Framework for Environmental Analysis of Residential Heating Systems

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To get a systematic assessment of a residential building heating system's environmental performance, the impacts that occur throughout the different stages of the system's life-cycle (raw materials acquisition and processing, construction, use, maintenance, and end-of-life) need to be identified and quantified. The environmental impacts that occur during the construction and end-of-life phases for heating systems are not well known. Once those impacts are known along with the impacts from the other building life-cycle stages, residential heating system designs could be evaluated for their environmental impacts, areas or processes of significant impact could be targeted for improvements, and alternate designs could be compared. This analysis is best performed using life cycle assessment (LCA) which identifies each component of a system (all resource input streams and potential emission or waste sources), and applies mass-balance calculations (where inputs equal outputs) to them. This paper focuses on an LCA framework for analysis of residential heating systems. The choice of study boundary, activity selection and detail, and direct vs. supply chain impacts are addressed. Process diagrams showing environmental impacts for the construction and end-of-life phases of gas-forced air and solar radiant floor heating systems are presented.

Keywords: Environmental impacts, residential construction, residential heating systems, life cycle assessment (LCA)

Introduction

The selection of a residential heating system is often made using cost-based criteria; either first cost or an energy efficiency rating showing the estimated annual energy costs. Both approaches share a common weakness; the exclusion of a life cycle perspective for environmental impacts. With environmental impacts occurring at every stage in a product's life cycle (raw materials acquisition and processing, construction, use, maintenance, and end-of-life), it is important to identify and quantify impacts from each of these stages. Once quantified, the life cycle environmental impacts can be evaluated in conjunction with life cycle costs for a more holistic decision making process for heating system selection.

Fossil fuel combustion is the largest source of Carbon Dioxide (CO_2) emissions and the United States (US) is the world leader in overall and per capita CO_2 emissions. In 2004 in the US, CO_2 (the dominant Green House Gas (GHG)) accounted for 84.6% of total GHGs with 21% coming from the residential sector (Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004, 2004). Heating systems are a major contributor to residential CO_2 emissions.

The Census Bureau estimates that there were 124.5 million homes in the US in 2005 (Cumulative Percent Change of Housing Unit Estimates for the United States and States Rankings: April 1, 2000 to July 1, 2005, 2006). With population expected to grow to an estimated 363.5 million by 2030 or, 63.5 million more than in 2006, 14.54 million new homes will need to be built based on an average family size of 2.5 persons (Interim Projections, 2005). The average annual CO_2 emissions for a single family home in 2001 were 11.3 metric tons/per year, an amount equal to the yearly output of 2.17 automobiles (Unit Conversion, Emission factors, and other Reference Data, 2004). Using this average, 164 million metric tons of additional CO_2 emissions per year would be generated if the estimated 14.54 million new homes are built, an amount equal to 31.5 million cars. Clearly there is opportunity for reducing residential CO_2 emissions by knowing the emissions from different types of residential heating systems. The overall objective of this paper is to create a framework that can be used to analyze the life cycle environmental impacts of residential heating systems. As examples, two heating systems are highlighted: gas forced air and solar radiant floor heat.

Method

Life cycle assessment (LCA) is a methodology that provides a systematic framework for the quantification of the environmental impacts of a product, process or system. LCA examines every identifiable stage in a product's life-cycle: raw materials acquisition and processing, manufacturing, use, maintenance, and end-of-life (Fava, Dennison, Jones, Curran, Vigon, Selke, and Burnum, 1991; Curran, 1996; Tiber & Feldman, 1996). LCA was developed and first used in the manufacturing industry. We will replace "manufacturing" with "construction" to better identify our adaptation of this methodology to the construction industry. There are three forms of LCA in use today: traditional process-based LCA, Economic Input-Output Life Cycle Assessment (EIO-LCA) and a hybrid approach that draws on the strengths of both process-based LCA and EIO-LCA.

Process-Based LCA

LCA methodology has been well defined by the International Organization for Standardization (ISO) and the Society of Environmental Toxicology and Chemistry (SETAC). ISO standards are used in this research since they are similar to the SETAC methodology (Azapagic, 1999). An LCA consists of three major steps each having its own ISO standard in the ISO 14040 series. The main elements of an LCA are: setting the goal and scope of the study and performing inventory analysis (ISO 14041), assessing the human impact of the environmental emissions (ISO 14042), and improving the product process through reducing environmental impacts (ISO 14043) (The ISO Family of Standards, Guides and Technical Reports-including drafts, nd.).

