# CRITICAL REVIEW OF LCA TREATMENT OF FEEDSTOCK ENERGY

## Final Report to the National Asphalt Pavement Association (NAPA)

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**July 2017**

**ACKNOWLEDGEMENT** This project was funded jointly by the National Asphalt Pavement Association and the State Asphalt Pavement Associations.

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## EXECUTIVE SUMMARY

This final report to the National Asphalt Pavement Association is a critical review of LCA treatment of feedstock energy. The first section is the Introduction in which Life Cycle Assessment (LCA), Environmental Product Declarations (EPDs), Product Category Rules (PCRs), Feedstock Energy, Allocation in LCA and the Research Questions are introduced. The second section is the Literature Review, including a Literature Synthesis on Energy Definitions and a Literature Synthesis on LCAs and EPDs (and PCRs) in Practice. The third section then analyzes the consistency in definitions relating to feedstock energy and other related energy terms, and then the consistency in reporting of energy use in various sectors. This is followed by summary conclusions and a section providing suggestions for schemes that might better handle some of the unique life cycle characteristics of asphalt, particularly its high recyclability and its stored energy (feedstock energy) and carbon.

Although there may be some consistency in various definitions of the energy terms, there is little consistency in how they are reported and/or compiled in EPDs and PCRs. Some reviewed documents include it in a material balance, while others in an energy balance. With both options being used without harmonization, the possibility for *double counting* exists. In addition, the storage component of the carbon cycle and the energy storage characteristics are not well addressed in many sources.

The preliminary conclusions are that EPDs are not currently harmonized or understood well enough to be required to be used for comparative material selection in this industry. The main reasons are that there are (1) inconsistencies in terminology, (2) the reporting of depletion versus use of energy may have different interpretations and therefore result in different conclusions of impacts, (3) there might be double counting of some items such as feedstocks as an energy and/or a material item, and (4) EPDs are typically not presented in a format that differentiates to the user or decision-maker how the various terms and quantities might be interpreted as positive and/or negative impacts such as with respect to recyclability. In addition, (5) there are few EPD methods that facilitate life cycle carbon counting when carbon is stored in a feedstock.

Thus, this report is suggesting that the asphalt paving industry might consider the following approach for EPDs, to be consistent with EN 15804 (BS EN 2012), and capture the unique energy and carbon characteristics of the use of asphalt in pavements.

- Requiring the reporting of Modules A1-A3 (Product Stage) <u>and Module D</u> (Benefits and loads beyond the system boundary) in both the impact and the use tables.
- Using the term *depletion of abiotic resources – fossil* in the impact table and the term *use of non-renewable primary energy as a material* (or something similar) in the use table, but also noting that feedstock energy is another term for this energy resource used as a material for clarification.
- For consistency defining Total Primary Energy or Cumulative Energy Demand (CED) to include feedstock energy, but requiring that the breakdown of how much is used as energy, and how much as material, are always included when reporting these totals.
- Defining embodied energy to not include feedstock energy.
- Including carbon equivalents of the carbon stored in the asphalt in Modules A1-A3 and Module D in the impact table.
- Considering the inclusion of Modules B3 or B4 (as applicable) and basing the analyses on functional units instead of declared units for life cycle assessments for in-place recycling, or a similar cradle-to-grave type reporting.

# 1. INTRODUCTION

## 1.1. LCAs, EPDs and PCRs

Life cycle assessment (LCA) is a methodology for quantitatively estimating the potential impact that a product or process may have on the environment over its lifetime. LCA usually relies on tracking uses of resources and emissions of substances throughout the product's life cycle, by tracing the processes involved in producing, using, and disposing of the product. Recent publications on decision-making in the transportation sector include environmental performance as an important indicator for transportation planning (Sinha and Labi 2011, Middleton and Regan 2015). The use of this methodology has been gaining momentum in private and public spheres (Simonen and Haselbach 2012, Ngo 2012).

Similarly, environmental product declarations (EPDs) are reports which present the results of an LCA or multiple LCAs on a product to a certain gate, such as prior to use, along with other relevant information, in a condensed and digestible format. Rules for creating an EPD for each specific product category type are laid out by various third parties in product category rules (PCRs). Those rules tend to be focused on more micro-scale details than the general requirements for LCAs or EPDs. These rules are made for a specific industry sector and product category, hence the name.

The LCA methodology is based on the ISO 14040 and ISO 14044 (ISO 2006a, ISO 2006b) standards. Similarly, EPDs are based on ISO 14025 (ISO 2006c). An LCA covers the entire life cycle of a product, process or system, whereas an EPD uses LCA methodology to a certain point of declaration (gate) such as after product manufacturing or system installation, but usually prior to use. LCA characterizes potential impacts on the environment based on a set of selected environmental impact categories. ISO 14044 requires a comprehensive set of impact categories to be considered. Many of the impact categories in LCA are characterized based on probable midpoint or endpoint effects. Midpoint effects are those occurring as a direct result of the environmental burden, such as an increase in global average surface temperature tied to greenhouse gas emissions. Endpoint effects are the damages to human health, the environment, and resources caused by the midpoint impacts, such as rising sea level with increased surface temperature. However, some impact types, such as water and energy use, are most frequently inventory-based.

## 1.2. Feedstock and Other Energies

ISO (2006a) defines feedstock energy as the "heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value". Various other industry groups and academic papers describe feedstock energy in essentially the same way (Yaros 1997, PlasticsEurope 2016, Sartori and Hestnes 2007). In the case of asphalt, bitumen is a fossil fuel with energy content that could be directly combusted or upgraded to lighter fuels for combustion (Santero et al. 2010), or of course remain as a material component. Several authors have discussed the appropriateness of including feedstock energy in cumulative energy demand (CED), with some questioning whether it should be included for all products regardless of system-wide implications (Ventrua and Santero 2012, Santero et al. 2010, Butt 2012).

ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) do mention feedstock energy and that it should be included in a LCA. However, according to this project's interpretation this implies a full LCA from cradle-to-grave, not necessarily a cradle-to-gate analysis. ISO 14040 also noted in the definition of feedstock energy that "care is necessary to ensure that the energy content of raw materials is not counted twice". Unless carefully crafted, many EPDs and other environmental reporting documents may count the energy content of materials that could be either used for energy or for materials, such as asphalt, twice. It is with these concerns in mind, that this report carefully reviews various documents and makes suggestions for the future to not have double counting occur.

Note that in many documents, the equivalent of feedstock energy is referred to as "Use of non-renewable primary energy used as raw materials" or "Use of renewable primary energy resources used as raw materials", depending on the source. This provides an opportunity to separate out these items, the danger is in totaling energy and material use without noting if those resources used as materials with energy content have been included in either category or both. Highlighted in Table 1.1 from *BS EN 15804—2012 Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products*, are examples of this terminology (BS EN 2012). The FUn in Table 1.1 refers to functional unit, and the DUn refers to declared unit.

Table 1.1. Parameters Describing Resource Use (BS EN 2012).

| **Parameter** | **Unit (expressed per FUn or DUn)** |
|---|---|
| Use of renewable primary energy excluding renewable primary energy resources used as raw materials | MJ, net calorific value |
| Use of renewable primary energy resources used as raw materials | MJ, net calorific value |
| Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials) | MJ, net calorific value |
| Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials | MJ, net calorific value |
| Use of non-renewable primary energy resources used as raw materials | MJ, net calorific value |
| Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) | MJ, net calorific value |
| Use of secondary material | kg |
| Use of renewable secondary fuels | MJ, net calorific value |
| Use of non-renewable secondary fuels | MJ, net calorific value |
| Net use of fresh water | $m^3$ |

Energy use is not straightforward, and could therefore be defined and treated differently by different LCA practitioners. Further complicating definitions is the question whether any given substance should be treated as an energy resource. Simonen (2014) says *sound judgement is required by the LCA practitioner* when deciding how to treat substances as energy or material resources. Simonen uses crude oil as an example, where it could count as an energy resource if combusted, or a material if used as plastic (both quantified in MJ).

### 1.3. Allocation in LCA

Life cycle assessments often include situations where it is not clear to what product systems the impacts from various processes or components should be assigned. Two common situations are recycling/reuse and processes with co-products (Klöpffer and Grahl 2014). In recycling/reuse, the final life cycle stage of one product is the same process as the first life cycle stage of another. To which system should the impacts of that process be assigned? In co-products, a single process creates more than one usable product. How much of the impact of that process should be assigned to each co-product? There is no standardized process for deciding how allocations should be made. For recycling some of the common methods include the 50/50 method, recycled content method, and end-of-life method (Allacker et al. 2014); for co-products, allocation might be by energy, mass, volume, or economic value (ISO 2006b). Feedstock materials complicate the allocation issues even more with their availability as either a material or energy resource, or a combination of both.

### 1.4. Research Questions

The following questions are sought to be answered by this research:

1. Are ISO requirements for feedstock energy allocation consistent with definitions of *energy use* from standards and regulatory groups?
2. Is the reporting of energy use in the pavement sector consistent with other sectors?
3. What impact does the feedstock energy captured in asphalt have on the carbon cycle (including appropriateness of the allocation scheme currently required, consideration for end-of-life, and carbon intensity of bitumen)?
4. How might the standards be amended or clarified to better represent the actual consequences of feedstock energy contained in the asphalt pavement?

## 2. LITERATURE REVIEW

This section presents an overview of many issues found related to energy definitions from a literature review and inventories energy definitions used in LCA and other standards. Embodied energy, energy demand, and energy content refer to various types of energy (energy needed to produce the product, energy used over the entire product life cycle, and energy contained when the material is combusted, respectively). Additional terminology with respect to which types of energy, and at what point in the energy chain, were included in the inventory such as fossil energy, renewable energy, cumulative energy demand, secondary energy demand, and net energy balance.

### 2.1. Literature Synthesis on Energy Definitions in Standards

This first part of the review is provided to describe the use of feedstock energy in life cycle assessments (LCA) as per the ISO standards as revised in 2006. It provides some insight into how this quantity is expected to be used. The two standards are ISO 14040 (2006a) and ISO 14044 (2006b).
The first step is to determine the definition of the terminology used in this analysis. The definition of *feedstock energy* is provided in Section 3.14 of ISO 14040 (and repeated in ISO 14044) as the following:

> *'heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in the terms of higher heating value or lower heating value. NOTE: Care is necessary to ensure that the energy content of raw materials is not counted twice.'*

This is followed by the definition of a *raw material* in Section 3.15 of ISO 14040 (and repeated verbatim in ISO 14044) as:

> *'primary or secondary material that is used to produce a product. NOTE Secondary material includes recycled material.'*

Therefore, the standards imply that when a raw material is used that has an energy content which could be used for energy, but is not used for energy in the product or process system, then the heat of combustion of that material can be reported as the feedstock energy for the input. Then the requirements for energy inputs and outputs are further set by ISO 14044 in Section 4.2.3.3.2 in that they:

> *'shall include inputs and outputs relevant for the production and delivery of fuels, feedstock energy and process energy used within the system.'*

Thus, ISO 14044 has further stated that feedstock energy shall be included for relevant inputs and outputs from the system. And, in the general section (4.3.3.1) that;

> *'combustible material can be transformed into an energy input or output by multiplying them by the relevant heat of combustion.'*

And finally, ISO 14044 cautions about the *risk of misunderstanding* such as with double counting in Section 4.3.2.1 and that allocation should be avoided *wherever possible*, such as by expanding the product system to avoid allocation. In the case of asphalt pavement, the asphalt is therefore typically recorded as an input in feedstock energy terms (i.e. combustible material not used for energy), but in an expanded system could also be then removed from the system in energy terms at the end-of-life.

*ASTM E2114-08 Standard Terminology for Sustainability Relative to the Performance of Buildings* has a definition of embodied energy, which is not inclusive of feedstock energy (ASTM 2008). This is contradictory with some of the interpretations prevailing in the pavement sustainability arena (Butt et al. 2014). In addition, the recently published report by US FHWA entitled *Sustainable Pavements Program Road Map* (FHWA-HIF-17-029) does not contain any mention of feedstock energy (US FHWA 2017). However, this Road Map does reference another document available for download from the FHWA. It is *Pavement Life Cycle Assessment Framework*, FHWA-HIF-16-014 in which it says that feedstock energy should be included, but not necessarily where or how to include it (US FHWA 2016). It should be noted that tracking feedstock as material with units of energy (kJ) is a possible alternative, and is very common in many LCAs and the literature under abiotic resource depletion (fossil fuel) (NSF International 2014).

Various definitions of the energy terms are compiled from the standards and glossaries mentioned in Appendix A, Table A.1. A full table of these energy definitions; including feedstock energy, renewable and non-renewable resources, energy recovery, cogeneration, embodied energy, energy flows and input-output terms; is provided in Appendix A, Table A.2.

### 2.2. Literature Synthesis on LCAs and EPDs in Practice

Distinct from official definitions of the energy terminology is the question of how that terminology is interpreted and applied in published studies. Stakeholder considerations can drive important methodological decisions in life cycle assessment (Choudhary et al. 2014). Therefore, it is reasonable to imagine that there may be variability in how energy definitions are interpreted and applied by various industries. Consideration should be given to the practices of many industries to learn if there is consensus on how these definitions are applied in studies. It is reasonable to imagine that there may be variability in how energy definitions are interpreted and applied by various industries. There may also be variability in how the information is presented in EPDs. EPDs are typically developed based on Product Category Rules (PCRs). PCRs are developed by various industries so that the EPDs from that industry have a similar basis and are determined using a similar methodology. However, there is currently no official harmonization of PCRs, and therefore EPDs, across industries in the United States. As such, an EPD for one material used for a particular construction object such as pavement might not be comparable to an EPD for another material used for the same purpose.

This section first identifies some sources of information. It then highlights some of the relevant issues found. This is followed by a detailed inventory of EPDs and PCRs and other products compiled into matrices available in Appendix B as Tables B.1, B.2 and B.3. Finally, additional literature on practice in the pavement industry is focused on. All of the aforementioned items are then compiled into a final review and matrix found in Appendix B, Table B.4.

Life cycle assessment, life cycle inventory, and other environmental assessments are examined for this part. US NAICS classification codes and broad industry sectors from the Economic Input-Output LCA software (CMU 2015) were consulted to identify other potential industries for inclusion. Relevant material industries which may include feedstocks with energy content are identified as paving, construction, roofing, wood, flooring, plastics, and agricultural fertilizers. Following industrial identification, studies and databases for products within each industry were located. Academic studies coming from sources such as the International Journal of Life Cycle Assessment, the Journals of Industrial Ecology, Cleaner Production, and Environmental Science and Technology were examined.

Non-academic reports and other sources were also searched. These included the following which are summarized further in this section:

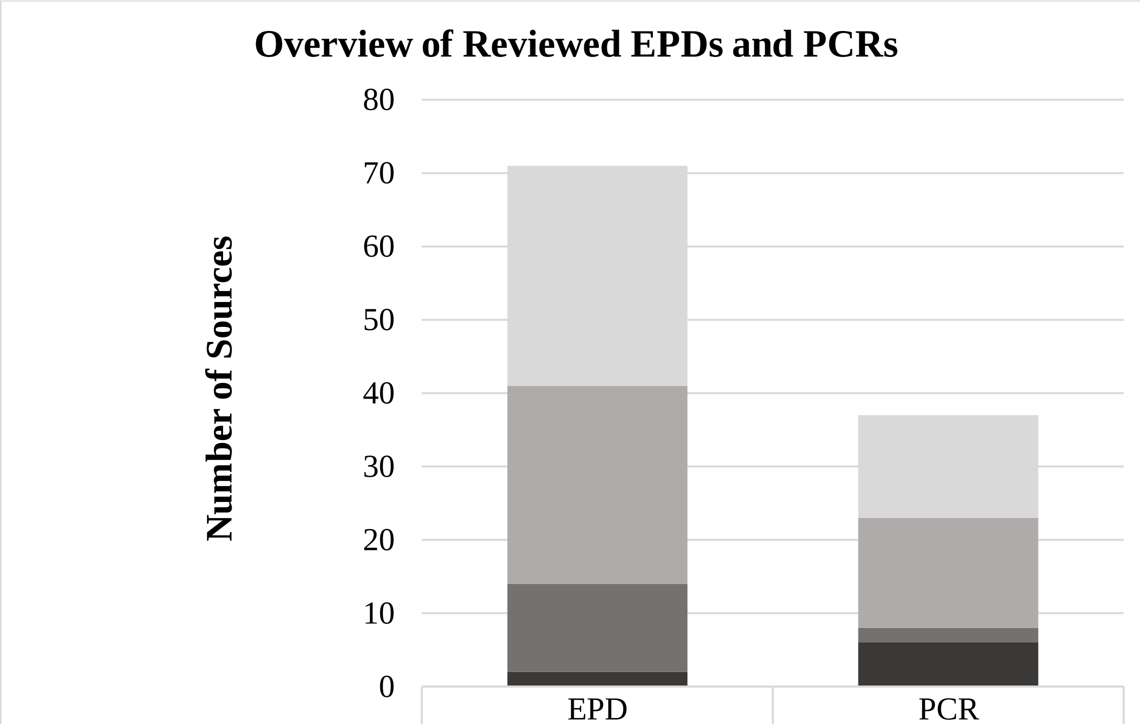
1. EPDs and PCRs from the Product Category Rule Guidance Development Initiative (PCR Guidance 2015).
2. Reports from organizations such as the FHWA.
3. Databases and tools including the US LCI, US Agricultural Commons, and the GaBi US extension databases, and the GaBi, Simapro, etc. tools.

In each case the methodologies for energy accounting were extracted. Specifically, the *system boundaries* and *energy definitions* were the targeted keywords for locating this information. The product from this effort consist of a matrix with respect to industry, feedstock and energy accounting, again found in Table B.4 in Appendix B.

