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Cradle-to-Pavement Carbon Footprint and Biogenic Carbon Accounting of Bio-Extended Bituminous Binders for Asphalt Pavements

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Abstract

The carbon footprint of bio-extended bituminous binders aiming for pavement decarbonisation was quantified using a "cradle-to-pavement" Life Cycle Assessment. The binders were extended with a plant-based bio-oil. By biogenic carbon accounting, the impact of biogenic carbon flow was analysed through different approaches. The results indicated that using the bio-oil as a bitumen extender slightly increases the fossil Global Warming Potential (GWP) of asphalt pavements, by about 1%. Both the absolute GWP levels and the effect of polymer modification on average annual GWP are variable, depending on the input data. When the "-1/+1" approach is adopted, two of the three analysed cases showed a lower average annual GWP of asphalt pavements with polymer-modified bitumen while one analysed case showed almost unchanged average annual GWP. All analysed cases confirmed that the biogenic carbon accounting by the "-1/+X" approach reduces the total and average annual GWP significantly for the cases with biogenic components.

Keywords: Bio-Extended Bitumen, Polymer-Modified Bitumen, Bio-Oil, Carbon Footprint, Biogenic Carbon.

1 Introduction

Bituminous binders such as neat petroleum bitumen and polymer-modified bitumen (PMB) are widely used in asphalt pavements. However, these binders have a relatively high environmental impact, and their use contributes greatly to the challenges currently faced by the asphalt paving industry, such as the dependence on non-renewable resources, relatively high energy consumption and greenhouse gas (GHG) emissions. To address these issues, researchers have explored the feasibility of using bio-based materials, particularly bio-oils derived from renewable resources, as bitumen extenders in asphalt mixtures (Ingrassia 2021; Riccardi and Losa 2024; Wang et al. 2020). The use of bio-oils has shown promising results as they usually have minimal negative impacts on binder properties, therefore are able to replace a significant portion of bitumen, and thus effectively address environmental challenges.

Among the different bio-oils, plant-based bio-oils are of particular interest due to their renewable nature and wide availability. They can be derived from resources like soybean oil, rapeseed oil, sunflower oil, tall oil, palm oil as well as waste materials such as waste cooking oil (He et al. 2023). Using plant-based bio-oils helps improve the sustainability of asphalt mixtures and decrease the dependence on fossil-based resources. Moreover, it has been reported that some plant-based bio-oils can even improve the flexibility, adhesion, and workability of bituminous binders (Ingrassia 2021), enhancing their application for paving purposes. The use of bio-oils can also be extended to PMB binders (Sun et al. 2019).

However, while many previous studies have focused on the initial benefits, the assessment of long-term durability and overall sustainability of asphalt pavements using plant-based bio-oils remains a challenge. For a comprehensive sustainability assessment, it is crucial to consider the environmental impacts across all the life cycle phases, including the raw material manufacturing, asphalt production, transportation, construction, service, maintenance, decommissioning, reusing, recycling, etc.

Life Cycle Assessment (LCA) is a method widely used to evaluate the carbon footprint and other environmental impacts of a product, process, or service over its entire life cycle. LCA tools are currently used by the pavement industry and research community for assessing the carbon footprints and environmental impacts of different pavement types and materials. For example, Samieadel et al. (2018) performed a LCA analysis of a bio-modified binder using animal wastes to replace bitumen. The study took a cradle-to-gate approach for the binders, eliminating the differences in the binders' effects on binder content and layer thickness. Similarly, another study undertaken by Tokede et al. (2020) also took the cradle-to-gate approach for assessing the carbon footprint benefit of substituting 25% of the bituminous binder with lignin. Some more recent studies (Moretti et al. 2022; Wang et al. 2025), again about the use of lignin in asphalt pavements, took a cradle-to-grave approach.

In this study, a LCA analysis is conducted for asphalt pavements made with bituminous binders (both unmodified and polymer-modified) extended by a plant-based bio-oil from a biorefinery in Sweden. The biorefinery refines bio-based by-products from the pulp and paper industry. The bio-oil contains primarily high-boiling esters as well as free acids. In terms of material source, the bio-oil is essentially derived from the forest (sustainable source). The upstream data enabled the inclusion of environmental impacts of the bio-oil in LCA for asphalt pavements. The analysis focuses on the carbon footprint and biogenic carbon accounting. A "cradle-to-pavement" approach (Zhu et al. 2024) was adopted for the analysis, covering the extraction and processing of raw materials in the asphalt pavements, transportation, asphalt mixing and paving operations. The effects of bio-oil and polymer modification on pavement performance were taken into account by conducting a mechanistic-empirical pavement design based on actual laboratory test data to ensure that comparable pavements are defined and modelled in the calculation of life cycle inventories. The aim of this study is to evaluate the carbon footprint of the investigated bio-extended binders and assess their potential benefits.

2 Research Scope and Methodology

2.1 Life Cycle Assessment and System Boundaries

For products, a LCA study involves the development of an inventory of the energy and materials needed for the entire supply chain as well as the corresponding emissions. It starts with defining a "function" of the product, stating boundaries for the analysis and the data sources. This is followed by developing a Life Cycle Inventory (LCI), which can quantify and compile the environmental inputs and outputs in the defined life cycle scope. The Life Cycle Impact Assessment (LCIA) translates the inventory results to a few impact categories that help with communicating the analysis results. For a defined functional unit (FU), the results of the LCI and/or LCIA will help to compare different options of designs and materials in an agreed scope and with transparent methodological choices.

For a LCA analysis, it is essential to select the system boundaries and unit processes that constitute the LCI. This defines the scope of the analysis and specifies the criteria for comparisons. The boundaries are important to ensure that the analysis is both complete and practical. As laboratory testing of the same bio-based material as in this study has shown that the conventional bituminous binders and bio-extended counterparts of the same quality grade would have similar properties (Ingrassia 2021), this study postulated the same maintenance and end-of-life scenarios for the conventional binders and their bio-extended counterparts. This is based on the best knowledge currently available. Therefore, a “cradle-to-pavement” approach was taken in this study, and the system boundaries of the selected pavement life cycle phases are presented in Fig. 1, including five processes:

1. **Aggregates extraction and production.** This process includes the extraction of quarried materials and the crushing and screening operations to produce the aggregates to size, namely coarse and fine aggregates as well as filler.
2. **Bio-oil and bituminous binders’ production.** This process includes the production of bio-oil, bituminous binders (unmodified, polymer-modified, and emulsion), bio-extended PMB, and their upstream supply chains.
3. **Asphalt mixture manufacturing**. This study considered the Hot Mix Asphalt (HMA) technology. For HMA, all raw materials are sequentially mixed under heated conditions (170-200 °C) in the proportion designed for the asphalt mixtures.
4. **Transportation**. This process includes the transportation of raw materials to the asphalt mixing plant or pavement construction site as well as the transportation of asphalt mixtures to the pavement construction site.
5. **Pavement placing**. This process includes the construction of all asphalt layers by laying and compacting the asphalt mixtures as well as applying the tack coat between layers.

