified projects in Illinois is $1067 \text{ MJ m}^{-2} \text{ yr}^{-1}$ ($94 \text{ kBTU ft}^{-2} \text{ year}^{-1}$) (United States Green Building Council 2009). Therefore, the CCGT has outperformed those benchmarks, presumably as the result of the geothermal and photovoltaic systems operating at the site.

8.2. Avoided impacts

Based on the preceding LCA for the rehabilitation of the existing building at the redeveloped brownfield site, the embodied energy of the building rehabilitation activities was compared to the embodied energy of a theoretical building of new construction, assumed to be the same size as the actual building. The theoretical building scenario included the most important materials used in a typical new building and their disposal, the transportation of the products to the building site and the final disposal at the building's end of life. The operational life-cycle stage was not included.

Based on the results of the CED calculations, the embodied energy of a new building, which simulated the demolition and disposal of the existing building followed by new building construction, was 39 TJ. The energy required to reconstruct a new building was over three times more than the energy required to rehabilitate the site's building (12 TJ). The results of the analysis have been shown graphically in figure 7.

The preservation and reuse of the existing building, which included the construction of both a geothermal and



Figure 8. Aerial view of the completed brownfield redevelopment project (courtesy of the city of Chicago).

a photovoltaic system, resulted in an avoided impact of approximately 27 TJ. Additionally, in lieu of conventional bituminous pavement (asphalt) for the site's parking lot, an emulsion, formulated from pine rosin and pitch in water, was used in order to reduce the urban heat island effect. The raw materials for the emulsion are by-products from the paper and pulp industry processes. The substitution of nearly 400 000 kg of bituminous pavement (4 in thick layer) with an estimated 10 000 kg of emulsified tar oil pitch resulted in an avoided impact of approximately 10 TJ. Supplementary material (available at stacks.iop.org/ERL/8/015038/mmedia) has been attached to provide intermediate data from the SimaPro software for the life-cycle assessment results described in sections 7.1, 7.2, 7.3 and 8.2 of this article.

9. Conclusions

The results of the LCA conducted for the CCGT have shown the operational energy is the dominant life-cycle stage after ten years of operation. For a more 'conventional' brownfield redevelopment project, the operating energy can be expected to be the most energy intensive life-cycle stage in less than ten years because conventional brownfield remediation does not typically involve the removal of 382 500 cubic meters of C&D debris over a year and a half. Second, irrespective of whether or not the sites were originally brownfields, the CCGT's operational EUI was only 54% of the median EUI for commercial buildings in the Midwest. Thus, for a conventional brownfield redevelopment project (in the Midwest) that did not include the installation of on-site renewable energy systems, the operational energy life-cycle stage could consume energy at nearly twice the rate of the CCGT ($1124/601 = 1.87$). At any rate, the long-term operational energy consumption for any brownfield redevelopment will likely be the most energy intensive life-cycle stage over a building life-cycle of 50–75 years.

Based on a comparison of the CCGT's EUI to the average EUI of commercial buildings in the Midwest, the CCGT avoided energy consumption impacts of 35 TJ because of its renewable (geothermal and photovoltaic) energy systems. Additionally, the preservation and rehabilitation of the existing building and the use of emulsified tar oil pitch instead of conventional asphalt avoided approximately 37 TJ of energy consumption. Between the preservation of the existing building and the reduced energy consumption at the site, 72 TJ of avoided energy impacts were calculated for the CCGT, which would provide approximately 14 years' worth of building and transportation operational energy for the site.

In October 2012, the site was recertified as LEED-Platinum through the USGBC's Existing Building Operation and Maintenance (EBOM) standard (USGBC 2012). A view of the renovated site, complete with its green roof, roof-mounted photovoltaic panels, and vegetated stormwater retention swale, has been shown in figure 8.

Acknowledgments

We would like to acknowledge the United States Environmental Protection Agency, who made this project possible through the issuance of a K6 grant (TR-83418401) to investigate the Best Management Practices and Benefits of Sustainable Redevelopment of Brownfield Sites. The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of the US Environmental Protection Agency. We would like to thank: Jenny Babcock, Bryan Glosik, Emma Peng, Steve Pincuspy, and Kelly Reiss of WRD Environmental, Stacey Munroe of the Chicago Department of General Services, and Kunal Dasai of the University of Illinois at Chicago.

Appendix. Life-cycle assessment input data

See tables A.1–A.3.

Table A.1. Summary of brownfield and remediation data. (Note: ‘tkm’ denotes ‘tonne-kilometer’, which is the work required to transport one tonne of material a distance of 1 km.)