As previously mentioned in the section on definitions, the first issue that arose is the use of different terminology. The Athena Institute wrote a report investigating embodied primary energy and global warming potential approximations for the construction and maintenance of flexible asphalt and Portland cement pavement structures in different road types and regions. In the report, several energy definitions are given and feedstock energy is identified as "the gross combustion heat value of any fossil hydrocarbon material input to a product system which is an energy source, but is not being used as an energy source including its related pre-combustion energy" (Athena Institute 2006). Conversely, in many EPDs, the equivalent of feedstock energy is referred to as "Use of non-renewable primary energy used as raw materials" and/or "Use of renewable primary energy used as raw materials" (EPD®, CSA Group 2017, epd-norge 2012a, ASTM 2015c, 2015d, 2015e, 2015f, 2016g, and 2017b). This provides a more visible opportunity to separate out energy sources used for energy and those used for materials. However, a concern is in totaling energy and material use without noting if those resources used as materials with energy content have been included in either category or both.

A first step towards considering how to look at EPD labeling with respect to feedstock energy in a full life cycle, is now being considered in ASTM Committee E60 on Sustainability. Subcommittee E60.13 on Sustainable Manufacturing is working on a draft standardization named *Standard Classification for Discarded Materials from Manufacturing Facilities and Associated Support Facilities*. The committee is considering to state that "discarded materials may be further classified based on the presence of feedstock energy content for the purposed of life-cycle inventories". (ASTM 2017d). This expression emphasizes that when feedstock energy is tracked in an LCA it may also be a positive input to a next stage as either energy or material. Feedstock energy and related terminology have only just begun to take their place in the standards, and until these practices are fully developed, their use in EPDs for material selection may not be comparative or useful.

Based on information from the Product Category Rule Guidance Development Initiative, a list of ISO 14025 program operators and other programs for LCA-based environmental claims were downloaded and each program operator's page examined regarding the product groups (PCR Guidance 2015). As previously mentioned, Table B.1 in Appendix B is a summary of these. Ten program operators, 57 EPDs and 29 PCRs are examined in total. In Figure 2.1 a numerical analysis is presented in terms of industry and existence of feedstock energy definition.




| | EPD | PCR |
|---|---|---|
| Pavement - Total | 30 | 14 |
| Other Industries - Total | 27 | 15 |
| Pavement - No data found related feedstock energy | 12 | 2 |
| Other Industries - No data found related feedstock energy | 2 | 6 |

Figure 2.1. Numerical analysis of reviewed EPDs and PCRs.

For the pavement industry, 18 EPDs and 12 PCRs; for other industries (i.e. construction, flooring, wood, roofing, plastic, and fertilizer) 25 EPDs and 9 PCRs have included the term *feedstock energy* in their reports. Obviously, the terminology used varies among the many industries.

TRACI is an environmental impact assessment tool developed by Environmental Protection Agency (EPA) which provides characterization factors for impact assessment and sustainability metrics. Some example impact categories are ozone depletion, climate change, acidification, eutrophication, smog formation, ecotoxicity and resource use of fossil fuels (US EPA 2012).

The CML methodology developed by the Institute of Environmental Sciences at the University of Leiden in the Netherlands in 2001, contains more than 1700 different flows. This methodology groups the life cycle impact consequences into midpoint categories, according to common mechanisms or groupings. Besides providing baseline impact category groups (such as acidification potential-average Europe, climate change-GWP100 and depletion of abiotic resources-elements/fossil fuels), it also provides a variety of non-baseline categories (such as acidification potential-generic, climate change-GWP20 and depletion of abiotic resources-economic reserve) (Acero et al. 2015). In the CML methodology, normalization is applicable; although being an optional step in LCA, no baseline method is proposed for weighting (EC 2010). The CML methodology baseline and non-baseline categories include depletion of abiotic resources impact category group. In the baseline category group *depletion of abiotic resources – elements, ultimate reserves* and *depletion of abiotic resources – fossil fuels* are represented separately. In the non-baseline category group *depletion of abiotic resources – elements, economic reserve* and *depletion of abiotic resources – elements, reserve base* are available (Acero et al. 2015).

In addition to TRACI 2.1 and CML Methodology, European Commission Joint Research Centre has published the *International Reference Life Cycle Data System (ILCD) Handbook* which aims to provide a common base to perform the life cycle studies in a consistent and quality-assured. In this handbook, the term *non-renewable* is determined explicitly. Non-renewable energy might be categorized as a type of energy resource and the mass and energy relationship should be given for all energy resource streams apart from nuclear ores. The energy content might be given in the lower calorific value measured in the reference unit as MJ, and *"the biomass of primary forests, peat and some other biogenic energy resources should be counted as non-renewable*" (EC 2010).

In the sources referred to in Figure 2.1, the impact categories of life cycle assessment are calculated mostly by using characterization factors indicated in Version 2.1 of TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) or CML 2001 (ASTM, CLF, EPD®, epd-norge, NSF International, CSA, ICC, UL and IBU). Alternative calculation methods are provided by some program operators. For instance, Environment and Development Foundation (EDF), which is known as Taiwan EPD, uses the *General Programme Instructions for The International EPD System, Version 2.01* and implements significant characterization factors for each impact category (EPD® 2015d). In addition, some operators modify the existing characterization methods in terms of regional features to achieve localization. For instance, with the present circumstances in the Chinese mining industry and its statistical characteristics, the procedures for characterization of abiotic resource in life cycle impact assessment have exhibited certain limitations in the Chinese materials industry. Because of this reason, the researchers have proposed new characterization factors for abiotic resource depletion categories in a localized context (Gao et al. 2009). Table 2.1 is a summary of the calculation methods used by various program operators.

Table 2.1. Characterization Methods Used by Each Program Operator.

| **Program Operator** | **Calculation method used in both PCRs and EPDs** |
|---|---|
| ASTM International | TRACI 2.1 |
| Carbon Leadership Forum | TRACI 2.1 and optionally CML 2010 |
| The Norwegian EPD Foundation | The CML 2001 or additionally ILCD handbook requirements |
| Environment and Development Foundation (EDF) | General Programme Instructions for The International EPD System, Version 2.01 |
| The International EPD System | TRACI 2.1 and optionally CML 2010 |
| NSF International | The most updated CML methodology |
| CSA Group | TRACI 2.1 |
| ICC Evaluation Service | TRACI 2.1 |
| UL Environment | TRACI 2.1 |
| IBU Institute Construction and Environment e.V. | Not mentioned |

There are many initiatives to develop a sustainable transportation approach. One of them is the Transportation Research Board's Sustainable Pavement Subcommittee which aims to identify methodologies to develop the sustainability of transportation systems and to ensure sustainable construction practices, pavement systems and management approaches. The Pavement Management Section of this subcommittee meeting was held in January 2017, in which the National Sustainable Pavement Consortium's activities were presented. This pooled-fund project is planned to be completed in 2018 and has five partners which are the Federal Highway Administration (FHWA), the Mississippi Department of Transportation (MDOT), the Pennsylvania Department of Transportation (PennDOT), the Virginia Department of Transportation (VDOT) and the Wisconsin Department of Transportation (WisDOT). The main objective of the consortium is to establish a research affiliation that works for improvement of pavement sustainability. The research group has worked on emerging sustainable materials, technologies, products and systems and their application methods. Additionally, they have developed some tools for decision makers to evaluate the sustainability of the systems including planning, design, construction, maintenance, management, and reclamation (TPF 2017).

Several articles were published under this consortium (TPF 2017) and they are examined within the scope of this project. An article published by Giustozzi et al. (2012) focuses on the LCA of road maintenance and rehabilitation works to investigate the environmental footprint of the activities over the life of the product. Since the maintenance and rehabilitation activities are both expensive and use many resources, the article describes a methodology to evaluate the environmental impact of preventive maintenance activities with a multi attribute approach including life cycle costing, performance and environmental analysis. The main aim is to compare the preventive maintenance practices with traditional rehabilitation approaches. Although a third-party critical review process is a requirement indicated in ISO 14044 (ISO 2006b) if the publication includes a comparative assertion, this article does not include any critical review content. Six maintenance strategies were computed according to their energy use, carbon emissions, and equipment and materials involved. Three preventive maintenance strategies, which were selected as micro surfacing, slurry seal, and thin overlay, were considered in terms of their carbon emissions and embodied energy. Two maintenance strategies were assumed for each preventive maintenance strategy depending the number of times that treatment was applied for the pavements. Thus, six different strategies were analyzed and compared with a standard maintenance and rehabilitation plan including just the major repairs when the pavement faces the minimum condition border. Raw materials, equipment and construction processes were calculated separately and converted into carbon equivalent emissions to compare the carbon footprint for each alternative. It was stated in the article that the preventive maintenance practices are more eco-effective -with respect to energy consumption and pollution cause-, well-performing and cost effective than the traditional ones.

Another article written by Santos et al. (2014) presents an application of an LCA model which considers the life of the pavement as follows: extraction of materials and production, construction and maintenance, transportation, work zone traffic management, usage and end-of-life. The researchers presented a model that highway agencies might use to quantitatively assess the environmental footprints of their procedures, strategies, and decisions regarding the construction and maintenance of flexible pavements used for either rural or interurban highways. In the impact assessment phase climate change, acidification, terrestrial eutrophication, photochemical ozone formation, human toxicity, abiotic resource depletion of fossil fuels and abiotic resource depletion of mineral resources are selected. The characterization models and characterization factors are selected according to the recommendations of the ILCD handbook (EC 2010). The feedstock energy is also reported in the LCIA table for each pavement type with cumulative fossil energy demand, cumulative nuclear energy demand, cumulative primary forest energy demand, cumulative renewable energy demand and sum of those as the cumulative total energy demand. Cumulative total energy demand means the usage of any sort of energy including feedstock energy of bitumen used as either energy or materials. However, since the feedstock energy inherent to bitumen remains while used as a binder in pavement, it should be presented separately from primary energy as prescribed by the UCPRC Pavement LCA guideline (UCPRC 2010).

In 2015, Santos et al. (2015a) worked on a different study called *A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices*. In their paper the comprehensive LCA model for pavements is conducted by extending the system boundaries with adding the use phase and the production and transportation of energy sources. Further, their paper examined the in-place recycling practices and the control mechanism to improve the environmental footprint of the pavement system. Three different strategies were compared: (1) recycling-based project, (2) traditional pavement reconstruction and (3) a corrective maintenance approach. The system boundaries were considered as materials extraction and production; construction and maintenance and rehabilitation; transportation of materials; work-zone traffic management; usage and end-of-life. In the life cycle impact assessment phase different methodologies were used for characterization of the impact categories. TRACI 2.0 (US EPA 2012) was used for climate change, acidification, eutrophication, human health criteria air pollutants and photochemical smog impact category. CML assessment methodology (Acero et al. 2015) was used for abiotic resource depletion of mineral resources and fossil fuels. The GREET (Greenhouse gas, Regulated Emissions, and Energy Use in Transportation) model (Argonne National Laboratory 1993) was used to analyze the cumulative energy demand indicators, expressed as fossil, nuclear and renewable resources. Cumulative energy demand was calculated for the usage of any type of energy, including direct and indirect energy, throughout the life cycle. As a result, the feedstock, process and primary energy along with the total cumulative energy demand was given with a table corresponding to each strategy, split up in fossil, nuclear and renewable resources. Since the feedstock energy in the bitumen remains unexploited while used as a binder in a pavement, it was presented separately as prescribed by the UCPRC Pavement LCA Guideline (UCPRC 2010). Researchers found out that the feedstock energy of the bitumen is almost three to five times the energy demand during the <u>raw materials phase</u> of each M&R strategy (traditional reconstruction, recycling-based and corrective maintenance). The feedstock energy was approximately 6%-9% of the total cumulative energy demand for each of the strategies and was considered while calculating the energy items (Santos et al. 2015a).

In 2015, Santos et al. (2015b) also published a different article named *A life cycle assessment model for pavement management: methodology and computational framework*. This paper aimed to develop a tool for pavement life cycle phases. It has six main modules including extraction of raw materials and production; construction, maintenance and rehabilitation; transportation of materials; work-zone traffic management; usage; and end-of-life. The data for this methodology was collected from on-site, literature and database sources. Results might be applicable for use by highway agencies, construction industry and private companies. The model described in this paper provides a customizable tool to assist users in quantitatively assessing the total environmental footprint of their procedures, strategies, and decisions regarding the construction and maintenance of flexible pavements used for a rural/interurban highway at project level. The model enables the user to evaluate the environmental impacts, energy sources consumption and materials consumption of alternative solutions for pavement design and maintenance throughout different phases. For the environmental impacts, climate change, acidification, terrestrial eutrophication, human toxicity (emissions to air), photochemical ozone formation and abiotic resource depletion (fuels and mineral) were considered. Additionally, because of using bitumen as a raw material, researchers focused on the feedstock energy term. In the case of bitumen, the feedstock energy is presented separately from other primary energy usage as prescribed by the UCPRC Pavement LCA Guideline (UCPRC 2010). In this guideline, it is emphasized that in the life cycle inventory phase the "feedstock energy must clearly be distinguished from combusted energy", and in the material production phase, *feedstock energy of materials that are used as a fuel* should be included. Again, the term feedstock energy is not necessarily used in the same manner by many groups, even in this one industry.

Besides environmental developments, researchers in the National Sustainable Pavement Consortium worked on both economic and social aspects of pavement management since the term *sustainability* should be examined with its three pillars: social, economic and environmental. Flintsch and Bryce (2014) investigated sustainable pavement management considering the equilibrium between economic, environmental and social impacts. The term sustainable pavement management is concerned with maintaining pavements which are in a good condition while also considering the interchange between cost, environmental impacts and social impacts of investments. The general purpose of an associated pavement LCA is to quantify the total environmental impact, mainly for greenhouse gas emissions or energy consumption, of the pavement throughout the pavements life which is divided into stages as raw materials and production, construction, use, maintenance and end-of-life. The Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) (University of California, Berkeley 2003) was used for both economic and environmental factors related to the construction processes of a pavement. In this tool the lifecycle stages defined as manufacturing of materials, construction maintenance and end-of-life (demolition, recycling) but the use phase is excluded. The main focus is on energy consumption and water pollution. PaLATE is an Excel-based tool for life-cycle assessment (LCA) of environmental and economic effects of pavements and roads. The tool takes user input for the design, initial construction, maintenance, equipment use and costs for a roadway, and provides outputs for the life-cycle environmental effects and costs. Environmental effects investigated include: Energy consumption, $CO_2$ emissions, $NO_x$ emissions, $PM_{10}$ emissions, $SO_2$ emissions, CO emissions and leachate information. One version, PaLATE 2.0, is currently publicly available on the web (RMRC-3G 2003).

Dehghanisanij et al. (2013) worked to develop a framework of a decision-making tool for estimating the resource allocation regarding functional, structural and environmental indicators for pavements. They indicated that land use, greenhouse gas emissions, recycling practices and material consumption should be considered for an overall environmental analysis decision framework. The main aim was to build a *sustainable and efficient* transportation infrastructure system with a reasonable budget allocation. The article (Dehghanisanij et al. 2013) mentions the calculation of emissions coming from the significant use of *non-renewable resources* (like bitumen) for comparison between design and maintenance phases but does not mention the specific methodology used for calculation and characterization. A similar study was conducted by Bryce et al. (2014a) for which the objective was to develop a decision-making tool for pavement management applications for decisions about impacts related to costs and energy consumption. The results of this study indicated that a cost-effective maintenance alternative may be the worst in environmental side in terms of energy consumption. However, preventive maintenance activities are less energy intensive and more cost efficient but these activities might not improve pavement roughness. Thus, the decision of being environmentally friendly and/or being cost-effective are linked with the decision makers' preferences (Bryce et al. 2014a). Other articles from the Consortium were not directly related to feedstock energy (Bryce et al. 2014b, Bryce et al. 2015, Bryce et al. 2016, Qiao et al. 2014).

Athena Impact Estimator has models for buildings and highways (Athena Institute 2014). *Impact Estimator for Buildings* can model 95% of the North American building stock and it is geographic region specific. It uses the TRACI methodology (US EPA 2012) for calculating global warming, acidification, human health, ozone depletion, photochemical smog creation, eutrophication and fossil fuel consumption potentials. In addition, the *Impact Estimator for Highways* is used to analyze initial paving materials, highway use, maintenance and end-of-life stages. This highway LCA tool currently covers Canadian Provinces and is designed to make LCA methodologies on pavements more accessible to transportation engineers and pavement designers. It is based on national averages with some regional data for distances and electrical grids. In this tool, non-renewable energy consumption is given in MJ, is indicated as a subset of *Total Primary Energy Consumption (MJ)* and includes all the fossil fuels and nuclear. Fossil fuel means all the energy sources except hydro, non-hydro renewable, nuclear and wood which are also given in MJ. The Athena IE Handbook reported that "embodied primary energy includes all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources."

BEES (Building for Environmental and Economic Sustainability) is a tool for analyzing the environmental and economic impacts of building products developed by the National Institute of Standards and Technology aka NIST (Lippiatt 2007). It has models for nearly 200 products including concrete, roofing, insulation, water distribution piping, cleaning materials, paving and many more. However, modeling parameters, applying sensitivity analyses, manual changing of inputs/outputs are not available in this tool. BEES accounts for the environmental impacts from energy consumption and combustion and reports embodied energy results in two ways: (1) by fuel and feedstock energy and (2) by fuel renewability. This tool defines feedstock energy as "the energy content of fuel resources extracted from the earth, while fuel energy is the amount of energy that is released when fuels are burned". For instance, if fuel resources such as petroleum and natural gas are used as material inputs, the energy value remains in the feedstock category. Whenever the extracted fuel resources are transformed into fuels and combusted to obtain energy, it is classified in the fuel category instead of feedstock energy. Since bio based products and plastics have *embodied* energy, BEES indicated that they may generate higher feedstock energy values. In addition to feedstock energy, this tool can calculate the total embodied energy within the categories of renewable (hydropower, wind, nuclear, geothermal, biomass) and non-renewable (petroleum, natural gas, and coal) energies.

BIRDS (Building Industry Reporting and Design for Sustainability) was also developed by NIST and covers the environmental and economic analysis of new commercial buildings including operating energy, environmental performance of materials, construction and use and life cycle costing (Kneifel 2015). It models different building types (apartment, dormitory, hotel, office, retail store, high school, restaurant, etc.) for different locations. In the BIRDS handbook, primary energy consumption definition is given as "fossil fuel depletion when fossil fuel resources are consumed at rates faster than nature renews them". The primary energy consumption is used to calculate the resource depletion side of fossil fuel extraction and the unit for this type of energy is given as kWh.