The goals and scope chosen for an LCA usually are in response to a question that is posed by an individual, group, or a governmental body (Curran, 1996). The scope also determines if the study will include all products in a group or a specific model. The boundaries of the study are then established to determine what is included and excluded from the model. For the inventory analysis, a mass-balance approach is used where system process diagrams are created and all the inflow and outflow streams of energy use, emissions, and waste are identified (Guggemos, 2003). Then mass-balance calculations (where inputs equal outputs) are applied to the system. Mass balance calculations are used to validate the unit process flows and may identify the presence of an unknown emission if inputs do not equal outputs (Hendrickson, Lave & Matthew, 2006). Once the energy use and environmental emissions are quantified through inventory analysis, the resulting data (impacts) are then used to determine the environmental impacts to human health (ISO 14042). Some of the common human health impacts are respiratory diseases, acid rain, and ozone. These impacts are then assessed to determine what product improvements may be possible to reduce these environmental impacts (ISO 14043).

Process-based LCA provides product-specific direct environmental impacts. The key strength of this type of LCA is a very detailed product specific process diagram supporting the inventory assessment. The traditional process approach is time consuming, data may be limited, and the boundary is tightly drawn limiting the scope of the study to a very narrow segment of the economy.

EIO-LCA

The use of input-output analysis enables inclusion of the environmental impacts of the supply chain using tools such as the EIO-LCA tool found at www.eiolca.net (EIO-LCA, 2006). EIO-LCA uses US economic industry data to evaluate average environmental impacts for each industry sector for a given dollar value of product. The EIO-LCA method uses aggregated economic data taken from the Department of Commerce North American Industry Classification System (NAICS) categories. The aggregation of data refers to the combining of several separate products into one industry category which may not provide the level of detail necessary for the environmental analysis of a single product. The strength of this type of data is that it expands the scope of the study to include the entire supply chain in the US economy, lowers time requirements to perform the analysis, and it can be preformed with an online tool.

Hybrid LCA

Process-based LCA identifies product-specific direct environmental impacts. EIO-LCA includes direct and supply chain impacts but only at an industry-average (rather than product-specific) level. While each tool has its relative strengths, using a combination of both tools in a hybrid approach provides the best information currently feasible in environmental analysis of product life-cycle impacts. EIO-LCA can be used for well-defined industry sectors with minimal product range. Process-based LCA will be used when more product-specific data is required to improve the accuracy of the assessment.

Process Diagrams

Process diagrams provide a detailed look at the activities and their associated environmental impacts for a particular process. As previously mentioned, the identification of inputs and outputs along with mass balance calculations provides some of the most reliable data relating to emissions throughout a product's life cycle. Some of the common impact categories are labor and material transportation, tool and equipment usage, energy usage, and material waste. The emissions can be liquid, solid, or gaseous and are identified on the process diagram. The energy use and emissions for all process activities are then aggregated into a total life cycle phase impact. Once the energy use and emissions are identified and quantified for each life cycle phase, the total environmental impacts for a product can be determined.

Results

Residential heating systems have five basic life cycle phases: raw material extraction and processing, construction, use, maintenance, and end-of-life. The environmental impacts of the raw material extraction and processing, use and maintenance stages can be analyzed using industry average supply chain data with EIO-LCA. The energy use and emissions from the construction and end-of-life stages of residential heating systems are not well known, are not addressed well by the existing NAICS industry categories used in EIO-LCA, and therefore would benefit from more product-specific data analysis through process-based LCA. This requires the creation of process diagrams for the construction and end-of-life phases for each type of heating system studied. The process diagrams identify which activities have impacts and what types of impacts occur. This information is used in an LCA to estimate the environmental impacts of energy usage, air emissions, and waste emissions. This combination of EIO-LCA and process-based LCA results in a hybrid LCA of heating systems.