In addition, biogenic carbon accounting was discussed for the end-of-life phase (also shown in Fig. 1). This process covers the entire biogenic carbon flow, both inward transfer and outward transfer of biogenic carbon.

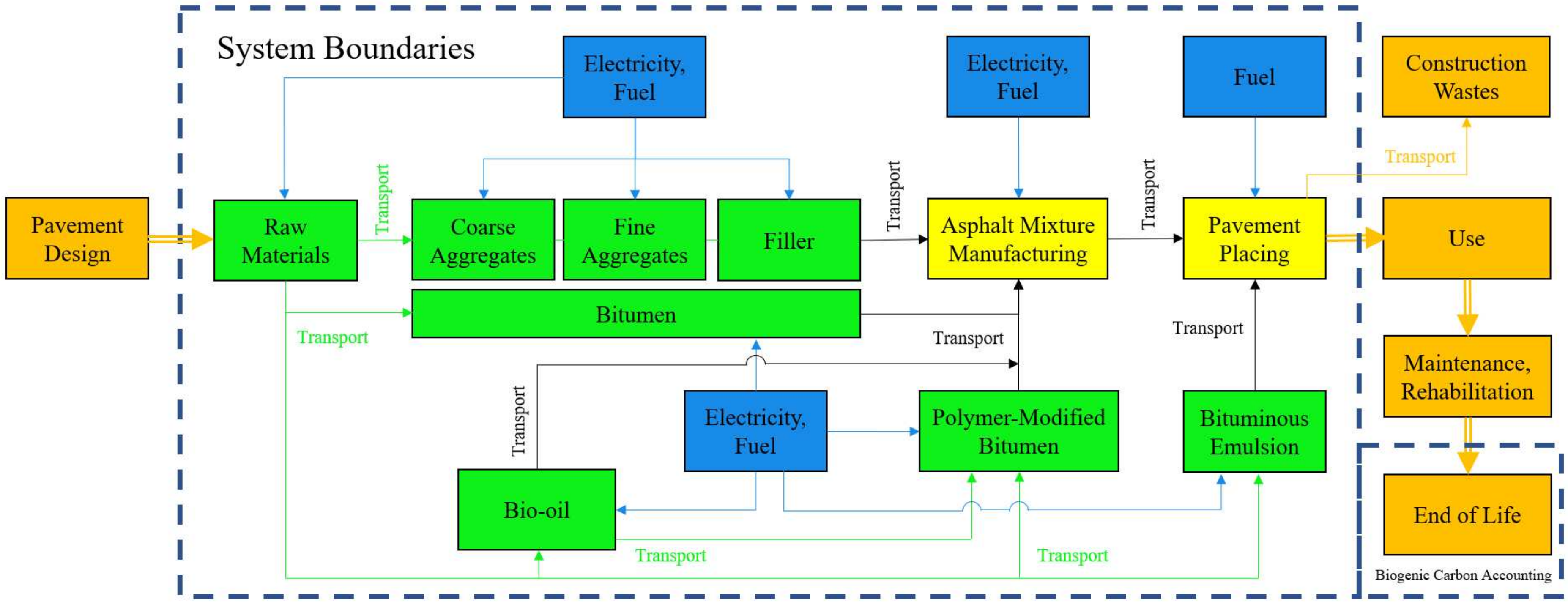

Fig. 1. *The system boundaries of pavement life cycle phases in this study.*

2.2 Pavement Materials and Structures

Comparable pavement structures are essential in a LCA study to ensure that the analysed pavements have the same “function”. In this study, the functional unit needs to be defined such that pavement layers made with different asphalt mixtures can be compared fairly. For this, a pavement section (the FU) of 1 km long and 3.6 m wide was considered. As mentioned above, laboratory testing of the same bio-based material as in this study has shown that the conventional bituminous binders and bio-extended counterparts of the same quality grade exhibit similar properties, particularly the stiffness which is used for pavement design. Fig. 2 presents the dynamic shear modulus of six short-term aged binders considered in this study at 10 rad/s. The laboratory tests were done according to the European standard EN 14770:2023 (CEN 2023) and the results show great similarity in stiffness between conventional binders and the bio-extended counterparts. Thus, in this study, five pavement structures (Cases A-E) were analysed with identical layer thickness but using six different binders (as in Fig. 2) in asphalt mixtures for the bound layers.