Being one of the most widely used LCA tools, GaBi (Ganzheitliche Bilanz) has extensive database options including its own database and integration with external databases, such as ecoinvent, US LCI, etc. (PE International 2012). This software calculates the results using sequential modeling and draws the plans as flowcharts to calculate the impacts. In this tool, a set of six indicators for primary energy consumption is: (1) primary energy demand from renewable and non-renewable resources (both gross and net calorific value), (2) primary energy from non-renewable resources (both gross and net calorific value), (3) primary energy from renewable resources (both gross and net calorific value).

Another common LCA tool is SimaPro. It uses a text/menu approach to modeling rather than graphical approach and calculates results using matrix inversion (PRé 2016). This tool uses two different energy expressions: (1) Cumulative Energy Demand (CED), and (2) Cumulative Exergy Demand (CExD). CED is divided into five impact categories as non-renewable fossil, non-renewable nuclear, renewable biomass, renewable wind/solar/geothermal and renewable water. CExD is defined as the sum of exergy of all resources required to provide a process or product. *Exergy* (MJ) identifies the quality of energy rather than the energy content (MJ) and may be used as a measure of the potential loss of *useful* energy resources. In CExD, 10 different impact categories are presented: non-renewable fossil, non-renewable nuclear, renewable kinetic, renewable solar, renewable potential, non-renewable primary, renewable biomass, renewable water, non-renewable metals and non-renewable minerals. As it can be seen among these impact categories, CExD includes non-renewable primary energy which may be considered as feedstock energy.

The tools GREET (Greenhouse gas, Regulated Emissions, and Energy use in Transportation) (Argonne National Laboratory 2016), Umberto (ifu 2016), OpenLCA (Winter et al. 2015), EIO-LCA (Economic Input-Output Life Cycle Assessment) (CMU 2015), PaLATE (The Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects) (RMRC-3G 2003) and FEC (Fuel and Emissions Calculator) (Georgia Tech 2016) do not take into account feedstock energy in their models.

As previously mentioned, there are several expressions related to feedstock energy and its allocation among the literature including EPDs, PCRs, LCA articles and reports from institutions and organizations, and tools or databases. Summaries of all reviewed references are compiled in tables indicating different statements of feedstock energy allocation and system boundaries in Appendix B.4. Identified material industries for this study which may include feedstocks with energy content are paving, construction, roofing, wood, flooring, plastics, and agricultural fertilizers. From all references, 15 different representations were collected for feedstock energy allocation and classified by specific industries.

### 2.3. Production and End-of-Life Scenarios for Asphalt Pavements

A review of the life cycle of asphalt pavements is useful to better understand potential allocation and carbon cycle impacts of bitumen feedstock energy. According to a NAPA report (Hansen and Copeland 2015), over 99% of all removed asphalt pavement is recycled into new asphalt. Under such a scheme, from a life cycle perspective, it may be appropriate to consider recycling allocation methodologies. If the energy content of the material is retained as it is recycled, is it not *multiple counting* to consider that energy demand in each new installation?

In Karlsson and Isacsson (2006), methods for asphalt recycling are examined including in-plant asphalt recycling, in-place asphalt recycling and other methods such as using recycled asphalt as base/subbase layer. Additionally, a guide for selection of recycling methods is included with a comprehensive table with different recycling methods (cold planning, hot in-plant recycling, hot and cold in-place recycling and full depth reclamation) for different types of pavement distresses. Another article for asphalt by Silva et al. (2012) was reviewed. In their research, the use of reclaimed asphalt pavement in hot mix asphalt to reduce produced wastes and resource consumption is examined. It also focused on using totally recycled hot mix asphalt mixtures as a sustainable solution in the pavement arena. It was found that totally recycled hot mix asphalt may be an alternative, however additional experiments are needed with respect to workability and durability. There was no mention of the effect of recycling to the carbon cycle in either of these two articles.

In Dony et al. (2013), the hot-mix asphalt concrete recycling was examined for both environmental performance and durability by comparing different percentages of recycling rates. Researchers also considered reducing the use of virgin materials such as bitumen and aggregates for environmental and economic reasons. In addition to the amount of asphalt and manufacturing parameters (time, temperature), equipment, methods used and the type of virgin binder were also found to be important factors for the homogeneity of the binder. Conventional and rheological tests were applied, and it was found that high recycling rates resulted in characteristics consistent with conventional designs. There was no mention of the effect of recycling with respect to the carbon cycle. All three of these recycling references recycle the asphalt as a material. Therefore, the energy content and the carbon are retained in a solid form.

Polat and Bektas (2015) studied the environmental impacts of three different asphalt products by applying gate-to-gate (raw materials to production) LCA. Special focus was given on reporting carbon footprint, resource and energy consumptions and various environmental impacts such as abiotic depletion, acidification, eutrophication, global warming potential, ozone depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation. Santero et al. (2011) focused on LCA of pavements mainly for the use and end-of-life phase. The use phase contained items such as *rolling resistance, albedo, carbonation, lighting, and leachate* operations that are generally excluded by researchers in pavement related LCAs. However, these five items may have significant impacts and might need to be taken into account for a cradle-to-grave LCA. In the carbonation process, carbon accounting was mentioned as this is a form of carbon sequestration that occurs during the use and end-of-life phases. The calculation methodology was not explained in detail. For the end-of-life phase, Santero et al. (2011) examined three different pathways which are *(1) demolished and landfilled; (2) demolished and recycled; or (3) remain in situ and serve as support for a subsequent pavement structure.* Both of these articles on asphalt and various portions of LCAs did not focus on feedstock energy and its relationship with the carbon cycle while calculating the environmental impact potentials.

In an article published by Miliutenko et al. (2013) possible ways to improve the LCA performance of asphalt recycling in terms of global warming potential (GWP) and cumulative energy demand (CED) were investigated. Hot in-plant and hot in-place recycling techniques were studied. The system boundary of this study was *asphalt waste treatment* for a certain amount of recycled asphalt pavement for which the production process was assumed to be identical. In this work, CED is defined as the sum of direct and indirect energy including feedstock energy (in MJ). Miliutenko et al. (2013) allocated the feedstock energy to the virgin asphalt and did not double count it later. Therefore, it should be noted that recycling would reduce the percent feedstock energy content in the asphalt after each recycling step. Different percentages for feedstock energy content in the CED for bitumen were searched throughout the literature by the Miliutenko et al. (2013) research team, was averaged as 88% in this article for virgin asphalt, and the subsequent calculations used this percentage. In CED, it was found that the largest share of avoided CED was feedstock energy coming from the production of bitumen. Consequently, hot in-plant recycling was found to be more environmentally friendly than hot in-place recycling for CED. In terms of GWP, the effect of feedstock energy was not mentioned. There was no information on whether carbon remaining in the bitumen was included in the GWP calculations either as an input or an output. Miliutenko et al. (2013) calculated GWP impacts and again hot in-plant recycling was found to be more environmentally friendly than hot in-place recycling for the scenarios investigated. As previously mentioned in the interim report, Santos et al. (2015a) has an article on recycling in which the results were similar with Miliutenko et al. (2013). Santos et al. (2015a) also found that hot in-plant recycling was an environmentally friendly option.

In summary, it was found that typically the carbon in the bitumen was not considered in a carbon cycle in any format from virgin asphalt and through the various recycling methods, when recycled as a material. However, the energy still contained in the bitumen (feedstock energy) was sometimes added into an energy demand to various life cycle gates, even though not used as energy.

### 2.4. Analysis of Feedstock Energy within the Carbon Cycle and other Environmental Systems

*Total energy use* is an inventory-style indicator which may not have a clear partitioning that would allow one to deconstruct the pathway from *use* to *effects*. Multiple potential midpoint and endpoint indicators could be linked to energy use, however, those would require a more subdivided level of detail than total energy use. For instance, impacts on Earth's energy supply (e.g. fossil fuel depletion potential) and effects on the carbon cycle (e.g. global warming potential) are indicators which consider some level of effect on relevant issues. In addition, Klöpffer and Grahl (2014) assert that "any kind of energy demand, according to ISO criteria, does not correspond to an impact category…"

As an energy source, bitumen can be directly combusted in specialized boilers or can be upgraded to lighter fuels (Santero et al. 2010). However, it has a carbon intensity of 80.7 kg $CO_2$/kJ, which is high by comparison to other liquid fuels such as gasoline with 69.3, diesel with 74.1, and LPG with 63.1 (Gómez et al. 2006). With respect to global warming potential, that translates to a potentially greater impact on the carbon cycle when combusted. For the case of upgrading bitumen to lighter fuels, the energy required to do so may be considerable (Santero et al. 2010).

Therefore, the question arises of when it is or is not appropriate to include feedstock energy, and if one does, should the associated carbon content also be included in environmental declarations since using the product as a fuel versus as a material may have varying benefits. Some logical arguments for not including feedstock energy are: Is it simply an allocation question where the energy content belongs? Was the bitumen truly a fuel or was it a waste that is better used in asphalt? Santero et al. (2010) went further stating that *Further research is also recommended for improved accounting of the mass composition of petroleum feedstocks that are (temporarily or permanently) sequestered in products. This would improve the ability of the LCI analyst to understand the environmental implications of petroleum feedstock use…. or tradeoffs in various environmental impacts associated with using petroleum as a feedstock material as opposed to its use as a direct fuel.*

#### *2.4.1. Definitions*

In this section, different definitions of carbon sinks, carbon cycles and related terminology are presented as are references to carbon from various sources.

##### *i. Standardizations*

In ISO 14064-2 (2006e), interaction and application of several definitions related to key carbon cycles are defined as:

- GHG source: *physical unit or process that releases a GHG into the atmosphere*;
- GHG sink: *physical unit or process that removes a GHG from the atmosphere*;
- GHG reservoir: *physical unit or component of the biosphere, geosphere or hydrosphere with the capability to store or accumulate a GHG removed from the atmosphere by a greenhouse gas sink or a GHG captured from a greenhouse gas source*;
- GHG emission: the *total mass of a GHG released to the atmosphere over a specified period of time*;
- GHG removal: the *total mass of a GHG removed from the atmosphere over a specified period of time*.

##### *ii. EPDs and PCRs*

In the wood industry, most of the EPDs and PCRs mentioned the words carbon sequestration and that it may be reported if information is available. The interior wood product standard (ASTM 2016d) suggests considering biogenic carbon sequestration and reporting it in the *additional environmental information* part of a PCR but excluding it from the global warming potential in cradle-to-gate studies. In that additional environmental section of a PCR recycled content, recycling rates and other potential factors that may affect the environment should be listed. In two UL wood standards on oriented strand board (OSB) and plywood the importance of the accounting of carbon sequestration in the wood product over its life cycle is expressed (UL 2013a and 2013b). In these EPDs, biogenic carbon dioxide emissions are considered as carbon neutral in terms of global warming potential. However, the PCR of these EPDs mentions that *carbon sequestration may only be credited to the product if the end-of-life fate of that carbon is considered* in the LCA.

EPD® 2014e is an example PCR for the construction industry. In this document, carbon sequestration is defined as *the removal of atmospheric carbon dioxide into biomass products*. The amount of biogenic carbon should be calculated and reported as $CO_2$ equivalent but it should be excluded from the environmental impact of the product. Additionally, there is a term called *temporary carbon storage* which is defined as *the potential effects from delayed emissions of carbon dioxide due to storage in non-atmospheric pools (such as timber, wood-based products, hemp, flax, etc.)*. Mostly, this type of carbon is not reported in PCRs. Carbonation is also taken into account in buildings because it occurs in concrete and forms calcium carbonate in presence of carbon dioxide and calcium oxide. Generally, there is a lack of data for carbonation schemes, for this reason it is not mandatory to report and calculate its effect in EPDs and PCRs.

Lastly, an example PCR from the agricultural fertilizer industry (EPD® 2010a) reported that there are two issues for carbon that should be taken into account, (1) atmospheric carbon may be taken up by a product over its life cycle, and (2) forest management activities may result in additional carbon storage through retention of forest biomass. Those emissions or removals should be reported separately in global warming potential calculations. EPD® 2013c is an example for highway, street and road construction, and it contains exactly the same expressions included in EPD® 2010a in terms of carbon sequestration and accounting information.

Therefore, in general, carbon is reported whether being released or removed, but when sequestered or contained in materials of any sort, the carbon is reported separately and not necessarily included in the GWP calculations. The important thing to note here, is that carbon in materials must be somehow reported separately so that it is obvious that it is in the material. When there are unknowns as to the carbon in the materials, such as in soils, the reporting may remain as a blank in a table.

#### *iii. Articles*

Mohareb and Kennedy (2012) published an article which indicates the methodology and assessment for gross urban carbon sinks classified as direct and embodied sinks. Direct sinks can be considered as natural processes and they are listed under natural sequestration. Embodied sinks are mainly related to human consumptive behavior resulting in the storage of carbon, for instance landfilling of waste and concrete construction. These researchers focused on cement and concrete examples for embodied sinks and found out that concrete carbon flux is decreasing over time. Figure 2.2 is taken from Mohareb and Kennedy (2012) and describes carbon fluxes over time associated with direct (biomass) and embodied (harvested wood product, concrete, landfill) carbon sinks. The carbonation process of concrete is an example of embodied carbon sink which happens after concrete is poured in the environment. In general, this article focuses on comparison of the magnitudes of embodied and direct sinks. However, these figures are difficult to interpret. The positive (emission) and negative (storage) fluxes are not additive in the figures but are presented separately. If one draws asphalt similarly, then it might look like Figure 2.3.

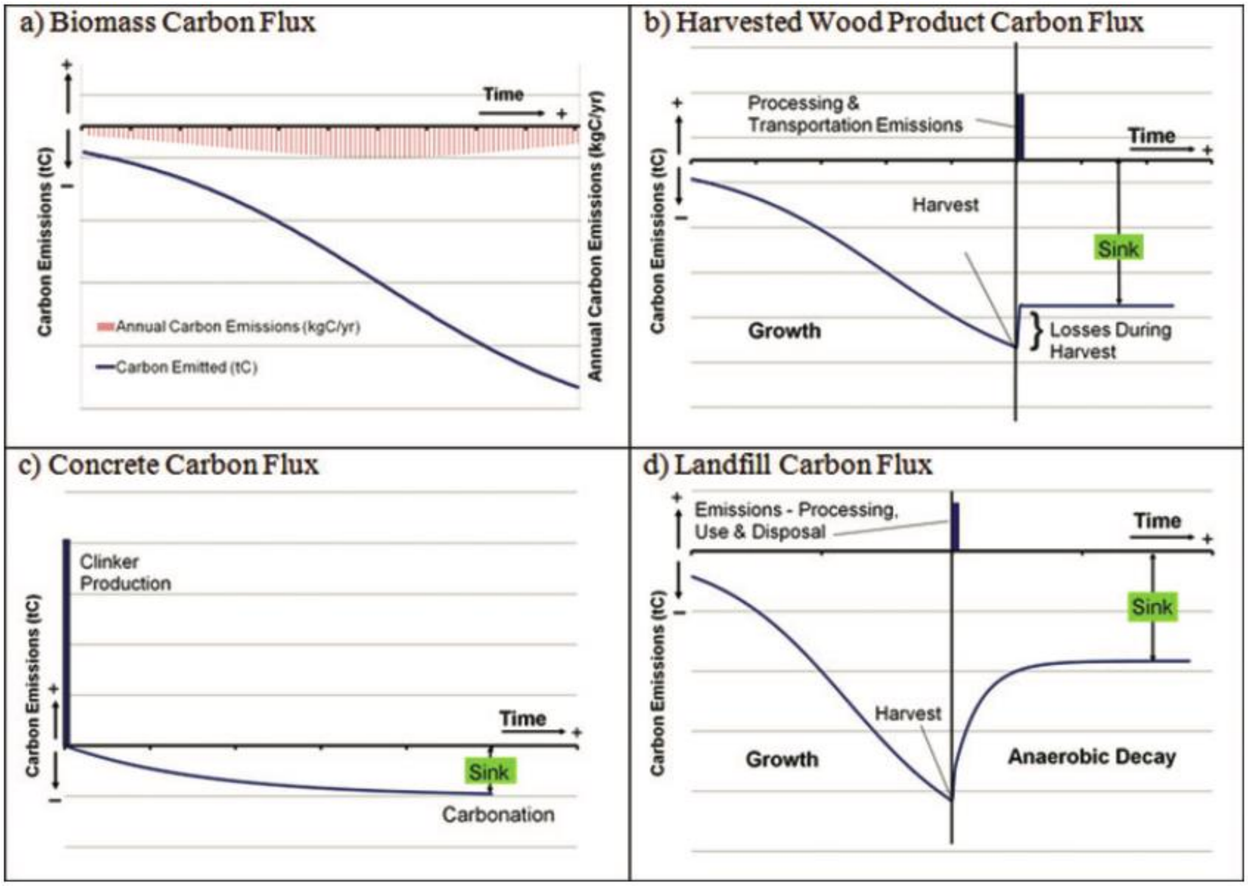



Figure 2.2. Carbon fluxes over time, scales not representative (Mohareb and Kennedy 2012).

