CRITICAL REVIEW OF LCA TREATMENT OF FEEDSTOCK ENERGY

Draft 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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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 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 2006

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 (ene

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-HIE Tm0 g0 G[ )]TJETQq0.00000912 0 612 792 reW* nBT/F13o15s08275

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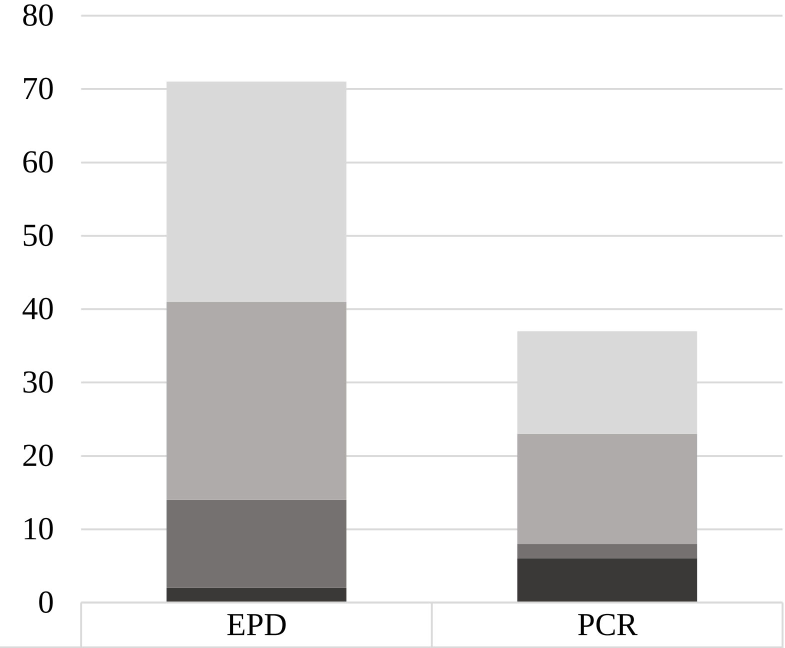
1. EPDs and PCRs from the Product Category Rule Guidance Development Initiative ACLCA 2015).
2. Reports from organizations such as the FHWA.
3. Databases and tools including the US LCI, US Agricultural Commons, and the GaBi US extension databases, and the GaBi, Simapro, etc. tools.

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



	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

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; usa-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 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

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, Santo4(nta-t al. ()3(2)-9(0930) D9;umen was includeece