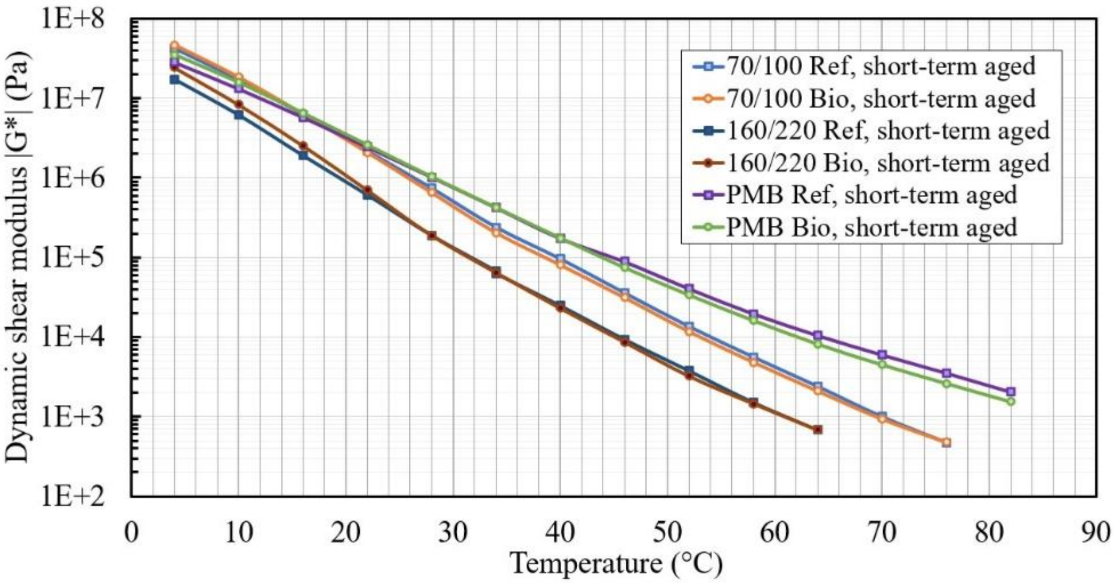

Fig. 2. *Dynamic shear modulus of short-term aged bituminous binders at 10 rad/s.*

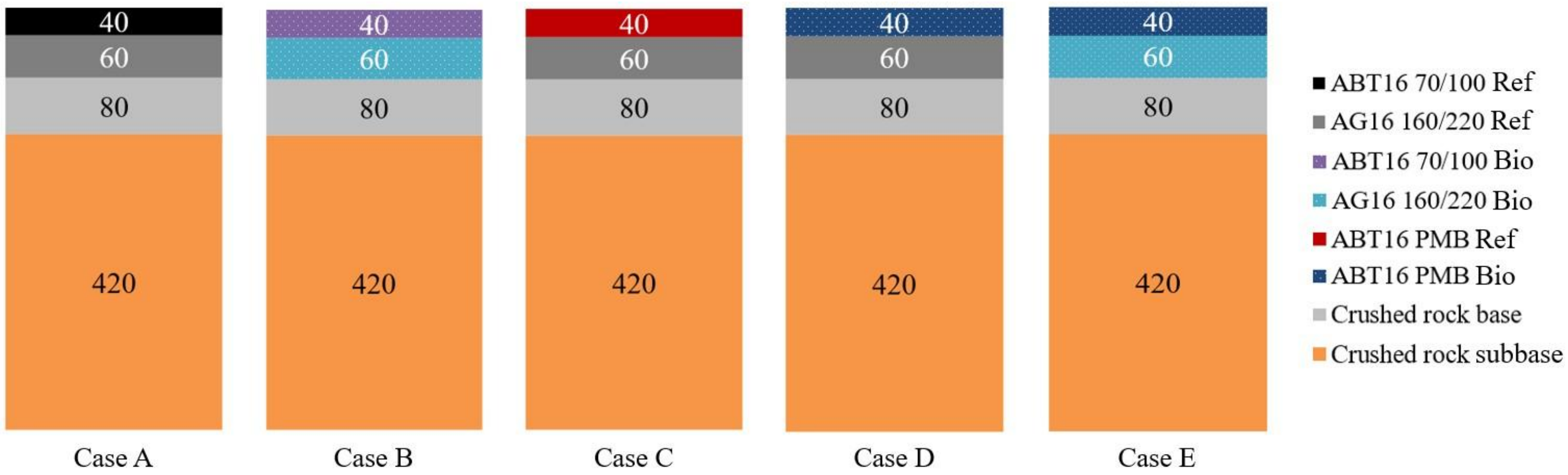

Fig. 3. *Cross-sections of the analysed pavement structures – four layers over a sand subgrade (numbers indicate the layer thickness in mm).*

As illustrated in Fig. 3, the analysed pavements were consisted of four layers over a sand subgrade, namely an asphalt surface course layer, an asphalt base course layer, a crushed rock base layer, and a crushed rock subbase layer. Swedish dense-graded asphalt mixtures having a maximum aggregate size of 16 mm and made with conventional 70/100 penetration grade bitumen (ABT16 70/100 Ref), bio-extended 70/100 bitumen (ABT16 70/100 Bio, 5% replacement of bitumen by bio-oil), conventional 40/100-75 PMB (ABT16 PMB Ref), and bio-extended 40/100-75 PMB (ABT16 PMB Bio) were considered for the asphalt surface course layers. Meanwhile, Swedish AG16 asphalt mixtures made with conventional 160/220 penetration grade bitumen (AG16 160/220 Ref) and bio-extended 160/220 bitumen (AG16 160/220 Bio, 21% replacement of bitumen by bio-oil) were considered for the asphalt base course layers. Five different combinations (Cases A-E) of the asphalt surface course layer and asphalt base course layer were included in the LCA analysis. Meanwhile, the materials of the crushed rock base and subbase layers as well as the thicknesses of all layers were kept constant.

3 Case Study Results and Discussion

3.1 Life Cycle Inventory

Case studies were carried out to compare the different types of asphalt pavements made with conventional bituminous binders and bio-extended counterparts. The unbound base and subbase layers were not included in this study due to being identical in both pavement types. For each type of asphalt mixture, the aggregate types and size portions (mixture gradation) were largely the same for the one with conventional binder and the other with bio-extended binder.

The density of the asphalt mixtures was assumed to be 2.4 t/m^3 for the calculation of transport inventory. Bituminous emulsion made of 67% bitumen was considered for the tack coat between the asphalt surface course (40 mm thick) and asphalt base course (60 mm thick). The application amount was 0.3 L/m^2. The binder content was 5.9% and 4.5%, respectively, in the ABT16 asphalt mixtures (for surface course) and AG16 asphalt mixtures (for base course). No reclaimed asphalt was used. Two types of trucks were taken into account for the transportation, i.e., 32 t trucks for transporting aggregates (5 km to the asphalt plant) and asphalt mixtures (15 km to the paving site), and 14 t trucks for transporting the other materials such as conventional bitumen (75 km to the asphalt plant), bio-oil (230 km to the asphalt plant) , PMB (470 km to the asphalt plant, including conventional PMB and bio-extended PMB) and bituminous emulsion (480 km to the paving site).

The energy type and usage for various processes in the production, transportation and construction phases were collected from secondary sources with consideration of the Swedish and European mainstream conditions. Only traditional fossil fuels and electricity energy sources were considered in this study. Details are shown in Table 1.