Construction and End-of-Life Impacts

As previously noted, more information is needed to determine the environmental impacts of the construction and end-of-life stages of residential heating systems. Creating detailed process diagrams for these life cycle stages will provide more product-specific information for the identification and quantification of the energy use, environmental emissions, waste generation, and any other discharges into the environment that may take place in these two stages. The construction phase diagrams will identify the impacts that happen once the product leaves the manufacturer through the end of the construction process. The end-of-life stage begins once the use phase of the building is complete and includes dismantling and disposing of the heating system.

As examples, process diagrams for the construction and end-of-life stages for two different types of residential heating systems, gas-forced air and solar radiant floor, were created. Gas-forced air systems use a gas-fired heat exchanger to heat air which is then circulated through a duct distribution system to registers. Solar radiant heat uses piping in or under a floor system to circulate water heated in externally mounted solar collectors. The gas-forced air system is commonly used in many parts of the country and solar radiant floor systems are typically considered a specialized system design based on the solar radiance for a specific location. Heating systems were chosen for study since they are a common system in almost all residential construction and are a significant portion of the energy used and emissions generated by residential buildings when in operation during the use stage. Process diagrams for the construction and disposal of these two systems do not currently exist. While the creation of the diagrams are an integral part of the hybrid LCA approach to determine environmental emissions, they can also be used in construction planning and productivity improvement work.

Boundary Selection

In traditional process-based LCA, a boundary must be set to identify what steps in the process will be included in the analysis. All supply chain impacts are not included. At most, a few levels of the supply chain are included within the study boundary if they are critical to the phase. This is mostly due to lack of detailed data availability, cost, and time constraints. It is the direct environmental impacts that occur in the construction and end-of-life phases that the process diagrams identify for detailed study. The wide range of activities that take place throughout the construction and end-of-life stages of residential heating systems vary by job, labor force, technology, schedule, and any number of additional factors that could have an affect on the project. It is important to identify the main activities and a level of detail that will encompass the greatest amount of potential impact categories. There are several steps that can be taken to help identify the correct boundary of a study. For the creation of the process diagrams presented here, mechanical subcontractors and builders were consulted to determine the activities, equipment use, material use, and approximate activity durations for the gas-forced air and solar radiant floor systems. These diagrams were then compared to estimates completed using RS Means Residential Cost Data Book (Means, 2005) for the gas-forced air system and the RS Means Green Building: Project Planning & Cost Estimating (Means, 2002) for the solar radiant floor system. Means was used to validate the processes for systems installation not the prices of the systems. The information from the subcontractors and builders and the Means review was then compared to an expert's opinion concerning the activities involved in the construction process of the two heating systems. This triangulation of information increases the reliability of the boundary selection and process diagrams while providing critical productivity data that can be used to quantify environmental impacts.

A specific example of boundary placement for this study would be for the sheet metal for a gas-forced air system plenum. The sheet metal is manufactured at a mill and may be transported to a fabrication shop for final manufacturing into ductwork before being transported to the site for installation. The work at the mill would be considered part of the raw materials extraction and processing phase and would not be included in the construction phase while the transportation from the mill to the fabrication shop and the work at the fabrication shop would be considered part of the construction phase even though it occurs off site. Transportation of the workers to and from the fabrication shop to the site and installation at the site would also be included in the construction phase. Examples of supply chain impacts that would be outside the boundary of study would be the energy use and emissions generated from manufacturing the truck that transports the materials or the energy use and emissions generated from manufacturing the equipment that creates the ductwork. The boundary of study for the end-of-life phase depends on the final disposition of the system components: landfill or recycle. In either case, the demolition or deconstruction that takes place on site as well as the transportation to the landfill or the recycler would be included in the end-of-life phase. Any remanufacturing of recycled materials would be associated with creation of a new product and therefore would be outside the scope of this analysis.