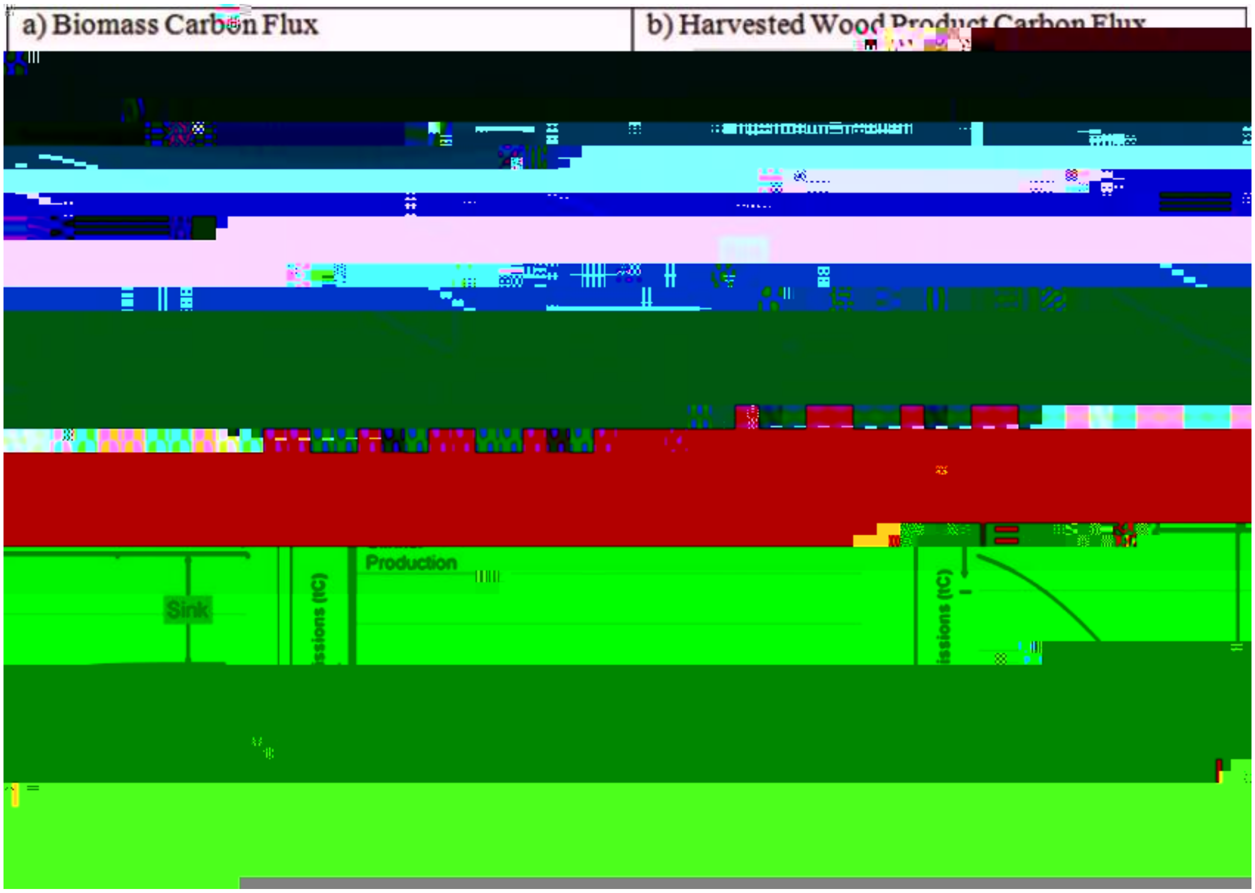


Figure 2.2. Carbon fluxes over time, scales not representative (Mohareb and Kennedy 2012).

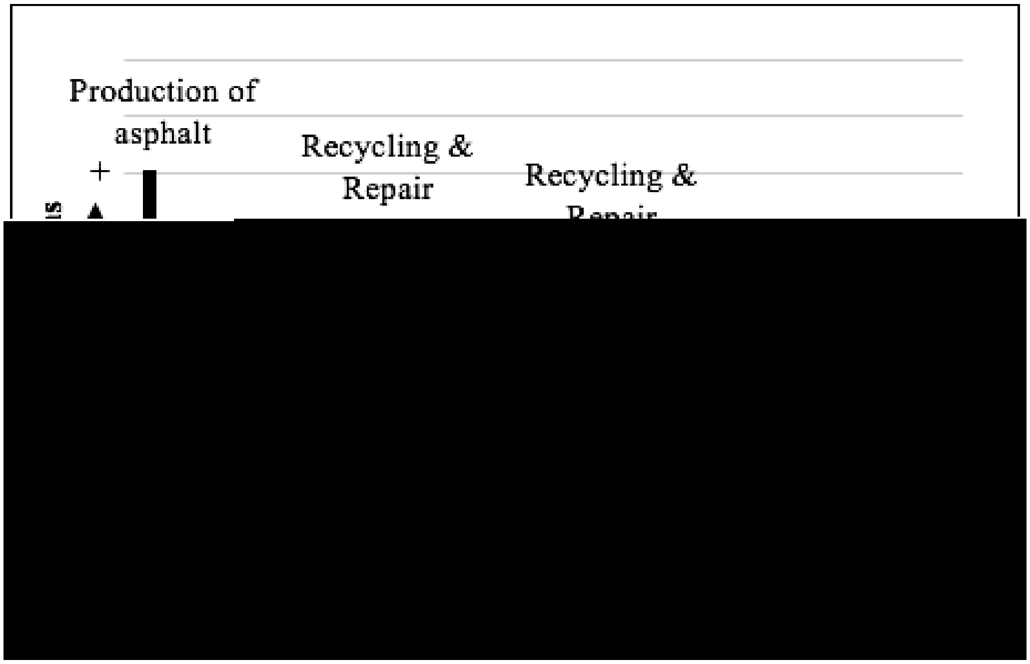


Figure 2.3. Asphalt carbon flux over time with relative scales not representative.