Table 1. *Energy consumption for various processes (production includes upstream energy use).*

Process	Unit (energy type)	Energy consumption	Reference
Aggregates production	L/t (diesel)	0.475	Stripple 2001
	kWh/t (electricity)	5.886	
Conventional bitumen production	L/t (heating oil and diesel)	29.6	Stripple 2001
	kWh/t (electricity)	70.0	
Bituminous emulsion production	L/t (fuel oil)	31.7	Eurobitume 2012
	kWh/t (electricity)	100.8	
Conventional PMB production	L/t (heating oil and diesel)	45.6	Nynas 2021; Stripple 2001
	kWh/t (electricity)	107.8	
Bio-extended PMB production	L/t (heating oil and diesel)	47.0	Nynas 2021; Stripple 2001
	kWh/t (electricity)	111.0	
Bio-oil production	L/t (heating oil and diesel)	41.3	Nynas 2021; Stripple 2001
	kWh/t (electricity)	97.8	
HMA mixing, conventional bitumen	L/t (fuel oil – Eldningsolja 1)	6.8	Butt 2014
	kWh/t (electricity)	8.3	
HMA mixing, PMB	L/t (fuel oil – Eldningsolja 1)	8.0	Butt 2014
	kWh/t (electricity)	9.7	
Asphalt laying	L/m^2 (diesel)	0.0166	Butt 2014
Asphalt compaction	L/m^2 (diesel)	0.0223	Butt 2014
Applying tack coat	L/m^2 (diesel)	0.0031	Stripple 2001

Based on the collected data, the calculation of inventory was carried out within the defined system boundaries. The LCA model consists of five units. Pavement parameters (Unit 1) and transport parameters (Unit 2) are explained both in the previous section and earlier in this section. Energy consumption parameters (Unit 3) are shown in Table 1. Combining with Unit 3, Units 1 and 2 are then multiplied by a unit inventory (Unit 4) to calculate the airborne emissions embodied in the production, transportation and construction (Unit 5). The obtained inventory results for some selected key airborne emissions are presented in Table 2.

Table 2. *Inventory results of the studied cases (selected key airborne emissions in g/FU).*

Case	**SO_2**	**NO_x**	**CO**	**CO_2**	**NMVOC**	**PM**	**CH_4**
Case A	4.37×10^4	2.42×10^5	1.33×10^5	2.97×10^7	3.49×10^4	1.69×10^4	7.51×10^3
Case B	4.42×10^4	2.44×10^5	1.35×10^5	3.00×10^7	3.52×10^4	1.70×10^4	7.81×10^3
Case C	4.66×10^4	2.80×10^5	1.52×10^5	3.37×10^7	4.03×10^4	1.84×10^4	7.51×10^3
Case D	4.68×10^4	2.81×10^5	1.55×10^5	3.39×10^7	4.04×10^4	1.85×10^4	8.58×10^3
Case E	4.72×10^4	2.83×10^5	1.57×10^5	3.41×10^7	4.07×10^4	1.86×10^4	8.83×10^3

Note: NMVOC = non-methane volatile organic compound; PM = particulate matter.

3.2 Fossil Global Warming Potential

For an impact assessment on climate change (i.e., carbon footprint assessment), the 100-year Global Warming Potential (GWP) of the studied cases was calculated using the inventory results for CO_2 and CH_4. A characterisation factor of 25 was used for CH_4. Since the LCI considered only traditional fossil fuels and electricity energy sources, the 100-year GWP analysed in this section corresponds to the fossil GWP. For each case, the cradle-to-pavement fossil GWP was broken down into different life cycle processes. The results of Case A (using conventional bitumen) and Case B (using bio-extended bitumen in two asphalt bound layers, without polymer) are shown in Fig. 4. It is indicated that using the investigated bio-oil as a bitumen extender slightly increases the 100-year fossil GWP of asphalt pavements, by about 1%. This small increase is primarily due to the upstream environmental impacts of extracting and processing the raw materials (bio-based by-products from the pulp and paper industry) for producing the bio-oil.

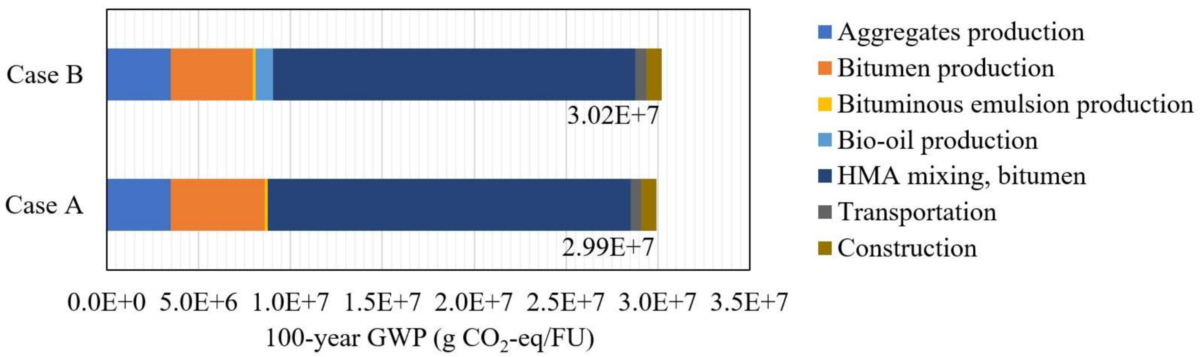

Fig. 4. *Cradle-to-pavement 100-year fossil GWP of Cases A and B based on CO_2 and CH_4 emissions.*

Regarding the life cycle processes, it is shown that the GWP of HMA mixing has the largest share of the total in both cases. This implies that lowering the asphalt mixing temperature would have the greatest potential for reducing the carbon footprint of asphalt pavements. The production of aggregates and binders (including the bio-oil) also has considerable shares of the total. Moreover, the transportation and construction processes such as asphalt laying, compaction, and applying tack coat have relatively small shares in both cases, even if some long-distance transportation has been considered in the analysis.