Gas-Forced Air – Construction Phase

Figure 1 shows the process diagram for the construction related activities for the gas-forced air system and includes both on and off site activities. Each item on the diagram displays a code identifying the type of emissions related to that step. The off site activity System Design includes using system parameters to create the heating system design and perform heat loss calculations. The material transport from the manufacturer to the furnace contractor and to the jobsite is included in the construction phase boundary. Each transportation activity will be counted as a round trip in terms of energy use and associated emissions. The number of trips will be based upon truck capacity. Material Transport to the furnace contractor includes sheet metal that will be fabricated into ductwork at the contractor's shop as well as items that cannot be shipped directly from the manufacturer to the job site. The Fabrication Worker Transport and Installer Transport activities are also round trip and the number of trips is based on productivity and job duration. Fabricate Ductwork is performed by the furnace contractor at their shop before delivery to the site. Material Delivery to the site includes the ductwork plus all items that were sent to the furnace contractor. The final outcome of Place in Service is shown as a milestone for completeness but the energy use and emissions from this activity are outside the construction phase boundary and will occur during the use phase.

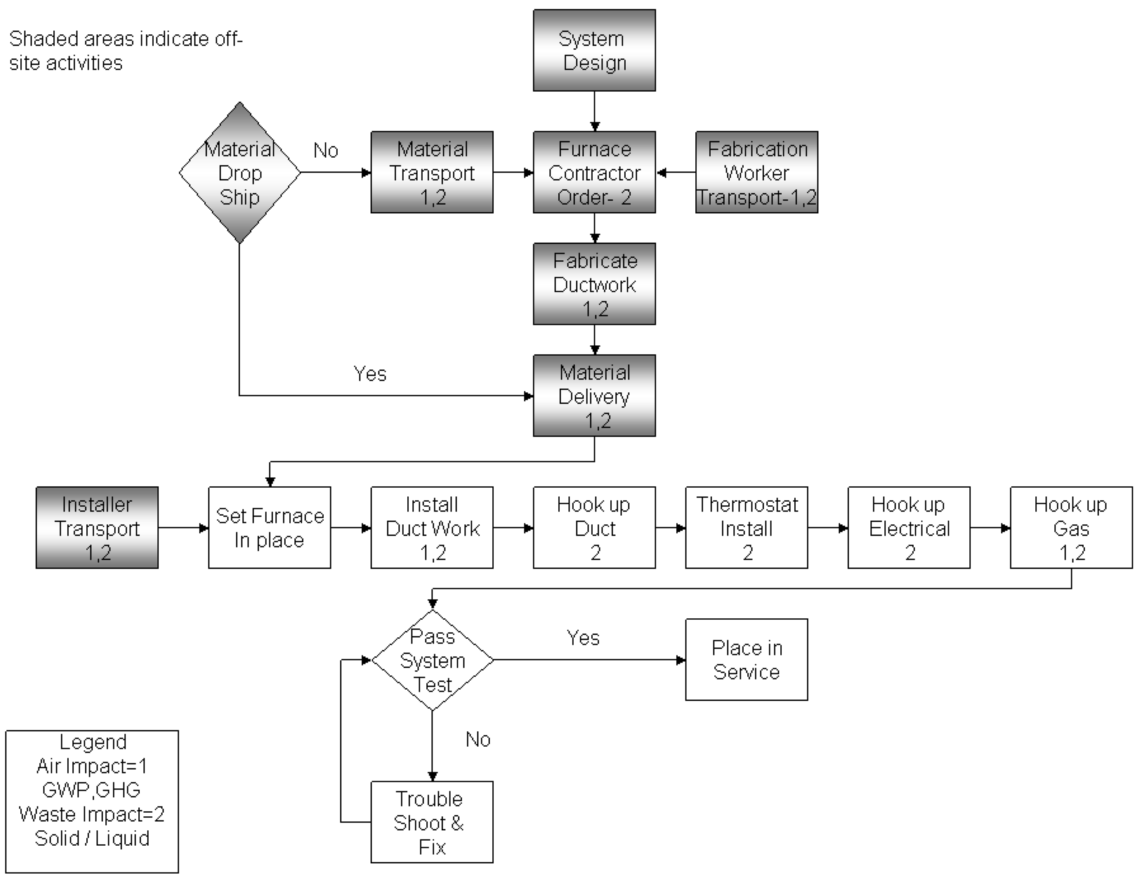

Figure 1: Gas-Forced Air Heating System Construction Phase Process Diagram.