2.4.2. Asphalt Feedstock Cycles with Respect to Carbon

i. Sources of Feedstock

Figure 2.4.

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

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 cont

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*

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

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

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, aspha

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*

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E *EPD for Ready-mix concrete*

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EPD for Railway Bridges on the Bothnia Line
Stockholm, Sweden.
EPD for Spunbond Reinforcements for Bituminous Membranes Made of Recycled Polyester
E *PCR for Construction Products and Construction Services*
System, Stockholm, Sweden.
PCR for Concrete, The International olm, Sweden.
PCR for Plastic Waste and Scrap Recovery (Recycling) Services, The International

E *PCR for Highways (Except Elevated Highways), Streets and Roads*, The International
ckholm, Sweden.
PCR for Bridges and Elevated Highways
Sweden.
E *EPD for N-340 Road*
EPD for Portland Cement II, The I
EPD for Aggregates
EPD for Gray Cements
EPD for Ready-Mix Concrete
PCR for Buildings
EPD for NCC Composite bridge
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APPENDIX A

Table A. 1.

	(ASTM 2014f)
Effects and Environmental Fate	(ASTM 2014g)
Designed to be Aerobically Composted in Municipal or Industrial Facilities	(ASTM 2012)
Fuels	(ASTM 2006)
A	(ASTM 2015h)
ISO/FDIS 13315-4:2016 Environmental management for concrete and concrete structures Part 4: Environmental design of concrete structures	(ISO 2016b)
tal labels and declarations - General principles	(ISO 2000)

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)

	Calorific value	the heat of combustion of a unit quantity of a substance. It may be
ASTM **Standard Test Method for Gross Calorific Value of Refuse-Derived Fuel by the Bomb Calorimeter (Withdrawn 2011)**		

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.	

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
	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

Table B.2. Feds

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

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.	(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.	(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.	(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.	(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.	(2006)

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.	(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	

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 - It is noted that the energy used as feedstock 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. Further, in case of incineration for the recovery of the product/energy, the combustion emissions must be allocated to the product. If there is a usage of feedstock energy used as energy should be declared and shown separately.

C- It is noted that special care should be taken since potential for incidents that may have 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. The allocation rules given in the standard EN 15804:2011 should be applied while reporting.

E- *Non-renewable energy flows* (i.e. feedstock) used to produce materials counted separately and reported as *non-renewable fossil energy* in MJ (removed from the *non-renewable materials* section) and it 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