As for the cases with PMB (Cases C, D and E), Fig. 5 presents the cradle-to-pavement 100-year fossil GWP based on CO_2 and CH_4 emissions. Similar as above, the comparison between Case C (using conventional PMB in the asphalt surface course layer) and Case D (using bio-extended PMB in the asphalt surface course layer) indicates that using the investigated bio-oil as a bitumen extender in PMB also slightly increases the 100-year fossil GWP of asphalt pavements, mainly due to the upstream environmental impacts of extracting the raw material for producing the bio-oil. Case E combines effects of the bio-oil in both PMB and bio-extended bitumen without polymer in two asphalt bound layers, showing the highest 100-year fossil GWP among all cases. In addition, with the same pavement structure and layer thickness, the 100-year fossil GWP of the PMB cases is about 13% higher than that of the cases without polymer. It is attributed to the relatively high environmental impacts of PMB binders (particularly the polymer modifier) as well as the increased production temperature for HMA mixing with PMB.

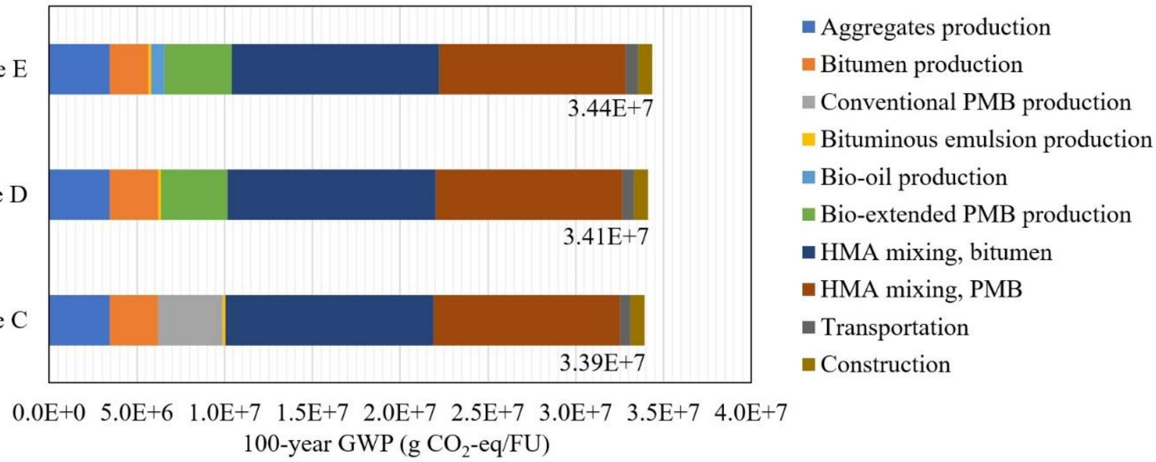

Fig. 5. *Cradle-to-pavement 100-year fossil GWP of Cases C, D and E based on CO_2 and CH_4 emissions.*

3.3 Biogenic Carbon Accounting and Impacts

According to the European standard EN 15804:2012+A2:2019/AC:2021 (CEN 2021), the total GWP of a construction product consists of three sub-categories – fossil GWP, biogenic GWP, and land use and land use change GWP. Within the system boundaries of this study, land use and land use change are not involved. As mentioned above, since the LCI considered only traditional fossil fuels and electricity energy sources, the 100-year GWP analysed in the previous section corresponds to the fossil GWP. The investigated bio-oil and bio-extended PMB do contain biogenic carbon due to transfers from the upstream product systems (pulp, paper, and eventually wood, and forest). Thus, the biogenic carbon content needs to be declared for the studied cases containing biogenic components. The impacts of biogenic carbon flow should be assessed.

For the biogenic GWP accounting, EN 15804:2012+A2:2019/AC:2021 takes the so called “-1/+1” approach. With this approach, inward transfers of biogenic carbon from the previous product systems into the studied product system are characterised in the LCIA as -1 g CO_2-eq/g CO_2 (i.e., about -3.67 g CO_2-eq/g C) while emissions of biogenic carbon and outward transfers from the studied product system into the subsequent product systems are characterised as +1 g CO_2-eq/g CO_2 (i.e., about +3.67 g CO_2-eq/g C). Thus, it provides an overview and leads to a net zero balance of the biogenic carbon flow.

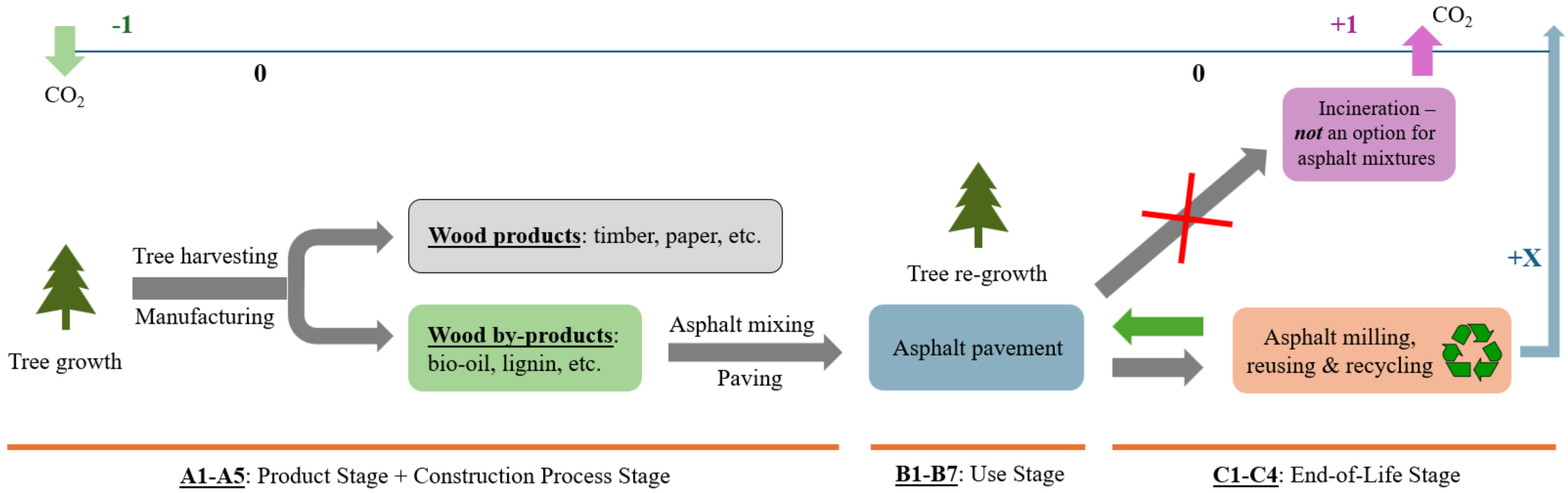

Fig. 6. *Different approaches for accounting plant-based biogenic carbon for asphalt pavements (this study covers A1-A5 and biogenic carbon accounting for Stage C).*