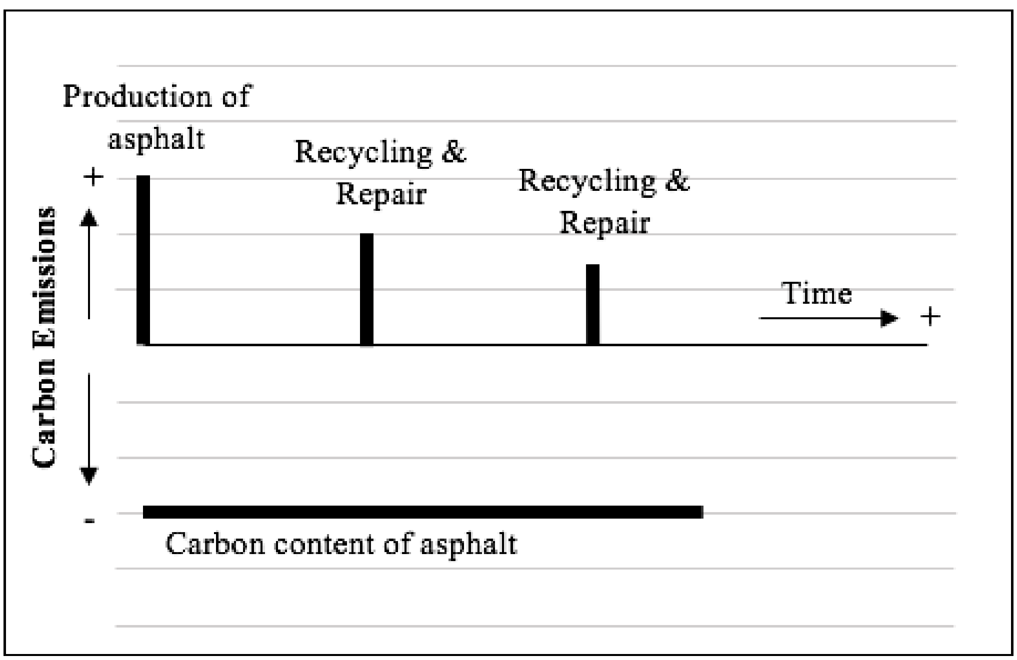



Figure 2.3. Asphalt carbon flux over time with relative scales not representative.

### *2.4.2. Asphalt Feedstock Cycles with Respect to Carbon*

#### *i. Sources of Feedstock*

An article published by Mui et al. (2010) gives the greenhouse gas emission factors for production of high carbon intensity crude oils which are produced with energy intensive processes resulting in high emissions. In their study, it is indicated that there were many studies for GHG emission factors calculation, however each of them used different data sources, methods, lifecycle boundaries, and assumptions so that the comparison of the results were very difficult. Tar sands, coal-to-liquids and oil shale are examined and comparative GHG emission factors are reported. Especially in coal to liquids types of fuels, the variables affecting the total fuel production emissions are listed with an order of importance. In the seven main variables, "feedstock quality (e.g. carbon and energy contents)" is reported as fifth. Other variables were: *overall plant efficiency, rates of* $CO_2$ *capture and disposal, production of other products including but not limited to electricity, rates of leakage from* $CO_2$ *transport, injection and sequestration sites, mining practices, and feedstock and fuel transport,* respectively. The three variables; *overall plant efficiency, rates of* $CO_2$ *capture and disposal, and production of other products including but not limited to electricity,* have the biggest impact on energy use and GHG emissions.

#### *ii. Converting Feedstock into Asphalt*

Most of the asphalt used for paving comes from petroleum crude oil. Crude oil passes through various distillation processes at the refinery to produce asphalt and other petroleum-based products. Asphalt is the main residue of this process; which is then processed to obtain desirable properties (Pavement Interactive, 2012).

EIO-LCA (CMU 2015) was produced by Carnegie Mellon University and it is a free web-based tool which calculates based on economic ties between sectors. It approximately reports required materials and energy resources, and environmental emissions resulting from economic activities. From the product list of EIO-LCA, *Petroleum and Basic Chemical* is selected as *Broad Sector Group* and *Asphalt Paving Mixture and Block Manufacturing* is selected as *Detailed Sector* and all results are computed. This sector is comprised of one NAICS sector and it is described as: “This U.S. industry comprises establishments primarily engaged in manufacturing asphalt and tar paving mixtures and blocks from purchased asphaltic materials.” Asphalt manufacturing EIO-LCA results for GWP are second to the oil and gas extraction process, and similar to the GWP from refining and power generation and supply as can be seen in Figure 2.4. The manufacturing process is compared to the total for asphalt paving in Figure 2.5.

**Sector** #324121: Asphalt paving mixture and block manufacturing
**Economic Activity:** $1 Million Dollars
**Displaying:** TRACI Impact Assessment
**Number of Sectors:** Top 10

Change Inputs (Click here to view greenhouse gases, air pollutants, etc...)

**Documentation:**
The environmental, energy, and other data used and their sources.
Frequently asked questions about EIO-LCA.

**This sector list was contributed by Green Design Institute.**

| | Sector | Glob Warm kg CO2e | Acidif Air kg SO2e | HH Crit Air kg PM10e | Eutro Air kg Ne | Eutro Water kg Ne | OzoneDep kg CFC-11e | Smog Air kg O3e | EcoTox (low) kg 2,4D | HH Cancer (low) kg benzene eq | HH NonCancer (low) kg toluene eq | EcoTox (high) kg 2,4D | HH Cancer (high) kg benzene eq | HH NonCancer (high) kg toluene eq |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Total for all sectors* | *1670000* | *6690* | *3310* | *183.* | *0.543* | *0.516* | *104000* | *35.4* | *122.* | *66800* | *37.0* | *491.* | *748000* |
| 211000 | Oil and gas extraction | 368000 | 582.0 | 35.6 | 30.1 | 0.000 | 0.000 | 20300 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 324121 | Asphalt paving mixture and block manufacturing | 347000 | 1970 | 1120 | 53.8 | 0.000 | 0.000 | 31100 | 0.000 | 0.042 | 72.0 | 0.000 | 0.103 | 172.0 |
| 324110 | Petroleum refineries | 297000 | 711.0 | 148.0 | 13.1 | 0.240 | 0.029 | 7490 | 0.743 | 8.21 | 1970 | 0.999 | 22.3 | 2370 |
| 221100 | Power generation and supply | 293000 | 1680 | 333.0 | 24.5 | 0.004 | 0.000 | 13500 | 3.40 | 4.99 | 2810 | 3.41 | 14.9 | 14700 |
| 486000 | Pipeline transportation | 60300 | 13.7 | 0.745 | 0.765 | 0.000 | 0.000 | 650 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 327310 | Cement manufacturing | 41600 | 176.0 | 42.1 | 5.10 | 0.000 | 0.000 | 2860 | 0.267 | 9.37 | 5580 | 0.268 | 17.9 | 14000 |
| 331110 | Iron and steel mills | 30800 | 36.2 | 13.3 | 1.07 | 0.017 | 0.000 | 596.0 | 0.403 | 3.21 | 3570 | 0.473 | 3.53 | 3800 |
| 484000 | Truck transportation | 25800 | 184.0 | 78.9 | 10.1 | 0.000 | 0.000 | 5700 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 325190 | Other basic organic chemical manufacturing | 21800 | 80.1 | 16.6 | 2.27 | 0.079 | 0.157 | 1290 | 0.103 | 1.83 | 228.0 | 0.358 | 8.49 | 561.0 |
| 212100 | Coal mining | 14600 | 34.7 | 12.0 | 1.52 | 0.010 | 0.000 | 859.0 | 0.584 | 2.37 | 950 | 0.584 | 34.2 | 36000 |

Figure 2.4. Asphalt paving mixture and block manufacturing EIO-LCA results.

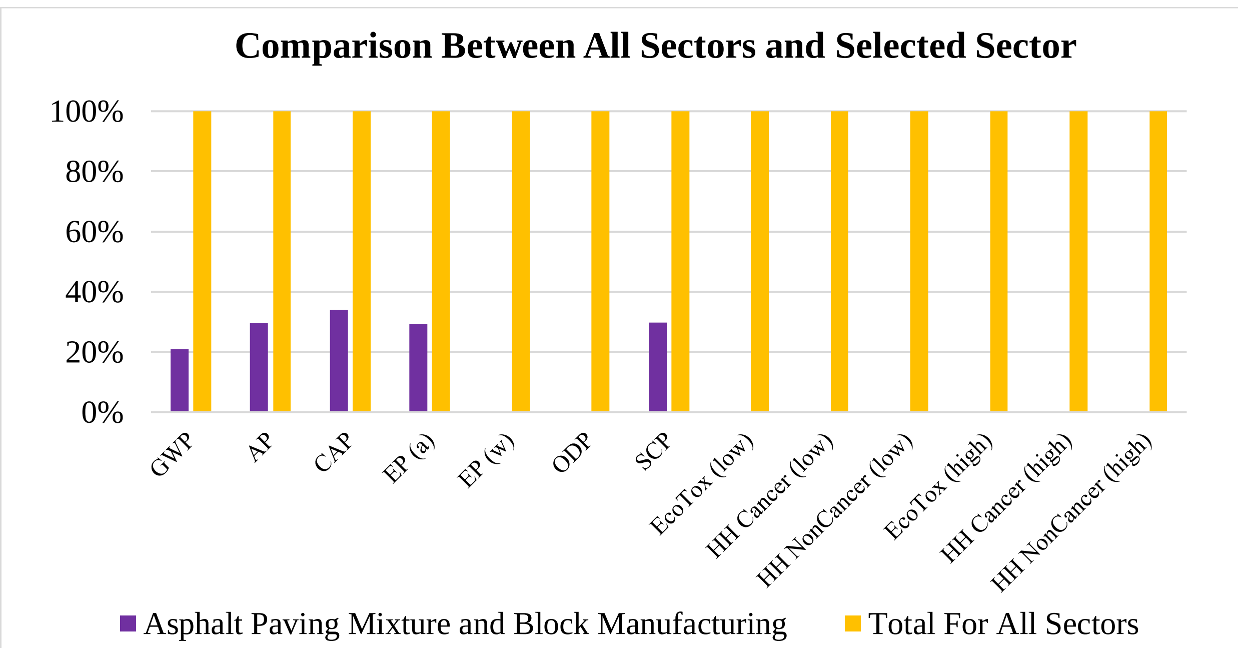



Figure 2.5. EIO-LCA results graph based on Figure 2.4.

### *iii. Use of Feedstock as Material in Asphalt*

A research paper by Peng et al. (2015) focused on calculating carbon emissions stage by stage for both asphalt mixture production and asphalt mixture construction. Energy saving schemes and environmental and economic advantages were listed. It is accepted that, carbon emissions were coming from loader (stacking aggregates), heavy oil (aggregate supply), fuel (heating aggregates and asphalt), electric energy (mixing) and diesel (transportation) and calculations were made with regard to these sources. The biggest share comes from heating aggregates; asphalt heating, and mixing process follow it respectively. These researchers did not include feedstock energy in their calculations and they did not take into account the effect of feedstock energy in framing the carbon scheme.

#### *iv. Reuse of Feedstock*

##### a) As Energy

Asphalt bitumen may be an energy source in the cement manufacturing industry, along with many other sources. Bituminous coals are the most often used coal types in the cement industry (Cement Kilns 2011). According to this article, coal sources generally have lower $SO_2$ and NOx emissions as compared to petroleum coke, but may have higher risks of fire and explosion hazards. Additionally, percentages of ash content and volatile matter in bituminous coal are typically higher than petroleum coke, however, percentages of fixed carbon and sulfur may be lower (PEC Consulting 2015).

##### b) As Material

As mentioned in previous sections, asphalt is highly recycled (Karlsson and Isaccson 2006, Silva et al. 2012, Dony et al. 2013). It may be crushed and reused/recycled back into new asphalt as a new asphalt hot mixes or sub-base for paved roads (US EPA 2015a). EPA does not consider the GHG benefits of recycling hot mix asphalt into aggregate, however for recycled asphalt concrete, EPA assumes the recycled material *offsets* the GHG emissions coming from the production phase. Manufacturing with nearly 100% recycled inputs results in close to 50% decreases in $CO_2$-eq emissions coming from process energy and large decreases in $CO_2$-eq emissions coming from transportation energy (US EPA 2015c).

Another example for using feedstock as material may be potholes since a small amount is lost to the environment. Statistics have showed that maintenance activities for pavements in the US requires $17 billion per year (Cheng and Miyojim 1997). In an online article by Lucius Riccio (2014), pothole analytics for New York City is studied. It was found out that there is a steady increase in potholes from around 70,000 to 80,000 in the mid-1990s to the 200,000 to 300,000 range in late-2013. City workers reported that they fixed 300,000 potholes during the first four months of 2014.

### *2.4.3. Example Carbon Cycles of other Materials that Can Store Carbon*

#### *i. Concrete*

Concrete production is a resource and emissions intensive process due to its cement content, especially the carbon dioxide ($CO_2$) emissions associated with the calcination phase. Every year, 10 billion tons of concrete are produced (Meyer 2009). The most important stage of the concrete production is the calcination of the raw materials to produce clinker which is then produced into cement. Cement production accounts for 5-8% of the current worldwide anthropogenic $CO_2$ emissions (Cembureau 2013). During the processing of cement, carbon dioxide is released when limestone ($CaCO_3$) is converted to lime (CaO), which is called calcination. In the reverse process, which is called carbonation, the cement absorbs carbon dioxide and forms calcite (Lagerblad 2006). Figure 2.2-c by Mohareb and Kennedy (2012) is a depiction of the concrete carbon flux. First, clinker processing emits carbon but with the carbonation process, the net carbon emissions becomes lower over time. Based on the hydrated chemistry of concrete, $CO_2$ may be released under certain pH conditions or absorbed in dissolved forms as well, in addition to other carbonation products (Boesch and Hellweg 2010). Several research papers indicate that $CO_2$ absorption in hydrated cements significantly impacts the amounts of the final carbonation products.

A report published by Cement Sustainability Initiative (CSI 2005) mainly focused on calculating and reporting $CO_2$ emissions. It covers both direct and indirect $CO_2$ emissions related cement manufacturing and helps to draw a framework for a $CO_2$ inventory. It indicates that calculation and reporting steps should be *relevant*, *complete*, *consistent*, *transparent*, and *accurate* to avoid *double-counting* of carbon emissions. CSI (2005) gives information on sources on direct $CO_2$ emissions generated in cement manufacturing. These can be sorted as; (1) calcination of carbonates, and combustion of organic carbon contained in raw materials, (2) combustion of conventional fossil kiln fuels, (3) combustion of alternative fossil kiln fuels, (4) combustion of biomass kiln fuels, (5) combustion of non-kiln fuels, and (6) combustion of the carbon contained in wastewater. It implies that $CO_2$ from biomass fuels may be accepted as *climate-neutral* since biomass can re-grow in the short term and, as a consequence, emissions may be compensated for. Generally, this step is associated with "Land use change and forestry" and $CO_2$ emissions may be reported as *forest depletion* (IPCC 1996). However, $CO_2$ from fossil fuel-derived wastes is quite different from the $CO_2$ from biomass fuels. Greenhouse gas emissions generated by this type of source are reported in the "Energy" category as waste-to-energy conversion (IPCC 1996). The cement sector has several uncertainties for $CO_2$ inventories, and suggestions to minimize them. For instance, in the raw material consumption phase, double-counting may occur if the recycled dust is not taken into account. Additionally, in calculating the emission factors of fuels, the biomass carbon should be accounted for in tires and impregnated saw dust. Another report by CSI (n.d.) concentrated on $CO_2$ and energy performance related to the global cement industry. An independently conducted database called "Getting Numbers Right (GNR)" has been designed by CSI researchers to report the progress and reach the goal of reducing carbon emissions and energy consumption. This database may help producers to contribute and develop for sustained carbon and energy management.

#### *ii. Wood*

Woody biomass may also be investigated in terms of carbon accounting. An article by Walker et al. (2013) mentioned that forest biomass should be considered in both the short and the long term for its costs and benefit over fossil fuels. With conventional technologies, burning fossil fuels emits lower carbon emissions compared to burning forest biomass to get an equivalent amount of energy. However, in the long term, the emitted amount of carbon may be re-sequestered by growing forests. This article focuses on comparing two different energy generation technologies, forest biomass and fossil fuel, and has a carbon accounting scheme for each. Energy generation is a GHG intensive process but the amount of released GHG varies by applied technology. Writers indicate that forest biomass combustion can be considered as "carbon neutral" in the long term. They considered methane and NOx in the life cycle impact of the combustion process. As previously indicated in Figure 2.2-b by Mohareb and Kennedy (2012), during the growth phase of wood products, the carbon emissions are negative over time. Carbon emissions are positive for harvesting, processing and transportation.

### *2.4.4. Comparing the Cycles (Full LCA from Cradle to Grave)*

Figure 2.6 is a depiction of the compilation of five carbon flux figures. Biomass, harvested wood product, concrete and landfill carbon fluxes were studied by Mohareb and Kennedy (2012) and were previously depicted in Figure 2.2, while Figure 2.3 for asphalt was added. It should be noted that in Figure 2.6 the line locations and the heights of the indicators are not scaled relative to each other within an industry or between industries.

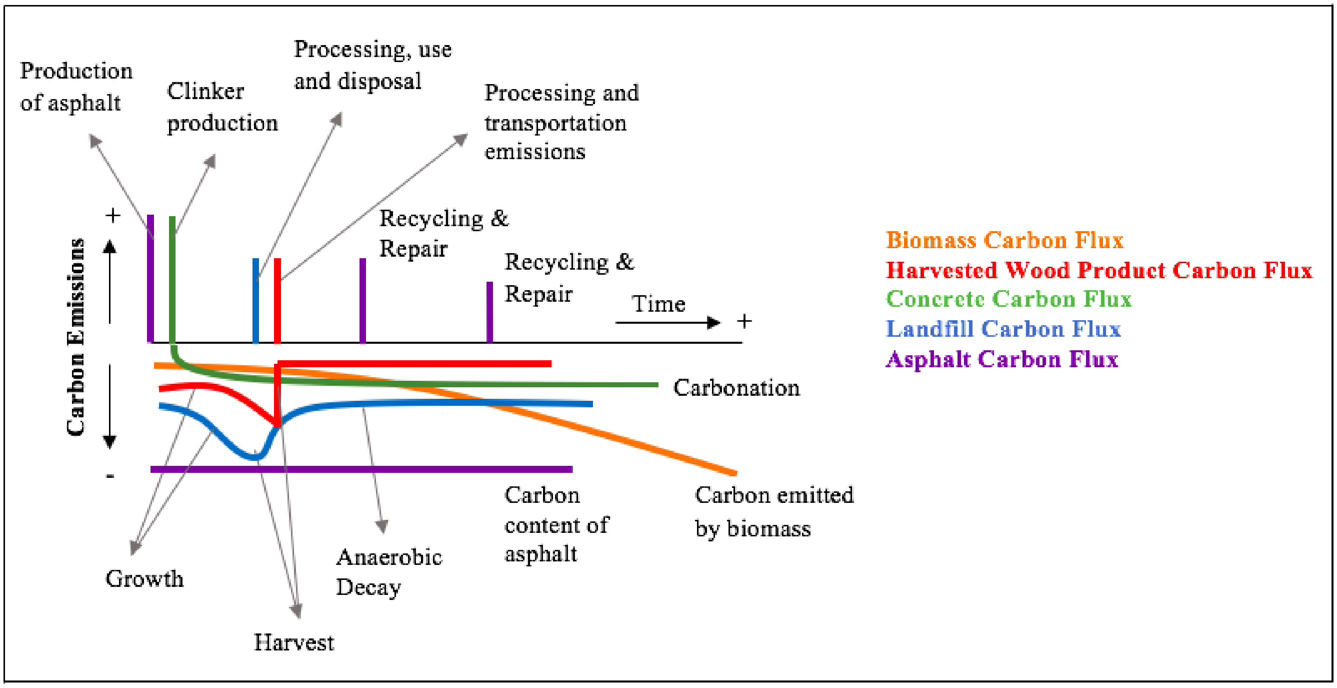



Figure 2.6. Comparing the cycles (Line locations are not relative between or within each sector).