Material or process	Quantity	Units	Description
(1) Construction and demolition debris removal			
Excavation hydraulic digger	382 500	m ³	C&D removal
Excavation skid-steer loader	382 500	m ³	C&D removal
Transport combination truck diesel powered	15 000 000	tkm	C&D removal
(2) Site assessments			
Diesel combusted in industrial equipment	75.7	l	Environmental drill rig
Passenger car	242	km	Engineer oversight transportation
Computer with monitor	60	h	Site assessment reporting
(3) Underground storage tank removal			
Diesel combusted in industrial equipment	56.8	l	Vacuum truck
40t semi	4 109	tkm	UST liquids removal
Excavator	589 550	kg	UST excavation
40t semi	76.7	tkm	UST removal transportation
Passenger car	105	km	Engineer oversight transportation
Computer with monitor	40	h	UST removal reporting
(4) Site remediation and engineered barrier construction			
Textile, woven cotton	500	kg	Geotextile for plant storage area
Gravel, crushed, at mine	695 111	kg	Gravel for plant storage area
Clay, at mine	1 540 909	kg	Clay for demonstration garden
Gravel, crushed, at mine	915 825	kg	Gravel for parking lot subbase
Clay, at mine	2 121 212	kg	Clay for Stormwater Retention Swale
Chemi-thermomechanical pulp, at plant	10 000	kg	Parking lot emulsion polymer
Truck 40t	57 477	tkm	Transportation of contaminated soil to landfill
Excavation, hydraulic digger	2 450	m ³	Excavation of contaminated soil
Truck 40t	13 429	tkm	Transportation of gravel backfill
Truck 40t	49 617	tkm	Transportation of clay backfill
Excavation, hydraulic digger	4 500	m ³	Site grading
Truck 40t	106 003	tkm	Transportation of site grading material
Truck 28t	12 360	tkm	Transportation of parking lot material
Excavator, technology mix, construction	383 838	kg	Construction of parking lot
Computer with monitor	500	h	Remediation reporting and project management

Table A.2. Summary of building rehabilitation input data.

Material or process	Quantity	Units ^a	Description
Bitumen adhesive compound, hot	7000	kg	Bitumen roof
Truck 40t	8126	tkm	Bitumen roof transportation
Carpets and rugs	15 625	USD	Carpet flooring
Truck 28t	507	tkm	Carpet flooring transportation
Mineral wool	27 851	USD	Ceiling tiles
Truck 28t	9130	tkm	Ceiling tile transportation
Galvanized steel sheet, at plant	8082	kg	Rainwater cisterns
Zinc coating, pieces	107	m ²	Rainwater cisterns
Truck 28t	22 563	tkm	Rainwater cisterns
Wood, cork oak	1	m ³	Cork flooring
Truck 28t	250	tkm	Cork flooring
Elevator	79 500	USD	Elevator
Architectural and ornamental metal work	21 015	USD	Fire stairs and railings
Borehole heat exchanger 150 m	12	p	Geothermal heating and cooling system

Table A.2. (Continued.)

Material or process	Quantity	Units ^a	Description
Heat distribution, hydronic radiant floor heating, 150 m ²	18	p	Geothermal heating and cooling system
Heat pump 30 kW	6	p	Geothermal heating and cooling system
Textile, woven cotton	40	kg	Green roof
High density polyethylene resin	344	kg	Green roof
Low density polyethylene resin	344	kg	Green roof
Grass seed IP, at farm	4	kg	Green roof
Excavation, hydraulic digger	37	m ³	Green roof
Truck 28t	1032	tkm	Green roof transportation
Gypsum plaster board	38 080	kg	Gypsum wall board
Truck 40t	3020	tkm	Gypsum wall board transportation
Steel hot rolled section	971	kg	Hollow steel doors
Zinc, from combined metal production	123	g	Hollow steel doors
Zinc coating, pieces	116	m ²	Hollow steel doors
Cellulose fiber, inclusive blowing in	25	kg	Hollow steel doors
Cold rolled sheet, steel, at plant	280	kg	Hollow steel doors
Truck 28t	603	tkm	Hollow steel doors transportation
Hard surface floor coverings, n.e.c.	7400	USD	Linoleum flooring
Truck 28t	956	tkm	Linoleum flooring transportation
Cellulose fiber, inclusive blowing in	6623	kg	Loose fill building insulation
Truck 28t	11	tkm	Loose fill building insulation transportation
Cut stone and stone products	26 351	USD	Masonry
Alkyd paint, white, 60% in H ₂ O	1873	kg	Paint: interior and exterior
Truck 28t	2114	tkm	Paint: interior and exterior transportation
Photovoltaic panel, a-Si, at plant	970	m ²	Photovoltaic system
Truck 40t	13 556	tkm	Photovoltaic system transportation
Packaging glass, white, at plant/RER U	3391	kg	Recycled glass tile
Ceramic tiles, at regional storage/CH U	2456	kg	Recycled glass tile
Truck 28t	2390	tkm	Recycled glass tile transportation
Pre-cast concrete, min. reinf.,	27 195	kg	Reinforced concrete
Polybutadiene	2227	kg	Rubber flooring
Truck 28t	2180	tkm	Rubber flooring transportation
Concrete, normal	85	m ³	Sidewalk concrete
Cold rolled sheet, steel	8628	kg	Steel framing
Truck 40t	430	tkm	Steel framing transportation
Steel hot rolled section	295	kg	Steel/glass doors
Zinc, from combined metal production	38	g	Steel/glass doors
Zinc coating, pieces	35	m ²	Steel/glass doors
Glazing, double (2-IV), $U < 1.1 \text{ W m}^{-2} \text{ K}^{-1}$, laminated safety glass	8	m ²	Steel/glass doors
Cold rolled sheet, steel, at plant	85	kg	Steel/glass doors
Truck 28t	176	tkm	Steel/glass doors transportation
Ceramic tiles	1775	kg	Ceramic tiles
Truck 28t	309	tkm	Ceramic tile transportation
Sanitary ceramics, at regional storage	460	kg	Sanitary ceramics
Truck 28t	80	tkm	Sanitary ceramic transportation
Other new construction	68 487	USD	Utilities
Window frame, wood	370.407	m ²	Windows
Glazing, double (2-IV)	297.135	m ²	Windows
Door, inner, wood	30	m ²	Wooden doors
Cold rolled sheet, steel	158	kg	Wooden doors
Truck 28t	1130	tkm	Wooden doors transportation
Door, inner, glass-wood, at plant/RER U	32	m ²	Wooden doors with glass
Cold rolled sheet, steel, at plant/RNA	171	kg	Wooden doors with glass
Truck 28t	1120	tkm	Wooden doors with glass transportation
Wood products	55 139	USD	Ornamental woodwork
Woodworking machinery	60 377	USD	Ornamental woodwork