However, the “-1/+1” approach does not reflect the characteristics of asphalt mixtures that are not incinerated after end of life but are 100% recyclable materials (Zaumanis et al. 2014). For a more appropriate biogenic carbon accounting particularly for asphalt mixtures and pavements, other approaches need to be considered and explored. Generally speaking, there are three different approaches within the LCA literature about accounting plant-based biogenic carbon for construction works (Hoxha et al. 2020; Ouellet-Plamondon et al. 2023), depending on how biogenic carbon fixation, transfer and eventual emission to the atmosphere are considered. Fig. 6 illustrates these approaches (so called “0/0”, “-1/+1” and “-1/+X”) in the context of asphalt pavements.

Besides the “-1/+1” approach, such as in EN 15804:2012+A2:2019/AC:2021, the “0/0” approach does not consider fixation, transfer, or emission of biogenic carbon for the carbon footprint analysis. Furthermore, in the case of recycling (or landfill) at the end-of-life stage, a variant of the “-1/+1” approach can be applied to consider the fixation, inward transfer of biogenic carbon while no or not all biogenic carbon is modelled as an emission or outward transfer at the end-of-life stage. This variant is named the “-1/+X” approach in this study. A summary of these three different approaches is presented in Table 3.

Table 3. *Summary of the biogenic carbon accounting approaches considered in this study.*

Approach	**Forest system**	**Pavement system (life cycle stages)**		
		A1-A5	B1-B7	C1-C4
0/0	–	–	–	–
-1/+1	Carbon fixation	Inward transfer (-1)	–	Outward transfer (+1)
-1/+X	Carbon fixation	Inward transfer (-1)	–	Carbon recycled* (+X)

* Note: Partial carbon emission and/or outward transfer.

Since the “0/0” approach does not involve the biogenic GWP, in this study, the biogenic carbon is accounted using both the “-1/+1” and “-1/+X” approaches. Because the “X” value for asphalt pavements has not been widely established, as a preliminary exploration, the value used for accounting biogenic carbon for wood buildings in a few countries is used for asphalt pavements in this study. The “X” value is 0.1 (Ouellet-Plamondon et al. 2023). The recently updated document of Norwegian Product Category

Rules NPCR 025 Part B for Asphalt (version 1.1 updated in 2022) supports the selection of this "X" value (EPD-Norge 2022). It is worth noting that more precise "X" values particularly for asphalt pavements of various types still need to be determined in future studies.

According to the bio-oil content in the asphalt mixtures in Cases A-E and carbon content in the bio-oil, determined by elemental analysis (Nynas 2021), the biogenic carbon content of the studied cases could be calculated, namely 4.67×10^6 g C/FU in Case B, 8.01×10^5 g C/FU in Case D and 4.62×10^6 g C/FU in Case E. With the biogenic carbon content and by taking the "-1/+1" and "-1/+X" approaches, the impacts of biogenic carbon flow on the 100-year GWP could be assessed. The results of Cases A and B (without polymer) are presented in Fig. 7. It is indicated that, for a pavement structure with two asphalt layers using bio-extended bitumen (Case B), the biogenic GWP reduction due to the inward transfer of biogenic carbon accounted for about 57% of the initial fossil GWP. However, the impacts of the outward transfer and eventual emission of biogenic carbon from the studied system at the end-of-life stage vary depending on the approach taken for the analysis ("-1/+1" or "-1/+X"). The "-1/+1" approach leads back to the initial fossil GWP level with a net zero biogenic carbon balance, while the "-1/+X" approach resulted in a halved (about 49%) total GWP as compared to the initial fossil GWP level.

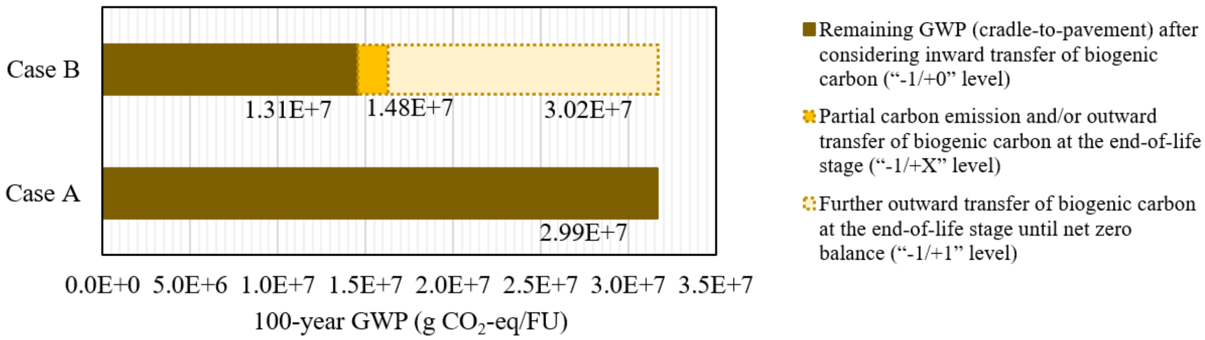

Fig. 7. *Impact of biogenic carbon flow on the 100-year GWP of Cases A and B (X = 0.1).*

As for the cases with PMB (Cases C, D and E), Fig. 8 presents the impact of biogenic carbon flow on the 100-year GWP. It is indicated that, for a pavement structure with the asphalt surface course layer using bio-extended PMB (Case D), the biogenic GWP reduction due to the inward transfer of biogenic carbon accounted for about 9% of the initial fossil GWP. However, the combination of an asphalt surface course layer using bio-extended PMB and an asphalt base course layer using bio-extended bitumen, namely Case E, almost halved (about 49%) the initial fossil GWP after considering the inward transfer of biogenic carbon. Similar as above, for the cases with PMB, impacts of the outward transfer and eventual emission of biogenic carbon from the studied system at the end-of-life stage also depend on which approach is taken for the analysis ("-1/+1" or "-1/+X"). The "-1/+1" approach always leads back to the initial fossil GWP level, while the "-1/+X" approach results in lowered total GWP as compared to the initial fossil GWP level (about 8% reduction in Case D and 44% reduction in Case E).