Solar Radiant System – Construction Phase

Figure 2 shows the process diagram for the construction phase activities for the solar radiant floor heating system including both on site and off site activities. The on site related activities are included in the boundary and consist of testing, trenching and backfilling, assembly, and the commissioning process that instructs the home owner in the proper operation and maintenance of the heating system. The off site activity System Design includes heat loss calculations, and a choice of distribution system (i.e. in floor or staple up) based on the architectural design of the floors and occupant needs. The off site activity Material Transport to the furnace contractor and Material Delivery to the jobsite are included as round trips and the number of trips are determined by truck capacity. The term "Furnace Contractor" is used generically since in many cases, the same companies sell and install both gas forced air and solar radiant systems. The inclusion of the Furnace Contractor Order activity is to account for packaging waste, splitting up bulk shipments, and providing an office/shop for the installers. Installer Transport to the jobsite is included based on productivity and job duration on a round trip basis. Although the Pour Concrete Flatwork activity is included in the process diagram for completeness, the emissions and energy use are not included in the heating system LCA as the flatwork would be poured regardless of the heating system choice. The usage of tools and equipment to install this system generate emissions either from directly burning fossil fuel (i.e. for trenching equipment) or indirectly from using electricity to run tools or charge batteries to power hand tools. The milestone Place in Service is shown for completeness but the emissions and energy use from this activity would be included in the use stage and are therefore excluded from this phase.