^a Note: 'p' denotes 'piece'; 'USD' denotes 'US dollars'.

Table A.3. Summary of long-term energy consumption input data.

Material or process	Quantity	Units	Description
Electricity, medium voltage, at grid/US	9 204 743	MJ	Electricity consumption (10 yr)
Heat, natural gas, at industrial furnace	6 415 398	MJ	Natural gas consumption (10 yr)
Transport, bicycle	83 040	personkm	Commuter transportation (10 yr)
Transport, passenger car, petrol, fleet average 2010	1 853 920	personkm	Commuter transportation (10 yr)
Transport, regular bus	1 644 680	personkm	Commuter transportation (10 yr)
Transport, metropolitan train	1 306 570	personkm	Commuter transportation (10 yr)
Walking	86 850	km	Commuter transportation (10 yr)

References

- Adalberth K, Almgren A and Peterson E H 2001 Life-cycle assessment of four multi-family buildings *Int. J. Low Energy Sustain. Build.* **2** 1–21
- Arpke A and Hutzler N 2005 Operational life-cycle assessment and life-cycle cost analysis for water use in multi-occupant buildings *J. Archit. Eng.* **11** 99–109
- Asif M, Muneer T and Kelley R 2007 Life cycle assessment: a case study of a dwelling home in scotland *Build. Environ.* **42** 1391–4
- ASTM 2002 *ASTM E1903-02: International Standard Guide for Environmental Site Assessments: Phase II Environmental Site Assessment Process* (West Conshohocken, PA: ASTM International)
- ASTM 2005 *ASTM E1527-05: International Standard Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process* (West Conshohocken, PA: ASTM International)
- Bartsch C 1999 National lessons and trends *Brownfields—Redeveloping Environmentally Distressed Properties* ed H J Rafson and R N Rafson (New York: McGraw-Hill)
- Bishop P 2000 *Pollution Prevention Fundamentals and Practice* (Long Grove, IL: Waveland Press)
- Bribian I Z, Capilla A V and Uson A A 2011 Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential *Build. Environ.* **46** 1133–40
- Building Green Inc. 2010 *Case Studies: Chicago Center for Green Technology* (www.buildinggreen.com/hpb/overview.cfm?projectID=97, accessed 12 August 2010)
- De Sousa C and D'Souza L A 2012 *The Chicago Center for Green Technology: A Sustainable Brownfields Revitalization Best Practice* (www.uic.edu/orgs/brownfields/research-results/, accessed 30 November 2012)
- ESE (Environmental Science & Engineering, Inc.) 2000a *Additional Site Investigation Report, 445 N. Sacramento Boulevard Site—Front, Chicago, Illinois. ESE Project No. 559-9198.5104*
- ESE (Environmental Science & Engineering, Inc.) 2000b *Remedial Objectives Report and Remedial Action Plan, 445 N. Sacramento Boulevard Site—Front, Chicago, Illinois. ESE Project No. 559-9198*
- Farr Associates 2000 A-0.1 site plan, A-1.1, first floor plan, A-1.2, second floor plan, A-1.3 roof plan, A-1.4 roof mounted photovoltaic panels plan, A-2.1 building elevations existing, C-3.1 phase 1 grading plan, C-3.2 phase 2 grading plan *Midwest Center for Green Technology Job Number 9924.0*
- Feist W 1996 Life-cycle energy balances compared: low-energy house, passive house, self-sufficient house *Proc. Int. Symp. CIP W67 (Vienna)* pp 183–90
- Frischknecht R *et al* 2007 *Overview and Methodology (Ecoinvent Report No. 1)* (Dubendorf: Swiss Centre for Life Cycle Inventories)
- Goedkoop M, Schryver A D and Oele M 2008 *Introduction to LCA with SimaPro 7* (Amersfoort: PRe Consultants)
- Harding ESE, Inc. 2002 *Remedial Action Completion Report, Sacramento Crushing Site, 445 North Sacramento—Front, Chicago, Illinois. Harding ESE Project No. 559198*