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-			

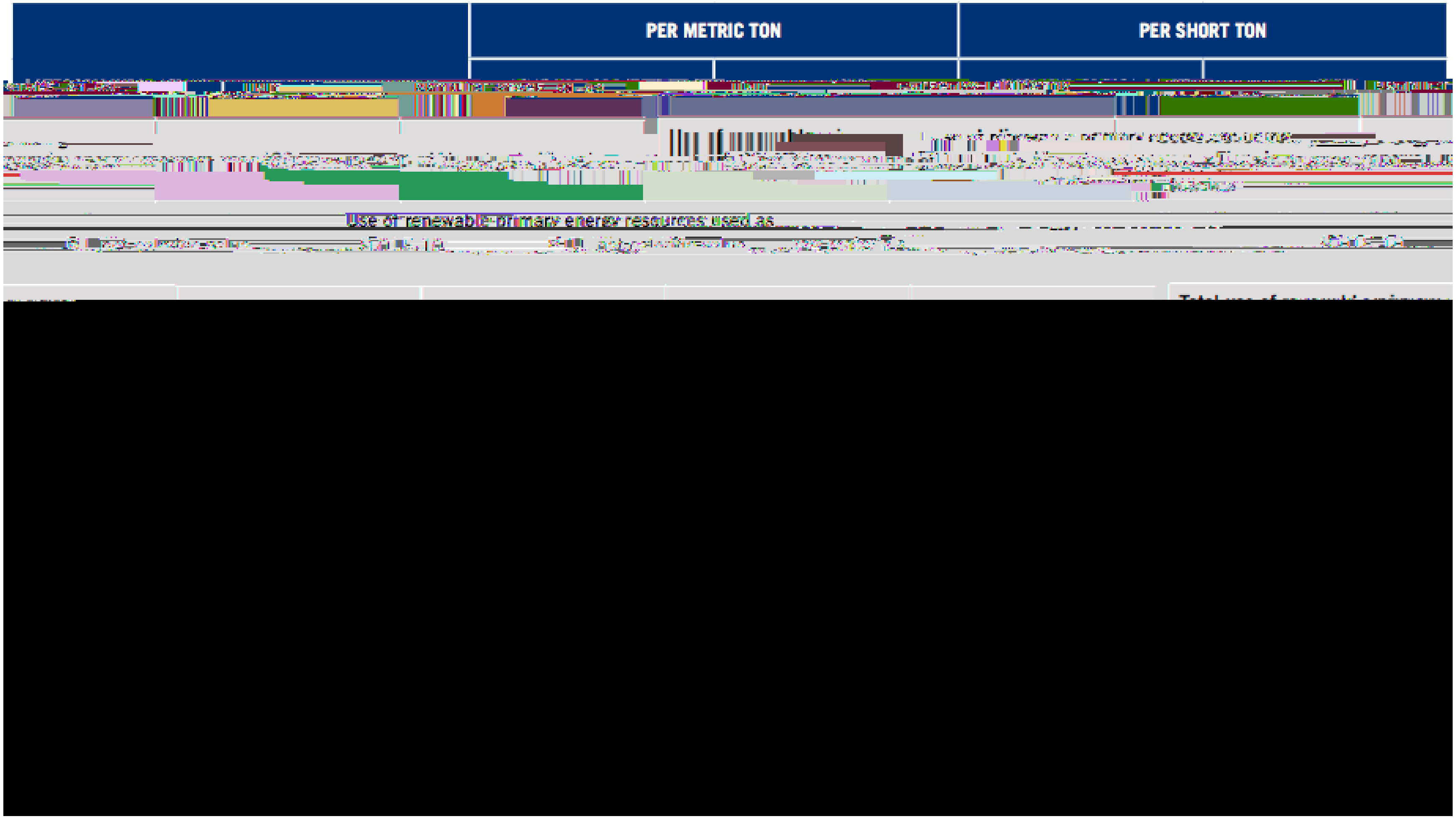
	EPD	UL 2013b	Yes	G	cradle-to-gate
Roofing	EPD	ASTM 2014d	Yes	E	cradle to building with end-of-life stage
	PCR	ASTM 2014e	Yes	A	cradle-to-gate
	PCR	ASTM 2016c	Yes	E	cradle-to-gate, cradle-to-grave or cradle-to-gate plus end-of-life
	EPD	ASTM 2016e	Yes	E	cradle-to-gate
	EPD	ASTM 2016f	Yes	E	cradle-to-gate
	EPD	ASTM 2016h	Yes	E	cradle-to-gate

APPENDIX C

NNv TJETOq0.000011802 0 792 612 reW* nO/F1 12 Tf1 0 0 1 72333.29 250.25m0 g0 G( )TJETOq0.000011802 0 792 612 reW* nO/F1 12 Tf1 0 0 1 72336.29 250

Total (of product stage)	A1 - A3	8.39E-02	3.10E-03	8.70E-02	6.14E-01	1.55E+00	2.17E+00	
Refurbishment	B5	1.82E-01	6.70E-03	1.89E-01	1.56E+00	3.26E+00	4.82E+00	Use stage
Transport	C2	2.87E-05		2.87E-05	3.93E-03		3.93E-03	
Waste processing	C3	1.58E-03		1.58E-03	1.76E-02		1.76E-02	End of life

Figure C.3. Roofing industry example,



	PER METRIC TON		PER SHORT TON	
Use of renewable primary energy resources used as	[illegible]	[illegible]	[illegible]	[illegible]