### 2.5. Recyclability

There are several industries in which products can be recycled with high rates. In this part, the metals industry is examined by compiling EPDs and PCRs for aluminum, copper and steel products.

In an EPD for *Hot-Rolled Aluminum* (UL 2014) it is noted that aluminum is infinitely recyclable (assumed 95%) and it does not lose its properties after recycling. Additionally, producing recycled aluminum takes 8% of the energy needed to produce a virgin aluminum, and as a result associated emissions are lower than primary production. This EPD includes an additional stage in the system boundary called "Benefits and Loads Beyond the System Boundaries" and reuse, recycling and recovery potentials are investigated in this part. Allocation is considered and a broad explanation is given for this part as (UL 2014):

> *"Allocation is used to address recycled content, post-production scrap, and waste at end-of-life. The avoided burden allocation approach was applied. Under this approach, end-of-life scrap is first balanced out with any open scrap inputs into production. Only the remaining net scrap is then modeled as being sent to material recycling in order to avoid double-counting the benefits of using recycled content. If more scrap is recovered at product end-of-life than is required in the manufacturing stage, the product system receives a credit equal to the burden of primary material production minus the burden of recycling scrap into secondary material based on the mass of secondary material produced. This credit represents the avoided burden of primary material production."*

Copper is a highly recyclable material, and may be processed into new materials with a very low energy need. Energy savings are approximately 90% compared to primary metal production (IBU 2012a). System boundaries are considered as cradle-to-gate with options and *recycling of copper sheets at end-of-life* is included in this study. Again, this EPD includes *Benefits and Loads Beyond the System*

*Boundaries* stage and reuse, recycling and recovery potentials are investigated in this part.

The final example from metals industry is steel. In an EPD for *Hot-Rolled Steel* (IBU 2016), it is stated that steel piling products are 100% recyclable with the same quality.

An LCA of pavements, mainly for the use and end-of-life phase was conducted by Santero et al. (2011) which is detailed in Section 2.3. In this article, it is indicated that:

> *"Recycled materials are prevalent in a pavement as both inputs and outputs of the life cycle. In practice and theory, it may seem reasonable to assert that a pavement being studied in an LCA should be rewarded for both using recycled inputs and the creating recyclable outputs. However, from a global perspective, the benefits (and impacts) from recycling are shared between the producer and user of the recycled product; allocation between these groups is necessary in order to avoid double counting."*

## 3. OUTCOMES, CONCLUSIONS AND SCHEMES

The philosophy of *less is better* is frequently assumed with respect to energy accounting in LCA (Swart et al. 2015) and recommendations made with respect to energy accounting should be mindful of this. However, resource depletion may be an important issue to consider with respect to feedstock energy. Do we have enough of the resource to use for either energy or material? Which alternatives should we consider? Replacing the energy source or replacing the material source? And if we keep the material as material during its full cycle, should we maybe discard the *less is better* philosophy if the depletion is not significant. The outcomes, suggestions and conclusions of this literature compilation follows.

### 3.1. Outcomes

#### *3.1.1. Consistency in Feedstock Energy Allocation and Various Energy Definitions*

It is pertinent to remember that in ISO 14040 Section 4.3 g) it is specifically stated that there is no single method for conducting an LCA and that organizations using these standards can implement the LCA in a manner related to the application thereof. It is also important to understand that in the implementation of an LCA, the product or process system has inputs and outputs, and both of these are to be modeled (Section 5.2.3 of ISO 14040), part of the data collection (Section 5.3.2 of ISO 14040) and reported (Section 6 of ISO 14040). In fact, in Section 5.2.3 of ISO 14040 it specifically states that:

> *"Ideally, the product system should be modelled in such a manner that inputs and outputs at its boundary are elementary flow"*,

Where elementary flow is defined in Section 3.12 of ISO 14040 as:

> *"material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation"*

Furthermore, ISO 14040 states that an LCA is from extraction through the end-of-life, and ISO 14044 requires that (Section 4.2.3.3.1):

> *"Deletion of life cycle stages, processes, inputs or outputs is only permitted it if does not significantly change the overall conclusions of the study.*"

In Annex Section A.1.2 of ISO 14040 (ISO 2006a) it is stated that the LCA *technique* can be applied to studies that are not LCA such as cradle-to-gate or gate-to-gate studies. In other words, an LCA with the requirements as set forth in ISO 14044 (ISO 2006b) is for studies that are from extraction through the end-of-life. This is where feedstock energy is mandated to be reported, not necessarily for the separate stages at various gates. In addition, even though the definition of feedstock energy in ISO 14040 is based on energy, there is no mention as to whether it should or should not be included as a material or as an energy resource.

Resource depletion is a critical issue for the utilization and improvement of sustainability metrics and LCA techniques. However, it is difficult to evaluate without using a good deal of estimation and other uncertainties, and there may not be sufficient models to use for many components. Due to these constraints, a decision was made that the initial resource depletion categories which would be indicated within TRACI would be fossil fuel use, land use, and water use (US EPA 2012). In the CML methodology handbook, it is noted that characterization of depletion-related impact categories, which are abiotic and biotic resource depletions, are still discussed. Abiotic resources are considered as natural resources which also include energy resources and are nonliving (EC 2010). Depending on the research boundaries, *depletion of abiotic resources* impact category focuses on natural resources, human health and natural and man-made environment for protection. Those energy inputs and outputs should be taken into account as other inputs and outputs in the LCA study.

In many specific situations, there is a focus on the extraction of energy resources. Depletion of energy resources is dealt with in the impact assessment as a component of general abiotic depletion. Energy resource utilization might be determined using the total energy content of all the abiotic energy resources included. For instance, utilizing the heat values as determined in the ETH database on energy transformation forms. However, this total energy content does not represent the calculations from the impact assessment (Guinée et al. 2001a). Biotic resources are material resources and energy resources which are living. Depending on the framework, *depletion of biotic resources* impact category usually focuses on the same categories for protection as *depletion of abiotic resources* (Guinée et al. 2001b).

In both methodologies (TRACI 2.1 and CML) the resource depletion expressions are given but the calculation methods for them are not necessarily detailed. In the BEES manual (Lippiatt 2007) it is indicated that TRACI uses the approach developed for the Eco-Indicator 99 (EI-99 2000) methodology. In this methodology, the amount of energy required to extract a unit of energy for consumption is measured over time per functional unit of product. In addition, in several EPDs the impact category results are reported compatible with *BS EN 15804:2012 Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products* standard. However, many EPDs do not include the resource depletion results, and instead report the total use of these items, but with the *use of non-renewable primary energy used as raw materials* itemized. Some example EPD tables prepared in this way for the pavement and other industries are presented in Appendix C.

Figure C.1 is taken from EPD® (2016e) to represent an example from the construction industry. Even though the term feedstock energy is not used in this EPD, *use of non-renewable primary energy resources used as raw materials [MJ, net calorific value]* is listed in the raw materials supply phase and is reported in the environmental performance table. In Figure C.2 the expression *non-renewable primary energy as material utilization [MJ]* is used for the paving industry (IBU 2014b). Although not mentioned directly, this may be considered as feedstock energy. An example for the roofing industry (EPD® 2016d) is in Figure C.3. Again, the words feedstock energy have not been used, however a type of energy is reported in the environmental performance table as *use of non-renewable primary energy* *resources used as raw materials [MJ]*. Figure C.4 represents an example for the construction industry in which the *use of non-renewable primary energy resources used as raw materials [MJ, net calorific value]* is calculated in the energy and material resource use consumption results table (ASTM 2015c) but again, the term feedstock energy has not been directly used. Figure C.5 is a screenshot from another EPD for the paving industry (CSA 2016b) that has materials in a non-renewable material category based on mass. An example EPD from the wood industry has also reported material resource consumption in the same manner in a cradle-to-gate impact assessment (UL 2013a) as shown in Figure C.6. It is obvious that there are some issues of consistency in reporting the energy and materials. In addition to feedstock energy having different names, there are differing units (energy versus mass) and total primary energy may or may not include materials that have energy content available for use. Therefore, there may be confusion as to the terminology, double counting may be occurring, and the accounting performed may not have readily transferable units between the various declarations.

### *3.1.2. Consistency in Reporting of Energy and Carbon in Various Sectors*

Carbon and energy accounting are valuable tools to evaluate products in terms of their environmental performances. Carbon sequestration refers to the carbon stored in biogenic construction products for example biogenic carbon sequestration in wood materials, fossil carbon sequestration in asphalt and inorganic carbon sequestration in limestone or carbonated concrete. In many materials, carbon can be stored in a constructed facility such as a building or a roadway during its whole life and released during incineration or degradation (EPD® 2015b), or further sequestered when reused, recycled or landfilled. In one case in the literature, PCRs and EPDs require that carbon sequestration only be accounted when the end-of-life fate of that carbon is considered in the product's LCA study (UL 2013a). ISO 14040 (ISO 2006a), the governing international document for most LCAs, covers the full life cycle of a product, process or system from extraction through its end-of-life, and mentions that feedstock energy should be considered. Thus, feedstock energy has a purpose beyond EPD reporting. An EPD is a report based on LCA methodologies used to track certain resource and environmental impacts to that specific *gate*, i.e. that product before its use. Thus, the feedstock energy, and in many cases the carbon, in a material at this *gate* may be valuable assets for future use as energy or continued sequestration. Many EPDs have been formatted and reported in such a manner that does not readily capture these concepts, so that in a full LCA, the feedstock energy and/or carbon reporting can be optimized through to the end-of-life. This may not allow the users of EPDs to be able to fully understand and consider the impacts of feedstock energy, especially when looking at the carbon, recycling and other benefits of the material use of this resource.

Butt et al. (2014) focused on the construction, maintenance and disposal of asphalt pavements because of their high environmental impacts in terms of energy use and greenhouse gas emissions ($CO_2$, $N_2O$ and $CH_4$) during their lifetime. Special emphasis was given on the calculation and allocation of the energy used for binder and additives. It was found that the feedstock energy is highly valuable in terms of the cost of the binder. Because the feedstock energy has an alternative value as a fuel, this may affect the cost of the binder. The article also mentioned that feedstock energy in a life cycle study could be considered as *borrowed from the nature*. Butt et al. considered feedstock energy for generating energy, and also as stored within the asphalt materials when it is not consumed. Ventura and Santero (2012) have an article dealing with the way that feedstock energy is reported in LCAs. It gives several definitions on primary energy, secondary energy and process energy, and presents a relationship scheme between those energy types. It defines feedstock energy as "when organics are used as materials, the energy associated with much of this input remains incorporated in the product." The article defends that primary energy should not be included in the inventory table, but total primary energy should be calculated because it is considered as a resource depletion indicator. It implies that feedstock energy which is not combusted is *a loss of available resource.* These two articles interpret feedstock energy in two very different lights, one positive, the other negative. A simple question that one might ask for asphalt is whether there is a net zero impact if asphalt binder is extracted, processed, used and then returned to the Earth in a landfill, going back to whence it came. Until there are more guidance or consensus standards from a life cycle perspective of the fate of the items in a material or product EPD, they cannot be used in a fair comparative manner for material selection.

An interesting aside from these investigations is how *non-renewable* is used for both energy, and then if that energy resource is used as a material, for many material resources. Asphalt as an energy resource would be considered as *non-renewable* and might therefore be categorized as *non-renewable* with respect to feedstock energy, although it might be conserved. However, as per the European Commission (EC 2010) some biogenic resources such as primary forests or peat are also considered to be *non-renewable*. This makes another case for confusion when using the term *non-renewable* without better definitions, especially with respect to timeframes and recyclability. In addition, if there are other reporting requirements that deal with material flows and if the use of the asphaltic binder is included in those flows, then this may result in double counting of the material.

## 3.2. Conclusions and Suggestions for EPD Schemes

This report is a literature review of the reporting of feedstock energy and similar terms in scientific reports, articles, tools and standardization documents. In the following sections, remember that life cycle assessment (LCA) is a methodology for quantitatively estimating the potential impact that a product or process may have on the environment over its lifetime. Whereas, environmental product declarations (EPDs) are reports which present the results of using the LCA methodology on a product to a certain gate, such as prior to use, along with other relevant information, in a condensed and digestible format. Also remember that feedstock energy is typically defined as the “heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value.” (ISO 2006a).

### *3.2.1. Conclusions*

The findings from this report for these items are as follows. The first bulleted items describe two different types of *allocation* issues, and the rest deal with the current lack of harmonization and consistency.

- ISO 14040 (2006a) requires that an LCA is from cradle to end-of-life. However, EPDs are typically to a gate such as prior to use. Therefore, inclusion of feedstock energy in an EPD may create confusion if there is no mechanism to determine whether the material, or its energy will be *allocated* as a negative or as a positive impact to the processes before, or the processes after the gate. Remember that ISO 14044 (2006b) indicates that this type of *allocation* should be avoided *wherever possible*. Typically, in LCA, the word *allocation* is used in this manner, as related to *allocation* to which process or product or system or life stage.
- In many documents, the equivalent of feedstock energy is referred to as “Use of non-renewable primary energy used as raw materials”. This and the ISO 14040 (2006a) definition provide the mechanism to report as either material or energy, ISO 14040 does not state as whether feedstock energy should be considered as a material or an energy resource. This is a different type of *allocation* in EPDs and other reporting that seems to create confusion. This is an *allocation* to a

material or an energy category, and with both options may cause uncertainty as to whether there may be double counting.

- There are differing units (energy versus mass) for the reporting of feedstock energy or its assumed equivalent in many of the reports, EPDs and other documents reviewed. There were no unit conversion methodologies provided.
- There are varying opinions as to whether total primary energy (or in some cases embodied energy) includes or does not include materials that have energy content available for use.
- There is also confusion on using terms such as use of non-renewable material resources, as many standards instead base environmental LCA work on abiotic resource depletion, which includes not just the use of a resource, but also availability. Depletion categories therefore including additional information on the impact of its use. LCAs are also intended to provide information on potential impacts, not simply use.
- These issues were also found in the paving industry.

The preliminary conclusions are that EPDs are not currently harmonized or understood well enough to be required to be used for comparative material selection. As previously stated, the main reasons are that there are inconsistencies in terminology, reporting of depletion versus use may have different interpretations or impacts, there might be double counting of some items such as feedstocks as an energy and/or a material item, and EPDs are typically not presented in a format that differentiates to the user or decision-maker how the various terms and quantities might be interpreted as positive and/or negative impacts such as with respect to recyclability. In addition, there are few, if any, methods that facilitate life cycle carbon counting when carbon is stored in a feedstock.

### *3.2.2. Suggestions for EPD Schemes for Asphalt*

Asphalt is a product type that has two features which might require special consideration in LCA. The first is that it is highly recyclable such as many metals. In addition, it has a stored carbon content such as wood, plastics and concrete. This research indicates that feedstock energy and carbon accounting for asphalt pavement can be adequately reported based on EN 15804 “Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products” (BS EN 2012) to capture both the recyclability aspects of the energy and the carbon contained in the feedstock energy. This standard already has a method for differentiating between primary energy resources used as energy or as materials (whether from renewable or non-renewable sources) which would be used to separate out feedstock energy. To capture the recyclability of feedstock energy the optional Module D, could be included. In addition, this standard provides for reporting other environmental information, which may be a mechanism for reporting carbon content stored in the bitumen. Thus, the conclusion of this research is that this international standard could be followed with the inclusion of some options to more adequately present environmental and resource use information for a material that is both highly recyclable, and has stored primary energy and carbon content in the material (feedstock energy). The following methodology for EPD presentation, when used in its entirety should affect a better representation of materials such as asphalt used in pavements, capturing both its primary use and as recycled.

EN 15804 (BS EN 2012) in Section 5.2 lists the following potential modules in a product’s life:

- Product Stage: Modules A1-A3: Raw material, transport, Manufacturing;
- Construction Stage: Modules A4-A5: Transport, Construction/Installation process;

- Use Phase Modules: Building Fabric (B1-B5) and Operation (B6-B7): where specifically Modules B1 through B7 are: Use, Maintenance, Repair, Replacement, Refurbishment, Operational Energy Use, and Operational Water Use;
- End-of-life Stage: Modules C1-C4: Deconstruction/demolition, Transport, Waste Processing, and Disposal; and
- Benefits and loads beyond the system boundary, Information Module: D: Which may include reuse-recovery-recycling potential (Supplementary information beyond the building life cycle).

Modules A1, A2 and A3 are required in an EPD, and all the other modules are optional. In many instances, asphalt should be adequately handled with Modules A1, A2, A3 and D in the EPD with the remaining modules not declared. Note that in addition to Module D being included in some EPDs for metals such as copper, it is also included in some asphalt roofing analyses as shown in Figure C.3 (UL 2014, EPD®2016d). Information Module D is specifically for "reusable products, recyclable materials and/or useful energy carriers leaving a product system" (BS EN 2012). In this scheme, the *Description of the System Boundary* would be as depicted in Table 3.1. Table 3.1 could be used to capture the characteristics of asphalt whether there is in-plant or in-place recycling, or no recycling as asphalt pavement, and these will be detailed separately later.