- IBC Engineering Services, Inc. 2010 *Chicago Center for Green Technology, An Engineering Perspective* (www.ibcengineering.com/features/ccgt/p2.html, accessed 12 August 2010)
- Jackson M 2005 Embodied energy and historic preservation: a needed reassessment *APT Bull.* **36** (4) 47–52
- Kellenberger D, Althaus H-J, Jungbluth N, Kunniger T, Lehmann M and Thalmann P 2007 *Life Cycle Inventories of Building Products. Final Report Ecoinvent Data v2.0 No. 7* (Dubendorf: EMPA Dubendorf, Swiss Centre for Life Cycle Inventories)
- Khasreen M M, Banfill P and Menzies G F 2009 Life-cycle assessment and the environmental impact of buildings: a review *Sustainability* **1** 674–701
- Kotaji S, Schuurmans A and Edwards S 2003 *Life-Cycle Assessment in Building and Construction: A State-of-the-Art Report* (Raleigh, NC: Society of Environmental Toxicology and Chemistry (SETAC))
- Patrick Engineering, Inc. 1999a *Phase I Environmental Site Assessment for the Sacramento Crushing Yard, 445 N. Sacramento Blvd. located in Chicago, Illinois. PEI Project No. 8008 AO-13*
- Patrick Engineering, Inc. 1999b *Report of Underground Storage Tank Removal Activities at 445 N. Sacramento Blvd., Chicago, Illinois. PEI Project No. 8008.AO-12*
- Peuportier B L P 2001 Life cycle assessment applied to the comparative evaluation of single family houses in the french context *Energy Build.* **33** 443–50
- Product Ecology Consultants 2012 *SimaPro 7.3 Installation Manual* (Amersfoort: PRe Consultants)
- Sartori I and Hestnes A G 2007 Energy use in the life cycle of conventional and low-energy buildings: a review article *Energy Build.* **30** 249–57
- Scheuer C, Keoleian G A and Reppe P 2003 Life cycle energy and environmental performance of a new university building: modeling challenges and design implications *Energy Build.* **35** 1049–64
- Sharma A, Saxena A, Sethi M, Shree V and Varun 2011 Life cycle assessment of buildings: a review *Renew. Sustain. Energy Rev.* **15** 871–5
- USEPA (United States Environmental Protection Agency) 2002 *Small Business Liability Relief and Brownfields Revitalization Act. Public Law 107-118 (H.R. 2869)* (www.epa.gov/brownfields/overview/glossary.htm, accessed 19 September 2012)
- USEPA (United States Environmental Protection Agency) 2005 *Emissions & Generation Resource Integrated Database (eGRID)* (www.epa.gov/cleanenergy/energy-resources/egrid/index.html, accessed 30 November 2012)

- United States Green Building Council 2009 *Regional Green Building Case Study Project: A Post-Occupancy Study of LEED Projects in Illinois. Year One Report* (Chicago, IL: US Green Building Council—Chicago Chapter)
- USGBC (United States Green Building Council) 2012 *LEED for Existing Buildings. LEED Online™. Chicago Center for Green Technology EBOM. Project ID 1000007705*
- USGBC (United States Green Building Council and Center for Neighborhood Technology) 2011 *Regional Green Building Case Study: Year Two Report* (Chicago, IL: CNT Energy and the US Green Building Council—Illinois Chapter)
- Winther B N and Hestnes A G 1999 Solar versus green: the analysis of a Norwegian row house *Sol. Energy* **66** 387–93
- Yohanis Y G and Norton B 2002 Life-cycle operational and embodied energy for a generic single-storey office building in the UK *Energy* **27** 77–92
- Zvenyach L and Littman T H 2006 From Brownfield to sustainability showcase: Chicago Center for Green Technology *ASHRAE J.* **48** 20–30