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

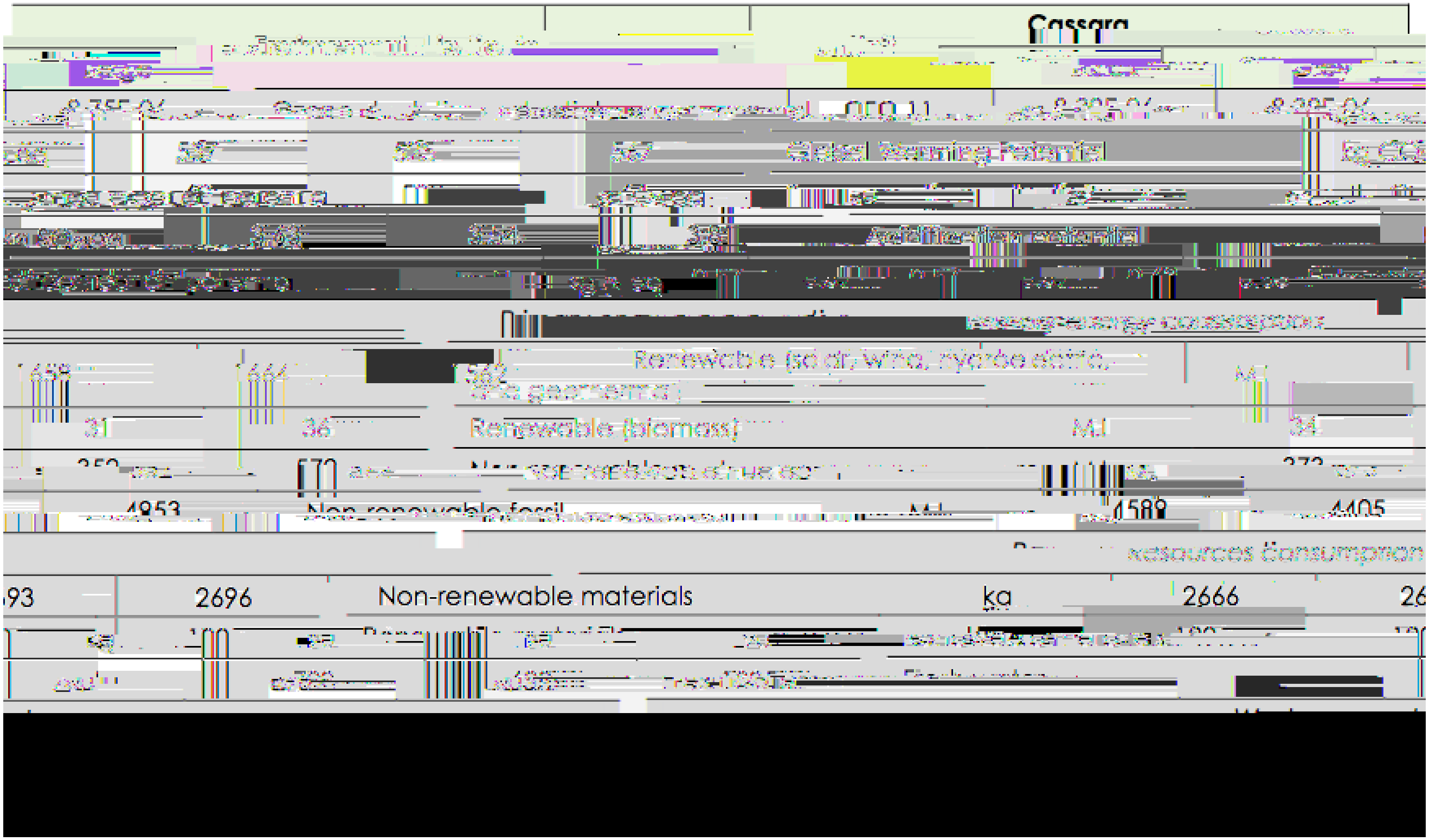


Figure C.5. Paving industry example, LCIA results (CSA Group 2016b).