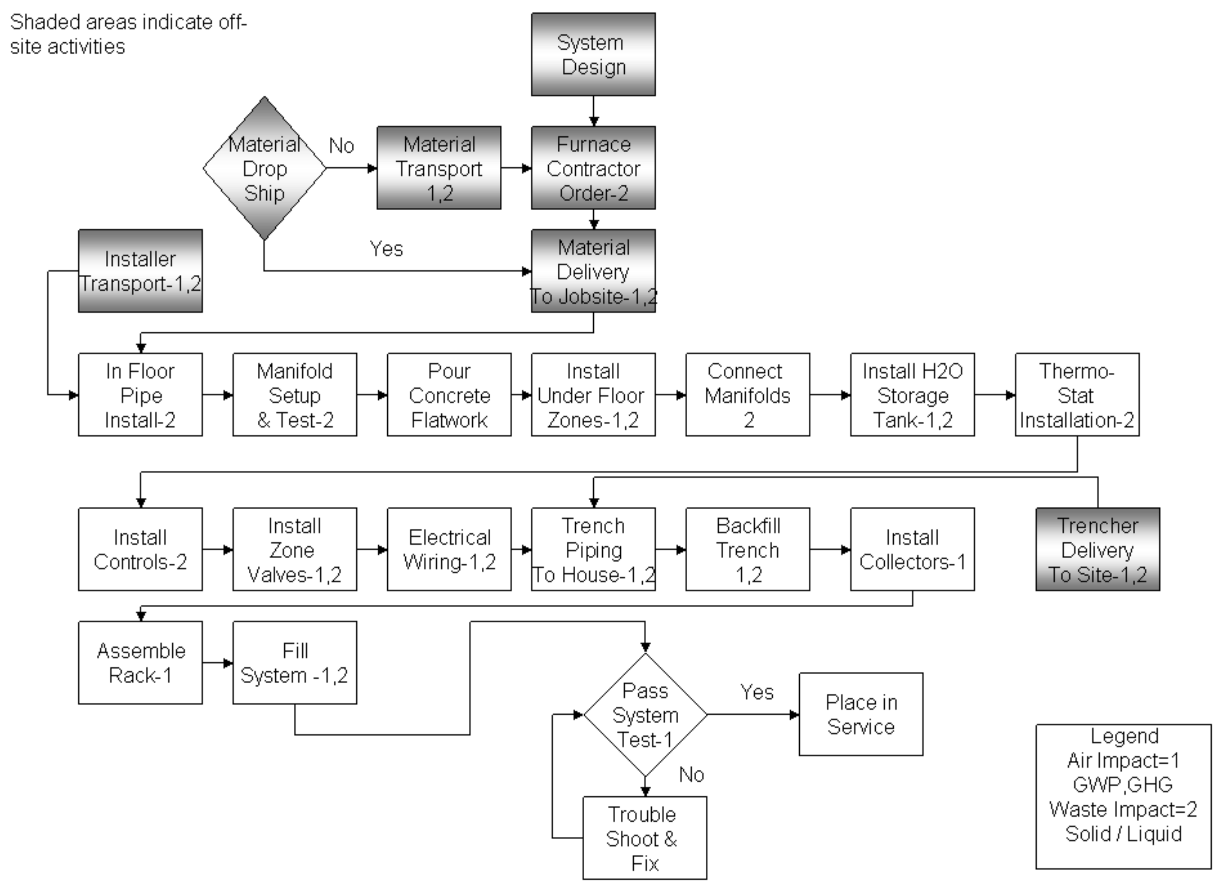

Figure 2: Solar Radiant Floor Heating System Construction Phase Process Diagram.

End-of-Life Phases for Gas-Forced Air and Solar Radiant Heat

Figures 3 and 4 show the end-of-life activities for the gas forced air heating and solar radiant floor systems based on the assumption that both the building and the heating system are at the end of their useful lives. The steps identified in these diagrams are based on current technology and demands for recycled materials. Acceptable items for recycling 30 to 50 years from now may vary significantly.

For both systems, Worker Transport to and from the job site are included as round trips. The energy and equipment use for demolition or removal are included and shown in the activities between Worker Transport and Recycle. For the gas-forced air system, disconnecting the electrical, gas, ductwork, and furnace removal will use power tools that are battery-operated or use electricity. Disconnecting the ductwork and removing the furnace will also create dust from these components. For the solar radiant floor system, the only tools required would be power tools that are battery-operated or use electricity.

For both systems, the user must decide if they will attempt to recycle all or part of the heating system. If no recycling is chosen, all materials will be delivered to a landfill unless subjected to mandatory disposal requirements. If recycling is chosen, several different recyclers may be used and there will still be some residual materials that cannot be recycled and will therefore still have to be sent to a landfill. Current practice allows for several components to be recycled. For both of the heating systems, the metal components, ductwork, collector frames, pumps, electronic controls, manifolds, furnace, and the electrical wiring can be recycled. The glycol water fluid mix from the solar system can be recycled through an automotive repair shop that does radiator service work. The solar collectors in most cases are sent to developing countries where they are considered new technology and used to provide hot water. The plastic piping may be reused depending on the care taken during deconstruction. If not reusable, it can be recycled. In the case where the materials are recycled for use in another product or process, the environmental impacts from the subsequent recycling process would be excluded from this study boundary. The assumptions for recycling are based on current recycling technology and demand for recycled products.

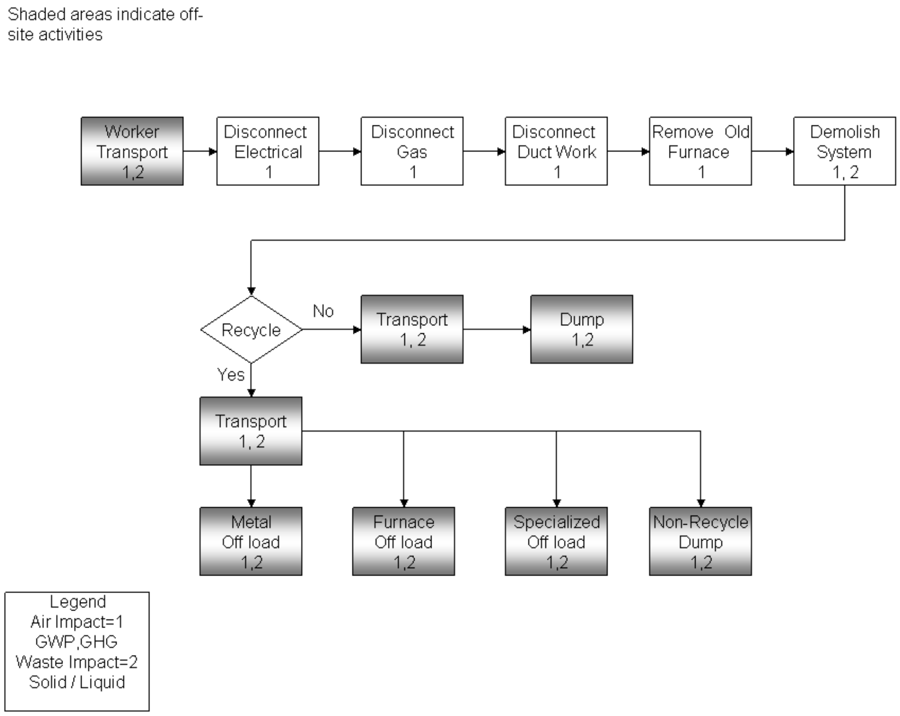

Figure 3: Gas-Forced Air Heating System End-of-Life Phase Process Diagram.