According to EN 15804 (BS EN 2012) A1 includes recycling processes upfront and could be used for in-plant recycling, whereas in-place recycling would be in one of the B modules in addition to a reduction in the amount of asphalt from the plant. Note also, that the EN 15804 standard follows both the "modularity principle" which means that elementary environmental inputs and outputs should be assigned to the module where they appear, and the "polluter pays principle" which means that waste is assigned to the system that generates the waste until the end-of-waste stage. Therefore, virgin feedstock energy belongs in A1, but recycled feedstock energy does not belong in A1.

Table 3.1. Description of the System Boundary (Y=Included: N=Module Not Declared)

| **Stage** | **Product** | | | **Construction** | | **Use** | | | | | | | **End-of-Life** | | | | **Benefits/Loads Beyond System Boundary** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Module** | A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| **Included** | Y | Y | Y | N | N | N | N | N | N | N | N | N | N | N | N | N | Y |

According to EN 15804 (BS EN 2012) in Section 6.3.9 all resources are in the units of kg except:

- resources used for energy input (primary energy) as kWh or MJ,
- water as $m^3$,
- temperature as degrees Celsius, and
- time as practical (minutes, hours, days, years).

EN 15804 (BS EN 2012) in Section 6.5 requires reporting the following impact assessments. ADPE and ADPF are to be calculated using the CML method (EC 2010), and ADPF shall be reported in net caloric values at the point of extraction.

- Global warming (GWP),
- Ozone depletion (ODP),
- Acidification (AP),
- Eutrophication (EP),
- Smog Formation (SP),
- Depletion of abiotic resources elements (ADPE), and
- Depletion of abiotic resources fossil (ADPF).

EN 15804 (BS EN 2012) in Section 7.2.4 requires the reporting of various resource use parameters including the following related to non-renewable primary energy resources (in MJ, net caloric value).

- Use of non-renewable primary energy resources excluding non-renewable primary energy resources used as raw materials (PENRE);
- Use of non-renewable primary energy resources used as raw materials (PENRM), i.e. feedstock energy;
- Total use of non-renewable primary energy resources (PENRT) - primary energy plus primary energy resources used as raw materials.

EN 15804 (BS EN 2012) in Section 7.3.4 allows for additional technical information at the end-of-life provided that the information on this as per Table 12 in EN 15804 is included. The examples in Table 12 of the EN 15804 standard include recovery systems such as recycling. This option could be used for the carbon content in the asphalt and would be applicable to many end-of-life options, whether landfilled, recycled or used for energy. However, to be consistent with reporting in all the modules, it is suggested that the same information on carbon content also be listed in Module A1, indicative of the near carbon neutrality of this particular aspect of the material, not accounting for minor losses to the environment during the use and other stages. Including stored carbon is consistent with some practices in the wood industry (ASTM 2016d).

Table 3.2 represents these aforementioned characteristics related to feedstock energy and carbon counting that might affect more informative EPDs. Note that Table 3.2 does not depict all the required items, just those most related to feedstock energy and carbon.

Table 3.2. Sample Reporting of Portions of an EPD Related to Feedstock Energy and Carbon

| | **Product**<br>Modules A1, A2 and A3 | **Benefits Beyond System Boundary**<br>Information Module D |
|---|---|---|
| **GWP** | Reported in kg $CO_2$ equiv. | -- |
| **ADPF** | Reported in MJ | -- |
| **PENRE** | Reported in MJ | -- |
| **PENRM (Feedstock Energy)** | Reported in MJ* | Reported in MJ* |
| **PENRT** | Reported in MJ^ | Reported in MJ^ |
| **Carbon Content** | Reported in kg $CO_2$* | Reported in kg $CO_2$* |

*Feedstock energy, and related carbon reported as $CO_2$ stored as material in the asphalt.
^Includes feedstock energy stored as material in the asphalt.

The following scenarios in Table 3.3 depict how the applicable rows in Table 3.2 might be completed for virgin asphalt, in-plant recycling (assume 50%), and in-place recycling (assume reduce hot mix binder needed by 50%). The values in Table 3.3 are fictional and are not indicative of actual mixes or products. Note that the values in the Information Module D might be slightly less than the Product Modules as there may a small amount of loss to the environment.

Table 3.3. Sample Scenarios Related to Feedstock Energy and Carbon Reporting[1]

| | **Product** Modules A1-A3 | **Benefits Beyond System Boundary** Information Module D |
|---|---|---|
| **Scenario 1: All Virgin** | | |
| **GWP** | X kg $CO_2$ equiv | -- |
| **ADPF** | < (Y + Z) MJ | -- |
| **PENRE** | Y MJ | -- |
| **PENRM** | Z MJ* | ~Z MJ* |
| **PENRT** | (Y + Z) MJ^ | ~Z MJ^ |
| **Carbon Content** | W kg $CO_2$-e* | ~W kg $CO_2$-e* |
| **Scenario 2: 50% In-plant** | | |
| **GWP** | A kg $CO_2$ equiv | -- |
| **ADPF** | < (B + 0.5Z) MJ | -- |
| **PENRE** | B MJ | -- |
| **PENRM** | 0.5Z MJ* | ~Z MJ* |
| **PENRT** | (B + 0.5Z) MJ* | ~Z MJ^ |
| **Carbon Content** | ~0.5W kg $CO_2$-e* | ~W kg $CO_2$-e* |
| **Scenario 3: 50% In-place** | | |
| **GWP** | X kg $CO_2$ equiv | -- |
| **ADPF** | < (Y + Z) MJ | -- |
| **PENRE** | Y MJ | -- |
| **PENRM** | Z MJ* | ~Z MJ* |
| **PENRT** | (Y + Z) MJ^ | ~Z MJ^ |
| **Carbon Content** | W kg $CO_2$-e* | ~W kg $CO_2$-e* |

[1] The values listed are fictional and are assumed to be on a declared unit basis. A functional unit basis and inclusion of some B modules may be needed to capture the recycling benefits of Scenario 3.
* Feedstock energy, and related carbon reported as $CO_2$ stored as material in the asphalt.
^ Includes feedstock energy stored as material in the asphalt.

The values for PENRM and the Carbon Content in Table 3.3 are consistent with the methodology used by Miliutenko et al. (2013), who allocated the feedstock energy to the virgin asphalt only. In Table 3.3 the benefit of in-place recycling of the asphalt is not captured as the information in Table 3.3 is based on a declared unit of mass or volume of asphalt from the plant. To capture the benefit of in-place recycling, a functional unit would need to be used such as area of pavement, in which case the amount of asphalt from the plant used would be reduced similar to the in-plant scenario, but differences in the two processes (in-plant versus in-place) would need to be captured by inclusion of Modules B3 or B4 as applicable. Note that the in-plant and in-place scenarios are very similar as related to the 50% feedstock replacement assumption, but could vary with actual primary energy use and GWP as noted by other researchers (Miliutenko et al. 2013, Santos et al. 2015a).

The US EPA (US EPA 2015b) provides additional information for relating the variables in Table 3.3 for the United States. Out of the 17.1 MMT (million metric tons) of carbon estimated to be stored annually in the United States in asphalt, only approximately 0.1 MMT of this is estimated to be lost. This and other factors from that report are summarized and converted to various units in Table 3.4. Based on the information from this report, the Module D values for PENRM and Carbon Content would be approximately 0.994Z and 0.994W respectively.

Table 3.4. Carbon Stored in Asphalt Annually in the United States (US EPA 2015b)

| | As C (MMT) | As $CO_2$ (MMT) | MMTC per $10^{15}$BTU* | MMT$CO_2$ per $10^{15}$BTU* | kg C/MJ* | kg $CO_2$/MJ* |
|---|---|---|---|---|---|---|
| **C Stored** | 17.1 | 62.7 | 20.55 | 75.35 | 0.019 | 0.071 |
| **C Lost** | 0.03-0.16 | 0.1-0.6 | -- | -- | -- | -- |

* Feedstock energy stored.

Thus, this report is suggesting that the asphalt paving industry might consider the following approach for EPDs, to be consistent with EN 15804 (BS EN 2012), and capture the unique energy and carbon characteristics of the use of asphalt in pavements.

- Requiring the reporting of Modules A1-A3 <u>and Module D</u> in both the impact and the use tables.
- Using the term *depletion of abiotic resources – fossil* in the impact table and the term *use of non-renewable primary energy as a material* (or something similar) in the use table, but noting that feedstock energy is another term for this energy resource used as a material.
- For consistency defining Total Primary Energy or Cumulative Energy Demand (CED) to include feedstock energy, but requiring that the breakdown of how much is used as energy, and how much as material, are always included when reporting these totals.
- Defining embodied energy to not include feedstock energy.
- Including carbon equivalents of the carbon stored in the asphalt in Modules A1-A3 and Module D in the impact table.
- Considering the inclusion of Modules B3 or B4 (as applicable) and basing the analyses on functional units instead of declared units for life cycle assessments for in-place recycling, or a similar cradle-to-grave type reporting.

**ADDITIONAL ACKNOWLEDGEMENTS**

I would like to thank Sila Temizel-Sekeryan, Quinn Langfitt, Heather Dylla and Richard Willis for their contributions to this study.

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## APPENDIX A

Table A. 1. Standards Reviewed for Energy Definitions.

| **Standard Name** | **Reference** |
|---|---|
| ASTM E2114 − 08: Standard Terminology for Sustainability Relative to the Performance of Buildings | (ASTM 2008) |
| ASTM E2129 − 10: Standard Practice for Data Collection for Sustainability Assessment of Building Products | (ASTM 2010) |
| ASTM E2921 – 16a: Standard Practice for Minimum Criteria for Comparing Whole Building LCAs for Use with Building Codes, Standards, and Rating Systems | (ASTM 2016j) |
| ASTM E1705 − 15: Standard Terminology Relating to Biotechnology | (ASTM 2015g) |
| ASTM E1971 − 05 (2011): Standard Guide for Stewardship for the Cleaning of Commercial and Institutional Buildings | (ASTM 2011a) |
| ASTM E2432 − 11: Standard Guide for General Principles of Sustainability Relative to Buildings | (ASTM 2011b) |
| ASTM E711 − 87: Standard Test Method for Gross Calorific Value of Refuse-Derived Fuel by the Bomb Calorimeter (Withdrawn 2011) | (ASTM 1996) |
| ISO 21930:2007 − Sustainability in building construction – Environmental declaration of building products | (ISO 2007) |
| ISO 14040:2006 − Environmental management - Life cycle assessment - Principles and framework | (ISO 2006a) |
| ISO 14021:2016 − Environmental labels and declarations - Self-declared environmental claims (Type II environmental labelling) | (ISO 2016a) |
| BS EN 15804:2012 − Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products | (BS EN 2012) |
| ISO 14044:2006 − Environmental Management - Life cycle assessment - Requirements and guidelines | (ISO 2006b) |
| ISO 14050:2009 − Environmental management -Vocabulary | (ISO 2009) |
| ISO 14064-1:2006 − Greenhouse gases — Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals | (ISO 2006d) |
| ISO 14064-2:2006 − Greenhouse gases — Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements | (ISO 2006e) |
| ISO 14064-3:2006 − Greenhouse gases — Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions | (ISO 2006f) |
| ISO 15686-6:2004 − Buildings and constructed assets - Service life planning - Part 6: Procedures for considering environmental impacts | (ISO 2004) |
| ISO 14025:2006 − Environmental labels and declarations - Type III environmental declarations - Principles and procedures | (ISO 2006c) |
| EN 15942:2011 − Sustainability of Construction Works - Environmental Product Declarations - Communication Format Business-to-business | (EN 2011) |

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| ASTM E833 − 14: Standard Terminology of Building Economics | (ASTM 2014f) |
| ASTM E943 − 08 (2014): Standard Terminology Relating to Biological Effects and Environmental Fate | (ASTM 2014g) |
| ASTM D6400 − 12: Standard Specification for Labeling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities | (ASTM 2012) |
| ASTM E870 − 82 (2006): Standard Test Methods for Analysis of Wood Fuels | (ASTM 2006) |
| ASTM E631 − 15: Standard Terminology of Building Constructions | (ASTM 2015h) |
| ISO/FDIS 13315-4:2016 – Environmental management for concrete and concrete structures – Part 4: Environmental design of concrete structures | (ISO 2016b) |
| ISO 14020:2000 − Environmental labels and declarations - General principles | (ISO 2000) |

Table A. 2. Energy Definition Matrix from Standards

| Standard Name | Energy Definitions | Reference |
|---|---|---|
| **ASTM E2114 − 08: Standard Terminology for Sustainability Relative to the Performance of Buildings** | **Alternative energy** — see renewable energy. | (ASTM 2008) |
| | **Cogeneration** — the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy stream, such as oil, coal, natural or liquefied gas, biomass, or solar. | |
| | **Embodied energy** — the energy used through the life cycle of a material or product to extract, refine, process, fabricate, transport, install, commission, utilize, maintain, remove, and ultimately recycle or dispose of the substances comprising the item. DISCUSSION—The total energy which a product may be said to *"contain"* including all energy used in, inter alia, growing, extracting, transporting, and manufacturing. The embodied energy of a structure or system includes the embodied energy of its components plus the energy used in construction. | |
| | **Energy recovery** — obtaining usable energy by consuming waste through a variety of processes. | |
| | **Renewable energy** — energy obtained from renewable or perpetual resources, including wind, solar, ocean (including tidal, wave, current, and thermal), geothermal, biomass, and hydroelectric energy resources. DISCUSSION—Adapted from the definition of renewable energy resources in Terminology E1705. | |
| **ASTM E2129 − 10: Standard Practice for Data Collection for Sustainability Assessment of Building Products** | **Energy efficient** — refers to a building product that requires less energy to manufacture or uses less energy, or both, when operating in comparison with a benchmark for energy use. | (ASTM 2010) |

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| **ASTM E2921 – 16a: Standard Practice for Minimum Criteria for Comparing Whole Building LCAs for Use with Building Codes, Standards, and Rating Systems** | **Operating energy** — energy loads that are related to building space conditioning, lighting, service water heating or ventilation for human comfort. | (ASTM 2016j) |
| | **Plug loads** — all energy use by devices, appliances and equipment connected to convenience receptacle outlets during the building service life. | |
| | **Process energy** — energy loads that are not directly related to building space conditioning, lighting, service water heating or ventilation for human comfort, sometimes referred to as “process loads.” | |
| **ASTM E1705 − 15: Standard Terminology Relating to Biotechnology** | **Renewable energy resources** — sources of energy that are regenerative or virtually inexhaustible, such as solar, wind, ocean, biomass, municipal wastes, and hydropower energy. Geothermal energy is sometimes also included in the term. | (ASTM 2015g) |
| **ASTM E1971 − 05 (2011): Standard Guide for Stewardship for the Cleaning of Commercial and Institutional Buildings** | **Non-renewable resource** — a resource that exists in a fixed amount in various places in the earth’s crust and that cannot be replenished on a human time scale. | (ASTM 2011a) |
| | **Renewable resource** — a resource that is grown, naturally replenished, or cleansed, at a rate which exceeds depletion of the usable supply of that resource. | |
| **ASTM E2432 − 11: Standard Guide for General Principles of Sustainability Relative to Buildings** | **Non-renewable resource** — resource that exists in a fixed amount that cannot be replenished on a human time- scale. | (ASTM 2011b) |
| | **Renewable resource** — a resource that is grown, naturally replenished, or cleansed, at a rate which exceeds depletion of the usable supply of that resource. | |
| | **Carbon sinking** — an approach to offset carbon dioxide emissions through the absorption potential of forests and other vegetation. | |

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|---|---|---|
| **ASTM E711 − 87: Standard Test Method for Gross Calorific Value of Refuse-Derived Fuel by the Bomb Calorimeter (Withdrawn 2011)** | **Calorific value** — the heat of combustion of a unit quantity of a substance. It may be expressed in joules per gram (J/g), British thermal units per pound (Btu/lb), or calories per gram (cal/g) when required. | (ASTM 1996) |
| | **Gross calorific value** — the heat produced by combustion of a unit quantity of solid fuel, at constant volume, in an oxygen bomb calorimeter under specified conditions such that all water in the products remains in liquid form. | |
| | **Net calorific value** — a lower value calculated from the gross calorific value. It is equivalent to the heat produced by combustion of a unit quantity of solid fuel at a constant pressure of one atmosphere, under the assumption that all water in the products remains in the form of vapor. | |
| | **Refuse-derived fuels** — solid forms of refuse-derived fuels from which appropriate analytical samples may be prepared are defined as follows in ASTM STP 832:7:<br>***RDF-1***—Wastes used as a fuel in as-discarded form with only bulky wastes removed.<br>***RDF-2***—Wastes processed to coarse particle size with or without ferrous metal separation.<br>***RDF-3***—Combustible waste fraction processed to particle sizes, 95 % passing 2-in. square screening. ***RDF-4***—Combustible waste fraction processed into powder form, 95 % passing 10-mesh screening. ***RDF-5***—Combustible waste fraction densified (compressed) into the form of pellets, slugs, cubettes, or briquettes. | |
| **ISO 21930:2007 − Sustainability in building construction – Environmental declaration of building products** | **Non-renewable resource** — resource that exists in a fixed amount that cannot be replenished on a human time scale | (ISO 2007) |
| | **Renewable resource** — resource that is grown, naturally replenished or cleansed on a human time scale. Examples: Trees in forests, grasses in grasslands and fetile soil. NOTE: A renewable resource is capable of being exhausted but can last indefinitely with proper stewardship. | |

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| **ISO 14040:2006 − Environmental management - Life cycle assessment - Principles and framework** | **Elementary flow** — material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation | (ISO 2006a) |
| | **Energy flow** — input to or output from a unit process or product system, quantified in energy units. Note: Energy flow that is an input can be called an energy input, energy flow that is an output can be called an energy output | |
| | **Feedstock energy** — heat of combustion of a raw material that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value | |
| | **Process energy** — energy input required for operating the process or equipment within a unit process, excluding energy inputs for production and delivery of the energy itself. | |
| | **Raw material** — primary or secondary material that is used to produce a product. Note: Secondary material includes recycled material. | |
| | **Input** — product, material or energy flow that enters a unit process. Note: Products and materials include raw materials, intermediate products and co-products | |
| | **Intermediate flow** — product, material or energy flow occurring between unit processes of the product system being studied | |
| | **Output** — product, material or energy flow that leaves a unit process. Note: Products and materials include raw materials, intermediate products, co-products and releases. | |
| **ISO 14021:2016 − Environmental labels and declarations - Self-declared environmental claims (Type II environmental labelling)** | **Recovered material** — material that would have otherwise been disposed of as waste or used for energy recovery, but has instead been collected and recovered as a material input, in lieu of new primary material, for a recycling or a manufacturing process | (ISO 2016a) |
| | **Offsetting** — mechanism for compensating for the carbon footprint of a product through the prevention of the release of, reduction in, or removal of, an equivalent amount of GHG emissions in a process outside the boundary of the product system. Example: External investment in renewable energy technologies; energy efficiency measures; afforestation/reforestation. | |