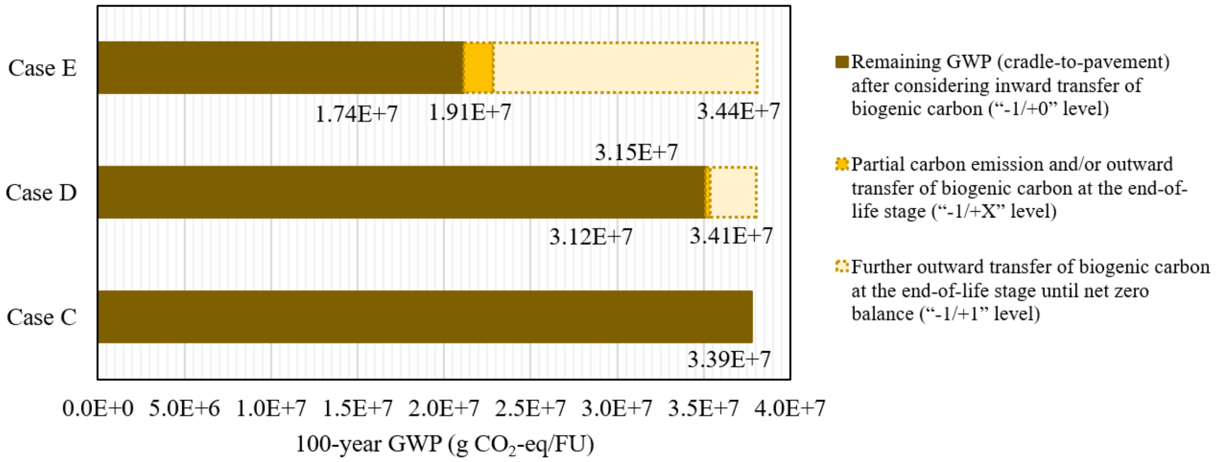

Fig. 8. *Impact of biogenic carbon flow on the 100-year GWP of Cases C, D and E (X = 0.1).*

3.4 Average Annual Impact on Climate Change

As the studied cases have the same layer thickness but different materials in the asphalt bound layers, their design service life may vary. Fig. 2 shows the similarity in stiffness between the conventional binders and their corresponding bio-extended counterparts. Thus, the pavement structures with materials of the same quality grade are expected to have the same design service life. This is supported by the laboratory test results of fatigue resistance of the AG16 asphalt mixtures for asphalt base course layer at 10 °C done according to EN 12697-24:2018 Annex E (CEN 2018), see Fig. 9 (AG16 asphalt mixtures after laboratory ageing). The results show that the studied cases do not have significantly different fatigue life by the cracking criteria at the bottom of asphalt base course layer. However, the use of PMB in asphalt surface course layer (such as in Cases C, D and E of this study) can extend the pavement service life. Some previous studies by other researchers (Von Quintus et al. 2007; Yan et al. 2023; Eklöf and Wendel 2024) reported different degrees of service life extension by using PMB under different circumstances, ranging from 8% up to 100%. In this study, the Swedish circumstance is considered. Based on Swedish data, the study by Eklöf and Wendel (2024) suggested that PMB can extend the service life of asphalt pavements by 8% to 24%. Thus, an overall assessment led to a relatively realistic and reasonable estimate for the service life extension in the cases with PMB in this study, namely 20% longer service life for Cases C, D and E as compared to Cases A and B.

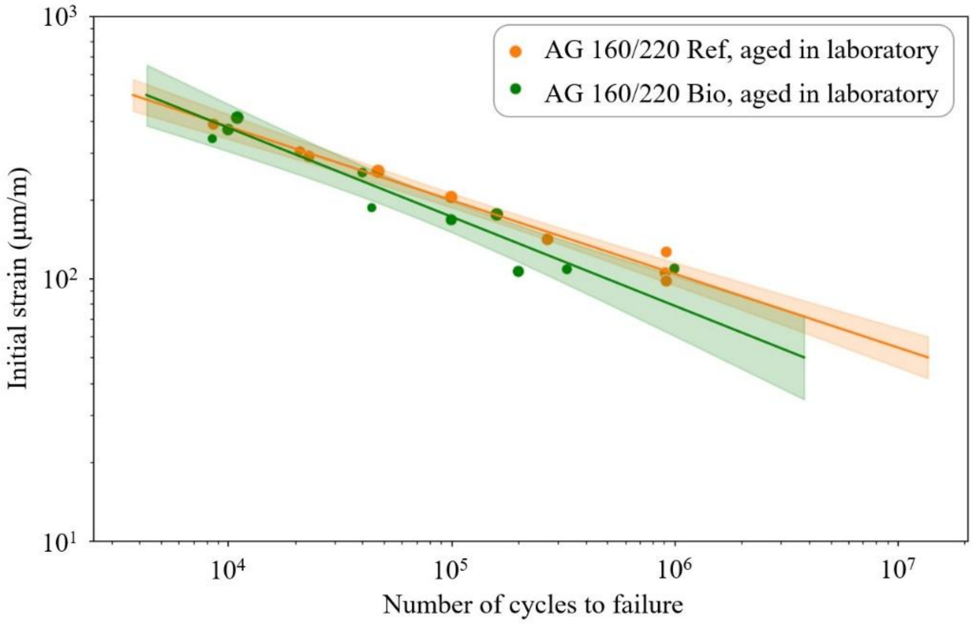

Fig. 9. *Fatigue resistance of the AG16 asphalt mixtures for asphalt base course layer at 10 °C (colour-shaded areas represent the 95% confidence intervals by statistical analysis of test data obtained from laboratory measurements).*

The calculation of design service life of Cases A, the reference case with conventional bitumen for which the most experience has been gained and the most reliable calculation could be done, indicated that Case A would have a service life of 13 years. By the estimation of 20% longer service life with PMB, Cases C, D and E would have a service life of 15.6 years. Then, with the total GWP values presented in the previous section (after biogenic carbon accounting by both the "-1/+1" and "-1/+X" approaches), the average annual impact of the studied cases on climate change, namely their average annual 100-year GWP over the whole service life, could be calculated and assessed. This assessment aims for fair comparisons between the cases taking into account the difference in design service life as a result of using PMB. The results are presented in Fig. 10. It is indicated that, when the "-1/+1" approach is employed, the cases with PMB (Cases C, D and E) have a lower average annual GWP than the cases without polymer (Cases A and B) over the whole service life. Furthermore, similar as for the total GWP, the biogenic carbon accounting by the "-1/+X" approach also reduces the average annual GWP significantly for the cases with biogenic components (Cases B, D and E).