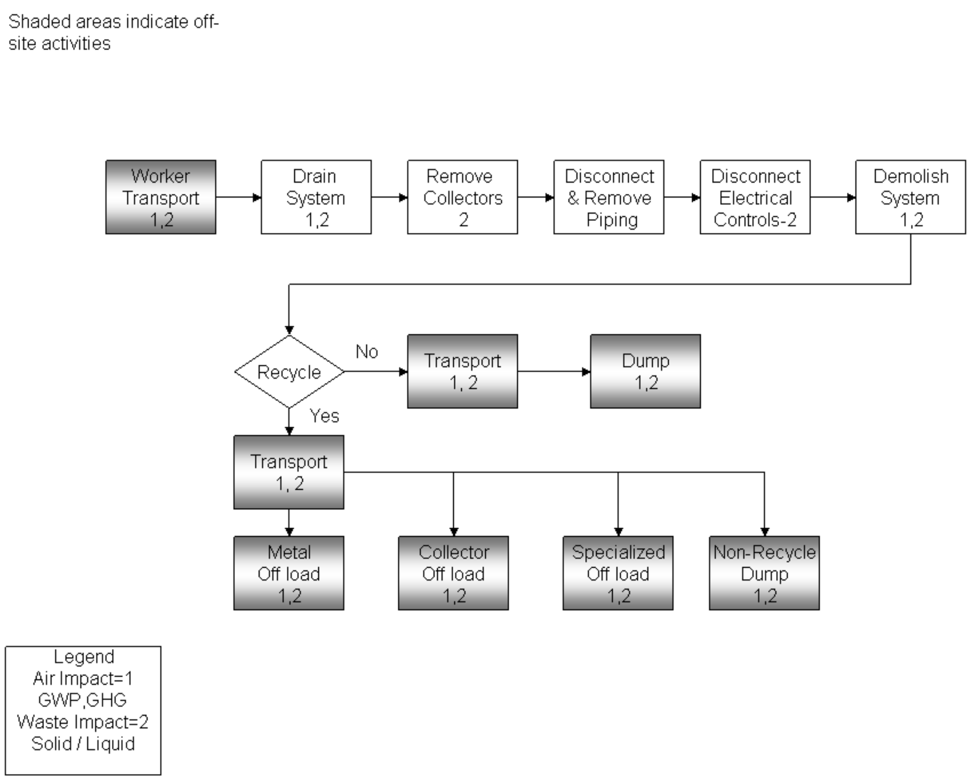

Figure 4: Solar Radiant Floor Heating System End-of-Life Phase Process Diagram.

Discussion

The successful use of a hybrid LCA approach to develop a framework for analyzing different residential heating system hinges on the proper identification of which life cycle stages of a residential heating system support the strengths of LCA and EIO-LCA when using the hybrid LCA model. For this paper we have identified the three stages which support the use of the aggregated economic data taken from the Department of Commerce NAICS categories: raw materials acquisition and processing, use, and maintenance. The construction and end-of-life stages cannot be accurately studied using this aggregated data and therefore need to be analyzed using the traditional process based LCA format requiring the development of product specific process diagrams. The creation of product specific diagrams for each of these stages ensures an accurate inventory. Following the development of the process diagrams is quantification of the environmental impacts from the construction and end-of-life stages and the integration of those findings into the overall environmental life cycle assessment of each heating system. This data can then be combined with the results of the EIO-LCA stages to form a complete and accurate hybrid LCA of a heating system. Once the environmental impacts of a heating system are known, the information can be combined with the results of a life cycle cost analysis to produce a decision support tool with a goal of balancing both environmental and cost concerns, a more holistic residential heating system selection process.

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