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|---|---|---|
| **BS EN 15804:2012 – Sustainability of Construction Works - Environmental Product Declarations - Core Rules for the Product Category of Construction Products** | **Non-renewable energy** — energy from sources which are not defined as renewable energy sources. | (BS EN 2012) |
| | **Non-renewable resource** — resource that exists in a finite amount that cannot be replenished on a human time scale. | |
| | **Renewable energy** — energy from renewable non-fossil sources. Examples: wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill, gas, sewage treatment plant gas and biogases. | |
| | **Renewable resource** — resource that is grown, naturally replenished or naturally cleansed, on a human time scale. NOTE: A renewable resource is capable of being exhausted, but may last indefinitely with proper stewardship. Examples include: trees in forests, grasses in grassland, fertile soil. | |
| **ISO 14044:2006 – Environmental Management - Life cycle assessment - Requirements and guidelines** | **Elementary flow** — material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation. | (ISO 2006b) |
| | **Energy flow** — input to or output from a unit process or product system, quantified in energy units. NOTE: Energy flow that is an input can be called an energy input, energy flow that is an output can be called an energy output. | |
| | **Feedstock energy** — heat of combustion of a raw material that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value. | |
| | **Process energy** — energy input required for operating the process or equipment within a unit process, excluding energy inputs for production and delivery of the energy itself. | |
| | **Raw material** — primary or secondary material that is used to produce a product. NOTE: Secondary material includes recycled material. | |
| | **Input** — product, material or energy flow that enters a unit process. NOTE: Products and materials include raw materials, intermediate products and co-products | |
| | **Intermediate flow** — product, material or energy flow occurring between unit processes of the product system being studied. | |
| | **Output** — product, material or energy flow that leaves a unit process. NOTE: Products and materials include raw materials, intermediate products, co-products and releases. | |

## APPENDIX B

Table B.1. ISO 14025 Program Operators and Other Programs for LCA Based Environmental Claims that were Reviewed for this Appendix

| **Program Operator** | **Country** | **Used**[1] |
|---|---|---|
| Eco-Leaf Environmental Label | Japan | No |
| Korean Environmental Industry & Technology Institute – Environmental Declaration of Products | Korea | No |
| The Sustainability Consortium (TSC) | USA | No |
| SCS Global Services | USA | No |
| Environmental Protection Agency (EPA) | USA | No |
| US Energy Information Administration | USA | No |
| Environmental Certification Center of China State Environmental Protection | China | No |
| Agenda de la Construcción Sostenible | Spain | No |
| Institute for Environmental Research and Education (IERE) | USA | No |
| FP Innovations | Canada | No |
| Environmental and health reference data for building (INIES) | France | No |
| French Agency on Environment and Energy Management (ADEME) French standardization organization (AFNOR) | France | No |
| Building Information Foundation - RT Environmental Declaration | Finland | No |
| Danish Building Research Institute | Denmark | No |
| BRE Environmental Profiles Certification Scheme for Building Materials | UK | No |
| EPD Denmark Danish Standards | Denmark | No |
| British Standards Institute | UK | No |
| Spanish Association for Standardization and Certification (AENOR) | Spain | No |
| Association P.E.P. | France | No |
| Sustainable Minds | USA | No |
| European Commission Directorate General Environment | EU | No |
| Greenhouse Gas Protocol | USA | No |
| ASTM International | USA | **Yes** |
| The Norwegian EPD Foundation | Norway | **Yes** |
| The International EPD System | Sweden | **Yes** |
| CSA Group (Canadian Standards Association) | Canada | **Yes** |
| ICC Evaluation Service | USA | **Yes** |
| NSF International | USA | **Yes** |
| UL Environment | USA | **Yes** |
| IBU Institute Construction and Environment e.V. | Germany | **Yes** |
| Carbon Leadership Forum | USA | **Yes** |
| Taiwan EPA/Environment and Development Foundation (EDF) | Taiwan | **Yes** |

[1] **No:** There are not any PCRs and EPDs developed related to our targeted product groups within the scope of this project. **Yes:** PCRs, EPDs and related standards are downloaded.

Table B.2. Feedstock Energy Allocation as Material or Energy Resource for Paving Industry

| Program Operator | Ref. Type | Product Group | Feedstock Energy Allocation | Reference |
|---|---|---|---|---|
| ASTM | PCR | Slag cement (ground granulated blast-furnace slag) | It is noted that feedstock used to produce materials must be allocated as material resources (kg), and process energy must be allocated as energy resources (MJ) | (ASTM 2014a) |
| ASTM | PCR | Interlocking concrete pavers, segmental concrete paving slabs, concrete grid paving units; structural, architectural, specialty, utility, and drainage precast concrete products used on, above, and below ground excluding concrete pavers and concrete masonry; concrete masonry units, segmental retaining wall units, articulating concrete block, and related units | Recycled and recovered materials should be considered as raw materials and if they have fuel content and used as fuels, they must be allocated as alternative energy. Further, in case of incineration for the recovery of the product/energy, the combustion emissions must be allocated to the paving product. It is noted that if there is a usage of feedstock energy used as energy should be declared and shown separately. | (ASTM 2016a, 2015a, 2014b) |
| ASTM | PCR | Portland, blended hydraulic, Portland-limestone, masonry, mortar, and plastic (stucco) cements; clay brick, clay brick pavers, and structural clay tile; any combination of sand, gravel, crushed stone, crushed concrete, iron and / or steel slag, sold to or used by the construction industry | It is noted that special care should be taken since potential for incidents that can have impacts on the environment such as energy content of the product for energy recovery in the end-of-life. | (ASTM 2014c, 2016b, 2017a), |
| ASTM | PCR | Expanded shale, clay, and slate lightweight aggregate in all applications but primarily in masonry, concrete, asphalt pavement, lightweight geotechnical fills, horticulture, soil amendment, and water treatment | In case of incineration for the recovery of the product/energy, the combustion emissions must be allocated to the product. It is noted that if there is a usage of feedstock energy used as energy should be declared and shown separately. | (ASTM 2015b) |

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|---|---|---|---|---|
| UL | EPD | Concrete masonry units | In this report, non-renewable primary energy demand is expressed as MJ and non-renewable material resources are reported as kg separately in the *LCA Results – Use of resources* part. | (UL 2016) |
| Carbon Leadership Forum | PCR | Concrete | In inventory part, energy from waste recovery is given in a separate row. There is a statement that indicates that all energy consumption is considered for all process phases for both production and services. Further, it is noted that all alternative fuels (recycled waste) must be quantified. | (CLF 2012) |
| The Norwegian EPD Foundation | PCR | Asphalt and crushed stone | In the report, input of non-renewable primary energy not including feedstock (non-renewable energy resources) as MJ and input of non-renewable feedstock (MJ) are reported as separate items in the impact assessment part, *Resources* table. | (epd-norge 2010) |
| Environment and Development Foundation | PCR | Flame Retardant Building Materials of Fiber Cement / Fiber Reinforced Cement and Gypsum Board | In this PCR, the energy content of the products is identified as useful information for the end-of-life management and declared in MJ. It is indicated that only the energy that is suitable for an eventual energy recovery at the end-of-life shall be considered. Further, the energy content of biomass used for feed or food purposes shall not be considered. | (EDF 2015) |
| IBU Institut Bauen und Umwelt e.V. | EPD | UK Average Portland Cement; cement produced in Turkey; calcium aluminate cement; concrete admixtures – plasticizers and superplasticizers; concrete admixtures – retarders; concrete admixtures | In the EPD report, in *Results of the LCA – Resource Use* table, non-renewable primary energy used as energy carrier (MJ) and non-renewable primary energy used for material utilization (MJ) are indicated individually. | (IBU 2013a, 2013b, 2014a, 2014b, 2014c, 2012b, 2014d) |
| The International EPD System | EPD | Flexible Bitumen Sheets for Roof Waterproofing | In *Environmental Performance* table, use of non-renewable primary energy resources used as raw material is reported separately as MJ net calorific value and the whole EPD divided into stages. | (EPD® 2016d) |

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|---|---|---|---|---|
| The International EPD System | PCR | Concrete | In *Parameters Describing the Resource Use* section of this PCR, use of non-renewable primary energy resources used as raw materials is reported separately as MJ net calorific value. Further, a guidance text is written to clarify the term and it is indicated that non-renewable primary energy used as an energy carrier and not used as raw materials. | (EPD® 2013a) |
| The International EPD System | EPD | Concrete, cement, green asphalt, ready mixed concrete using cement, Portland cement | In *Use of Resources* table, use of non-renewable primary energy used as energy resource and non-renewable primary energy used as raw materials are reported separately as MJ net calorific value. | (EPD® 2016a, 2016b, 2017a, 2016c, 2014a) |
| The International EPD System | EPD | Aggregates, grey cements, ready-mix concrete- | In the EPD report, in *Results* table, non-renewable primary energy used as energy carrier (MJ) and non-renewable primary energy used for material utilization (MJ) are indicated individually. | (EPD® 2014b, 2014c, 2014d) |
| The International EPD System | EPD | Spunbond Reinforcements for Bituminous Membranes Made of Recycled Polyester | In the EPD, it is indicated that each kg of finished product has a calorific value (feedstock energy) which can be converted into useful energy as a raw material. There are not any tables given regarding the relationship of non-renewable primary energy resources. | (EPD® 2011) |
| The International EPD System | EPD | Ready-mix concrete | In the EPD, non-renewable energy sources without energy content (kg) is reported in *Use of resources without energy content* table and non-renewable resources with energy content (MJ-thermic) is reported in *Use of resources with energy content* table. | (EPD® 2006) |

Table B.3. Feedstock Energy Allocation as Material or Energy Resource for Other Industries

| **Program Operator** | **Ref. Type** | **Product Group** | **Feedstock Energy Allocation** | **Reference** |
|---|---|---|---|---|
| ASTM | PCR | Thermoplastic or thermoset membrane of compounded synthetic materials for use in roofing and waterproofing | In the allocation rules part of this PCR, is noted that *non-renewable energy flows* (i.e. feedstock) used to produce materials must be counted separately and reported as non-renewable fossil energy in MJ and it contributes to total primary energy consumption. | (ASTM 2016c) |
| ASTM | PCR | Wood stile and rail door leaves for use in commercial buildings | Recycled and recovered materials should be considered as raw materials and if they have fuel content and used as fuels, they must be allocated as alternative energy. Further, in case of incineration for the recovery of the product/energy, the combustion emissions must be allocated to the paving product. It is noted that if there is a usage of feedstock energy used as energy should be declared and shown separately. | (ASTM 2016d) |
| ASTM | EPD | Thermoplastic or thermoset membranes of compounded synthetic materials manufactured in a factory for use in roofing; PVC roofing membranes with different thicknesses | In results part of the EPD report, energy flows used as feedstock energy is reported under the *non-renewable fossil* energy and removed from the *non-renewable materials* section. | (ASTM 2016e, 2014d, 2016f) |
| ASTM | PCR | Asphalt shingles applied over underlayment, and low-slope roofing assemblies consisting of various combinations of factory-produced asphalt-saturated/coated base sheets, ply sheets and cap sheets together with specified viscous asphalt coatings, adhesives and surfacing | It is noted that feedstock used to produce materials must be allocated as material resources (kg), and process energy must be allocated as energy resources (MJ). In case of incineration for the recovery of the product/energy, the combustion emissions must be allocated to the product. | (ASTM 2014e) |

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|---|---|---|---|---|
| ASTM | EPD | Concrete reinforcing steel; light structural shapes; fabricated concrete reinforcing steel, merchant bar; fabricated carbon-steel and low-alloy uncoated reinforcing bar; fabricated steel reinforcing bar | In the EPD report, in *Energy and Material Resource Use Consumption Results* table the use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials and non-renewable primary energy resources used as raw materials are reported separately in MJ. | (ASTM 2015c, 2015d, 2015e, 2015f, 2016g, 2017b) |
| ASTM | EPD | PVC and HP roofing membranes | In the EPD report, non-renewable energy flows used as feedstock energy used as energy is reported under the *non-renewable fossil* energy. | (ASTM 2016h, 2016i) |
| ASTM | PCR | Decorative foils, light basis weight papers, resin impregnated decorative paper, and film overlays | It is noted that special care should be taken since potential for incidents that can have impacts on the environment such as energy content of the product for energy recovery in the end-of-life. | (ASTM 2017c) |
| UL | EPD | Asphalt shingles, built-up asphalt membrane roofing and modified bituminous membrane roofing | Primary energy demand (non-renewable energy part) is expressed in three separate non-renewable energies which are non-renewable fossil energy, non-renewable nuclear energy and non-renewable biomass in MJ. | (UL 2015) |
| UL | EPD | North American oriented strand board, North American softwood plywood (wood) | In *Cradle-to-Gate Impact Assessment Results* table of this EPD, *non-renewable fossil energy (MJ)* is reported in *total primary energy consumption* section, and *non-renewable materials (kg)* is reported in *material resources consumption* section. | (UL 2013a, 2013b) |
| NSF International | PCR | Flooring: Carpet, Resilient, Laminate, Ceramic, Wood | It is indicated that non-renewable material resources such as abiotic resource depletion potential (ADP), not including primary energy and primary energy demand of non-renewable resources (MJ) shall be declared in the EPD per functional unit. | (NSF International 2014) |
| CSA Group | EPD | Cladding products | In the EPD, *use of non-renewable primary energy excluding the non-renewable primary energy resources used as raw materials (MJ)* and *use of non-renewable primary energy resources use as raw materials (MJ)* are reported separately in LCIA results table. | (CSA Group 2017) |

| | | | | |
|---|---|---|---|---|
| The Norwegian EPD Foundation | PCR | Technical - Chemical products for the building- and construction industry | In this PCR, instead of presenting the feedstock energy concept separately, it is indicated that the allocation rules given in the standard EN 15804:2011 must be applied exactly the same way while reporting. | (epd-norge 2012a) |
| IBU Institut Bauen und Umwelt e.V. | EPD | Woodfibre insulation materials produced in the dry process | In the EPD report the *non-renewable primary energy stored as an inherent characteristic of the material* is reported separately as MJ in end-of-life section. Additionally, in *Results of the LCA – Resource Use* table, non-renewable primary energy used as energy carrier (MJ) and non-renewable primary energy used for material utilization (MJ) are indicated individually. | (IBU 2014e) |
| IBU Institut Bauen und Umwelt e.V. | EPD | Wood Fiberboards | In the EPD report, in *Results of the LCA – Resource Use* table, non-renewable primary energy used as energy carrier (MJ) and non-renewable primary energy used for material utilization (MJ) are indicated individually. Further, the major share of the non-renewable primary energy is used energetically, mostly as natural gas to produce the product. A small portion is used as a material, for example as components of the gluing systems; which is not used within the life cycle of this product. | (IBU 2014f) |
| IBU Institut Bauen und Umwelt e.V. | EPD | Melamine-faced lightweight boards Eurolight decor – wood product; Pedestrian and bicycle bridge | In the EPD report, in *Results of the LCA – Resource Use* table, non-renewable primary energy used as energy carrier (MJ) and non-renewable primary energy used for material utilization (MJ) are indicated individually. | (IBU 2014g, 2015) |
| The International EPD System | PCR | Buildings | In *Tables for Environmental Information* of this PCR, use of non-renewable primary energy resources used as raw material is reported separately as MJ net calorific value. It is also indicated that only the energy that is suitable for an eventual energy recovery at the end-of-life shall be considered as the energy content of the material. | (EPD® 2014e) |

| | | | | |
|---|---|---|---|---|
| The International EPD System | PCR | Plastic Waste and Scrap Recovery (Recycling) Services | It is indicated that energy content of biomass used for feed or food purposes shall not be considered in the LCA report. | (EPD® 2013b) |
| The International EPD System | PCR | Construction products and construction services, hot-drawn reinforcing steel for concrete in bars | In *Use of Resources table*, use of non-renewable primary energy resources used as raw material is reported separately as MJ net calorific value and the whole EPD divided into stages. | (EPD® 2012, 2015a) |
| The International EPD System | EPD | Flat Sheet in Fiber Cement | In the *Environmental Performance* table, use of non-renewable primary energy excluding renewable primary energy resources used as raw materials (MJ, net calorific value) and use of non-renewable primary energy resources used as raw materials (MJ, net calorific value) are reported separately. | (EPD® 2016e) |
| The International EPD System | EPD | Folkhem's concept building, composite bridge, medium density fibreboard (MDF) | In *Use of Resources* table, use of non-renewable primary energy used as energy resource and non-renewable primary energy used as raw materials are reported separately as MJ net calorific value. | (EPD® 2015b, 2014f, 2015c) |

**B.4. Energy Terminology Application in Studies and Databases**

The following listing provides information on how feedstock energy is defined in the various resources in Table B.3 as noted by the uppercase lettering scheme.

A - Feedstock energy to produce materials should be allocated as material resources (kg), and process energy should be allocated as energy resources (MJ).
B- Recycled and recovered materials should be considered as raw materials and if they have fuel content and used as fuels, they must be allocated as alternative energy.
C- Special care should be taken to consider impacts on the environment such as energy content of the product for energy recovery in the end-of-life.
D- The use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials and non-renewable primary energy resources used as raw materials are reported separately in MJ.
E- Non-renewable energy flows used to produce materials is counted separately and reported as non-renewable fossil energy in MJ (removed from the non-renewable materials section) and contributes to total primary energy consumption.
F- Each kg of finished product has a calorific value (feedstock energy) which can be converted into useful energy as a raw material.
G- Non-renewable primary energy demand is expressed as MJ and non-renewable material resources are reported as kg.
H- Energy content of biomass used for feed or food purposes shall not be considered in the LCA report.
I- Feedstock energy in a life cycle study could be considered as *borrowed from the nature*. It is considered for generating energy, and as stored within the asphalt materials when it is not consumed.
J- In the life cycle inventory phase the *feedstock energy must clearly be distinguished from combusted energy,* and in material production phase, *feedstock energy of materials that are used as a fuel* should be included (UCPRC Pavement LCA Guideline).
K- Feedstock energy is defined as *when organics are used as materials, the energy associated with much of this input remains incorporated in the product.*
L- Non-renewable energy sources without energy content (kg) is reported in *Use of resources without energy content* table and non-renewable resources with energy content (MJ-thermic) is reported in *Use of resources with energy content* table.
M- Feedstock energy is "the energy content of fuel resources extracted from the earth, while fuel energy is the amount of energy that is released when fuels are burned".
N- Feedstock energy is "the gross combustion heat value of any fossil hydrocarbon material input to a product system which is an energy source, but is not being used as an energy source including its related pre-combustion energy".
O- Feedstock is tracked as a material with units of energy (kJ) under abiotic resource depletion of fossil fuels.

Table B.4. Energy Terminology Application in Studies and Databases

| Industry | Type | Citation | Inclusion of feedstock energy? | Feedstock allocation scheme | System Boundary Considerations |
|---|---|---|---|---|---|
| Paving | PCR | ASTM 2014a | Yes | A | cradle-to-gate |
| | PCR | ASTM 2014b | Yes | B | cradle-to-gate |
| | PCR | ASTM 2014c | Yes | B, C | cradle-to-gate |
| | PCR | ASTM 2015a | Yes | B | cradle-to-gate |
| | PCR | ASTM 2015b | Yes | B | cradle-to-gate |
| | EPD | ASTM 2015i | No | - | cradle-to-gate |
| | EPD | ASTM 2015j | No | - | cradle-to-gate |
| | EPD | ASTM 2015k | No | - | cradle-to-gate |
| | EPD | ASTM 2015l | No | - | cradle-to-gate |
| | PCR | ASTM 2016a | Yes | B | cradle-to-gate |
| | PCR | ASTM 2016b | Yes | C | cradle-to-gate |
| | EPD | ASTM 2016l | No | - | cradle-to-gate |
| | EPD | ASTM 2016m | No | - | cradle-to-gate |
| | EPD | ASTM 2016n | No | - | cradle-to-gate |
| | EPD | ASTM 2016o | No | - | cradle-to-gate |
| | PCR | ASTM 2017a | Yes | C | cradle-to-gate |
| | Article | Butt et al. 2014 | Yes | I | cradle-to-grave |
| | PCR | CLF 2012 | Yes | B | cradle-to-gate |
| | EPD | CSA Group 2016a | No | - | cradle-to-gate |
| | EPD | CSA Group 2016b | No | - | cradle-to-gate |
| | EPD | CSA Group 2016c | No | - | cradle-to-gate |
| | PCR | epd-norge 2010 | Yes | D | cradle-to-gate and construction stage |
| | PCR | epd-norge 2012b | No | - | cradle-to-gate or cradle-to-grave |
| | EPD | EPD® 2006 | Yes | D | cradle-to-gate |
| | EPD | EPD® 2011 | Yes | F | cradle-to-grave |

| | | | | | |
|---|---|---|---|---|---|
| | PCR | EPD® 2013a | Yes | D | cradle-to-gate, cradle-to-site, cradle-to-gate with options or cradle-to-grave |
| | PCR | EPD® 2013c | No | - | cradle-to-gate |
| | EPD | EPD® 2013e | No | - | cradle-to-building |
| | EPD | EPD® 2014a | Yes | D | cradle-to-gate |
| | EPD | EPD® 2014b | Yes | D | cradle-to-gate |
| | EPD | EPD® 2014c | Yes | D | cradle-to-gate |
| | EPD | EPD® 2014d | Yes | L | cradle-to-gate |
| | EPD | EPD® 2016a | Yes | D | cradle-to-gate |
| | EPD | EPD® 2016b | Yes | D | cradle-to-gate |
| | EPD | EPD® 2016c | Yes | D | cradle-to-gate |
| | EPD | EPD® 2016d | Yes | D | cradle-to-grave |
| | EPD | EPD® 2017a | Yes | D | cradle-to-gate with options |
| | EPD | IBU 2012b | Yes | D | cradle-to-gate |
| | EPD | IBU 2013a | Yes | D | cradle-to-gate |
| | EPD | IBU 2013b | Yes | D | cradle-to-gate |
| | EPD | IBU 2014a | Yes | D | cradle-to-gate |
| | EPD | IBU 2014b | Yes | D | cradle-to-gate |
| | EPD | IBU 2014c | Yes | D | cradle-to-gate |
| | EPD | IBU 2014d | Yes | D | cradle-to-gate with options |
| | Article | Santos et al. 2014 | Yes | J | cradle-to-grave |
| | Article | Santos et al. 2015a | Yes | J | cradle-to-grave |
| | Article | Santos et al. 2015b | Yes | J | cradle-to-grave |
| | PCR | Universal Cement and Taiwan Green Building Material Council 2015 | Yes | C, H | cradle-to-grave |
| | EPD | UL 2016 | Yes | G | cradle-to-gate |
| | Article | Ventura and Santero 2012 | Yes | K | - |
| | Tool | RMRC-3G 2003 | No | - | N/A |
| | Report | Athena Institute 2006 | Yes | N | cradle-to-gate |

| | | | | | |
|---|---|---|---|---|---|
| Construction | EPD | ASTM 2015c | Yes | D | cradle-to-gate |
| | EPD | ASTM 2015d | Yes | D | cradle-to-gate |
| | EPD | ASTM 2015e | Yes | D | cradle-to-gate |
| | EPD | ASTM 2015f | Yes | D | cradle-to-gate |
| | EPD | ASTM 2016g | Yes | D | cradle-to-gate |
| | EPD | ASTM 2017b | Yes | D | cradle-to-gate |
| | EPD | CSA Group 2017 | Yes | D | cradle-to-gate |
| | PCR | epd-norge 2012a | Yes | D | cradle-to-gate or cradle-to-gate with options |
| | EPD | EPD® 2010b | No | - | cradle-to-gate |
| | PCR | EPD® 2012 | Yes | D | cradle-to-gate, cradle-to-gate with options or cradle-to-grave |
| | PCR | EPD® 2013d | No | - | cradle-to-grave |
| | PCR | EPD® 2014e | Yes | D, C | cradle-to-grave |
| | EPD | EPD® 2014f | Yes | D | cradle-to-grave |
| | EPD | EPD® 2015a | Yes | D | cradle-to-gate |
| | EPD | EPD® 2015b | Yes | D | cradle-to-grave |
| | EPD | EPD® 2015c | Yes | D | cradle-to-gate |
| | EPD | EPD® 2016e | Yes | D | cradle-to-gate with options |
| | EPD | IBU 2014g | Yes | D | cradle-to-gate with options |
| | EPD | IBU 2015 | Yes | D | cradle-to-grave |
| | Tool | Athena Institute 2014 | No | - | N/A |
| | Tool | Lippiatt 2007 | Yes | M | N/A |
| | Tool | Kneifel 2015 | No | - | N/A |
| Wood | PCR | ASTM 2016d | Yes | B | cradle-to-gate |
| | PCR | ASTM 2016k | No | - | cradle-to-grave |
| | EPD | EPD® 2004 | No | - | cradle-to-gate |
| | PCR | EPD® 2017b | No | - | cradle-to-gate, gate-to-gate or gate-to-grave |
| | EPD | IBU 2014e | Yes | D | cradle-to-gate with options |
| | EPD | IBU 2014f | Yes | D | cradle-to-gate with options |
| | EPD | UL 2013a | Yes | G | cradle-to-gate |

| | | | | | |
|---|---|---|---|---|---|
| | EPD | UL 2013b | Yes | G | cradle-to-gate |
| Roofing | EPD | ASTM 2014d | Yes | E | cradle-to-building with end-of-life stage |
| | PCR | ASTM 2014e | Yes | A | cradle-to-gate |
| | PCR | ASTM 2016c | Yes | E | cradle-to-gate, cradle-to-grave or cradle-to-gate plus end-of-life |
| | EPD | ASTM 2016e | Yes | E | cradle-to-gate |
| | EPD | ASTM 2016f | Yes | E | cradle-to-gate |
| | EPD | ASTM 2016h | Yes | E | cradle-to-gate |
| | EPD | ASTM 2016i | Yes | E | cradle-to-gate |
| | PCR | EPD® 2014g | No | - | cradle-to-grave |
| | EPD | UL 2015 | Yes | G | cradle-to-gate and end-of-life |
| Flooring | PCR | ASTM 2017c | Yes | C | cradle-to-gate |
| | PCR | NSF International 2014 | Yes | O | cradle-to-install and end-of-life or cradle-to-grave |
| Fertilizers | PCR | EPD® 2010a | No | - | cradle-to-gate, gate-to-gate or gate-to-grave |
| Plastics | PCR | EPD® 2013b | Yes | H | cradle-to-gate, gate-to-gate or gate-to-grave |
| Multiple Industries | Tool | PE International 2012 | No | - | N/A |
| | Tool | PRé 2016 | No | - | N/A |
| | Tool | CMU 2015 | No | - | N/A |
| | Tool | Winter et al. 2015 | No | - | N/A |
| | Tool | ifu 2016 | No | - | N/A |
| Transportation | Tool | Argonne National Laboratory 2016 | No | - | N/A |
| | Tool | Georgia Tech 2016 | No | - | N/A |

# APPENDIX C

NATURAL OR MASS COLOR SHEET - THICKNESS 4 mm

| NON RENEWABLE RESOURCES | UPSTREAM | CORE | | DOWNSTREAM | TOTAL |
|---|---|---|---|---|---|
| | A1 Raw material supply | A2 Transport | A3 Production Process | A4 Product distribution | |
| Use of NON RENEWABLE primary energy excluding renewable primary energy resources used as raw materials [MJ, net calorific value] | 91.86 | 2.51 | 1.64 | 8.22 | **104.23** |
| Use of NON RENEWABLE primary energy resources used as raw materials [MJ, net calorific value] | 0.47 | - | - | - | **0.47** |
| Total use of NON RENEWABLE primary energy resources (primary energy and primary energy resources used as raw materials) [MJ, net calorific value] | 92.33 | 2.51 | 1.64 | 8.22 | **104.70** |

Figure C.1. Construction industry example, environmental performance table (EPD® 2016e).

| Parameter | Unit | A1-A3 |
|---|---|---|
| Renewable primary energy as energy carrier | [MJ] | 1.51E+0 |
| Renewable primary energy resources as material utilization | [MJ] | 0.00 |
| Total use of renewable primary energy resources | [MJ] | 1.51E+0 |
| Non-renewable primary energy as energy carrier | [MJ] | 2.66E+1 |
| Non-renewable primary energy as material utilization | [MJ] | 4.82E+0 |
| Total use of non-renewable primary energy resources | [MJ] | 3.14E+1 |
| Use of secondary material | [kg] | 0.00 |
| Use of renewable secondary fuels | [MJ] | 0.00 |
| Use of non-renewable secondary fuels | [MJ] | 0.00 |
| Use of net fresh water | [m³] | 6.04E-3 |

Figure C.2. Paving industry example, results of the LCA (IBU 2014b).

| Single layer - System 1 fully torched system | | | Use of renewable primary energy excluding renewable primary energy resources used as raw materials | Use of renewable primary energy resources used as raw materials | Total use of renewable primary energy resources | Use of non renewable primary energy excluding non renewable primary energy resources used as raw materials | Use of non renewable primary energy resources used as raw materials | Total use of non renewable primary energy resources |
|---|---|---|---|---|---|---|---|---|
| units per FU | | | MJ | MJ | MJ | MJ | MJ | MJ |
| Product stage | Raw material supply | A1 | 4.92E-02 | 9.01E-06 | 4.92E-02 | 5.14E-01 | 1.53E+00 | 2.05E+00 |
| | Transport | A2 | 2.34E-05 | - | 2.34E-05 | 1.65E-02 | - | 1.65E-02 |
| | Manufacturing | A3 | 3.47E-02 | 3.09E-03 | 3.78E-02 | 8.33E-02 | 2.06E-02 | 1.04E-01 |
| | Total (of product stage) | A1 - A3 | 8.39E-02 | 3.10E-03 | 8.70E-02 | 6.14E-01 | 1.55E+00 | 2.17E+00 |
| Construction process stage | Transport | A4 | 4.91E-05 | - | 4.91E-05 | 2.34E-02 | - | 2.34E-02 |
| | Construction installation | A5 | 8.71E-03 | 3.10E-04 | 9.02E-03 | 1.58E-01 | 1.55E-01 | 3.13E-01 |
| Use stage | Refurbishment | B5 | 1.82E-01 | 6.70E-03 | 1.89E-01 | 1.56E+00 | 3.36E+00 | 4.92E+00 |
| End of life | Transport | C2 | 2.87E-05 | - | 2.87E-05 | 2.03E-02 | - | 2.03E-02 |
| | Waste processing | C3 | 1.58E-03 | - | 1.58E-03 | 1.76E-02 | - | 1.76E-02 |
| | Disposal | C4 | 7.40E-04 | - | 7.40E-04 | 2.10E-02 | - | 2.10E-02 |
| Benefits and loads beyond the system boundaries | Reuse, recovery or recycling and/or recovery potentials | D | -2.93E-02 | - | -2.93E-02 | -1.15E+00 | - | -1.15E+00 |

Figure C.3. Roofing industry example, environmental performance table (EPD® 2016d).

| CATEGORY INDICATOR | PER METRIC TON | | PER SHORT TON | |
|---|---|---|---|---|
| | PRODUCT STAGE A1-A3 | UNIT | PRODUCT STAGE A1-A3 | UNIT |
| Use of renewable primary energy excluding renewable primary energy resources used as raw materials | 429 | MJ, net calorific value | 3.69E+05 | BTU, net calorific value |
| Use of renewable primary energy resources used as raw materials | 9.01E-10 | MJ, net calorific value | 9.01E-10 | BTU, net calorific value |
| Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials) | 429 | MJ, net calorific value | 3.69E+05 | BTU, net calorific value |
| Use of nonrenewable primary energy excluding nonrenewable primary energy resources used as raw materials | 9.81E+03 | MJ, net calorific value | 8.43E+06 | BTU, net calorific value |
| Use of nonrenewable primary energy resources used as raw materials | 542 | MJ, net calorific value | 4.66E+05 | BTU, net calorific value |
| Total use of nonrenewable primary energy resources (primary energy and primary energy resources used as raw materials) | 1.04E+04 | MJ, net calorific value | 8.90E+06 | BTU, net calorific value |
| Use of secondary material | 1.13 | metric ton | 1.13 | short ton |
| Use of renewable secondary fuels | - | MJ, net calorific value | - | BTU, net calorific value |
| Use of nonrenewable secondary fuels | - | MJ, net calorific value | - | BTU, net calorific value |
| Net use of fresh water | 3.26 | $m^3$ | 782 | gallons |

Figure C.4. Construction industry example, energy and material resource use results (ASTM 2015c).

| Environmental indicator | Unit | Cassara | | |
|---|---|---|---|---|
| | | Black | Grey | Beige |
| Ozone depletion potential | kg CFC-11 eq | 8.39E-06 | 8.39E-06 | 8.75E-06 |
| Global Warming Potential | kg $CO_2$ eq | 537 | 525 | 567 |
| Smog creation potential | kg $O_3$ eq | 60 | 59 | 64 |
| Acidification potential | kg $SO_2$ eq | 3.63 | 3.54 | 3.81 |
| Eutrophication potential | kg N eq | 0.57 | 0.57 | 0.63 |
| *Primary energy consumption* | | | | |
| Renewable (solar, wind, hydroelectric, and geothermal) | MJ | 1658 | 1664 | 1562 |
| Renewable (biomass) | MJ | 34 | 31 | 36 |
| Non-renewable nuclear | MJ | 373 | 352 | 572 |
| Non-renewable fossil | MJ | 4589 | 4405 | 4953 |
| *Resources consumption* | | | | |
| Non-renewable materials | kg | 2666 | 2693 | 2696 |
| Renewable materials | kg | 190 | 190 | 190 |
| Fresh water | L | 700 | 698 | 1005 |
| *Waste generated* | | | | |
| Non-hazardous | kg | 209 | 200 | 200 |
| Hazardous | kg | 0.14 | 0.12 | 0.12 |

Figure C.5. Paving industry example, LCIA results (CSA Group 2016b).

| Impact category indicator | Unit | Total | Forestry operations | OSB production |
|---|---|---|---|---|
| Global warming potential | kg $CO_2$ eq. | 248.30 | 17.40 | 230.90 |
| Acidification potential | H+ moles eq. | 130.48 | 8.98 | 121.50 |
| Eutrophication potential | kg N eq. | 0.1021 | 0.0298 | 0.0723 |
| Ozone depletion potential | kg CFC-11 eq. | 0.0000 | 0.0000 | 0.0000 |
| Smog potential | kg $O_3$ eq. | 34.55 | 4.49 | 30.06 |
| **Total primary energy consumption** | **Unit** | **Total** | **Forestry operations** | **OSB production** |
| Non-renewable fossil | MJ | 4260.78 | 268.10 | 3992.68 |
| Non-renewable nuclear | MJ | 513.83 | 2.53 | 511.30 |
| Renewable, biomass | MJ | 3590.40 | 0.00 | 3590.40 |
| Renewable, other | MJ | 93.43 | 0.74 | 92.69 |
| **Material resources consumption** | **Unit** | **Total** | **Forestry operations** | **OSB production** |
| Non-renewable materials | kg | 2.11 | 0.00 | 2.11 |
| Renewable materials | kg | 661.47 | 0.00 | 661.47 |
| Fresh water | L | 395.10 | 5.51 | 389.59 |
| **Non-hazardous waste generated** | **Unit** | **Total** | **Forestry operations** | **OSB production** |
| Solid waste | kg | 30.72 | 0.17 | 30.55 |

Figure C.6. Wood industry example, cradle-to-gate impact assessment results (UL 2013a).