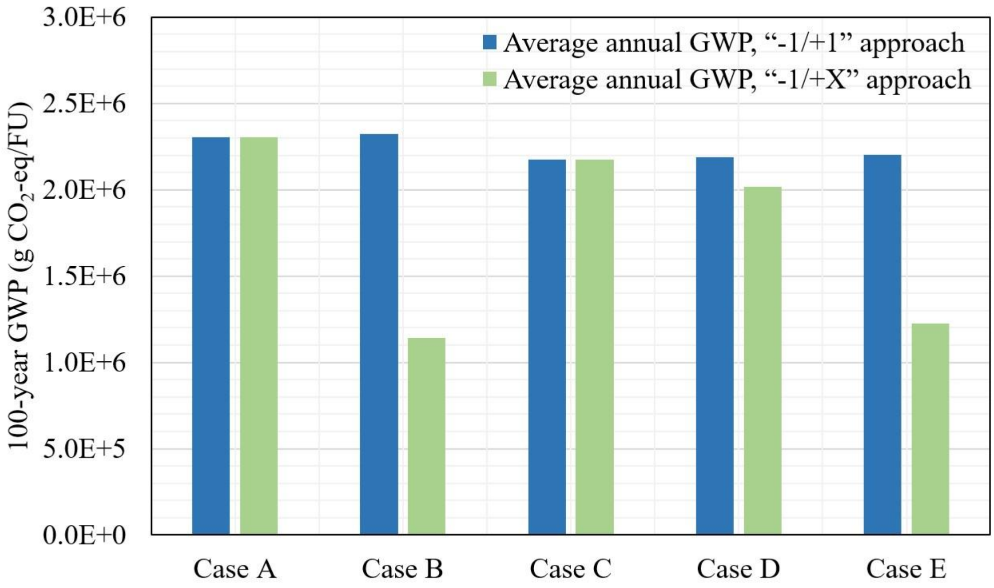

Fig. 10. *Average annual 100-year GWP of the studied cases.*

3.5 Sensitivity Analysis

To verify the reliability of the carbon footprint results discussed above, two sensitivity analysis (SA) cases, SA1 and SA2, were carried out by replacing the LCI input data of the high-impact processes with data from other sources. A summary of the employed SA approaches is presented in Table 4. In each SA case, three input data were replaced and all the other data remained the same as in Table 1. SA1 focused on the sensitivity to binder production data while SA2 focused on aggregates and HMA production data.

Table 4. *Summary of the sensitivity analysis approaches.*

Sensitivity analysis (SA)	Analysed data	Alternative data source	Original data source
SA1	Conventional bitumen production	Eurobitume 2012, 2021	Stripple 2001; Nynas 2021
	Conventional PMB production		
	Bio-extended PMB production*		
SA2	Aggregates production	A British contractor	Stripple 2001; Butt 2014
	HMA mixing, conventional bitumen		
	HMA mixing, PMB		

* Note: Alternative data were estimated based on the Eurobitume data in 2012.

The results of the SA cases are presented in Fig. 11, showing the average annual 100-year GWP of the five pavement structures (Fig. 3) after biogenic carbon accounting by both the "-1/+1" and "-1/+X" approaches. It is indicated that the absolute GWP levels can be variable, depending on the input data. Especially for the cases without polymer (Cases A and B), SA2 resulted in significantly higher GWP values than SA1, although their differences were not as large for the cases with PMB. Regarding the effect of PMB when the "-1/+1" approach is adopted, SA2 led to the same conclusion as in the previous section, namely lower average annual GWP when PMB is used. But SA1 showed almost unchanged average annual GWP. Thus, the effect of PMB on average annual GWP over the whole service life may be variable, depending on the specific input data. Furthermore, both SA1 and SA2 confirmed that the biogenic carbon accounting by the "-1/+X" approach reduces the average annual GWP significantly for the cases with biogenic components.

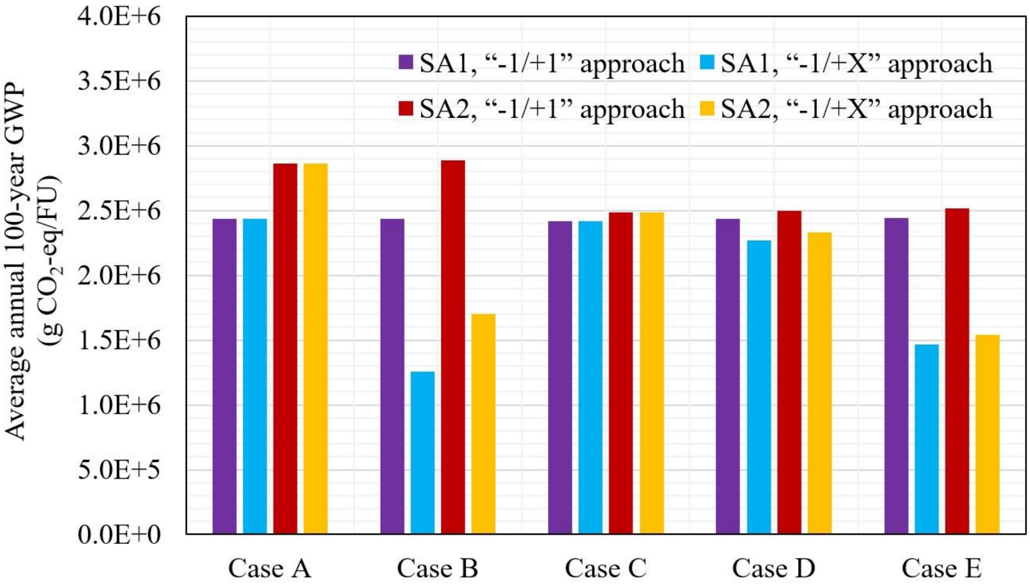

Fig. 11. *Average annual 100-year GWP of the sensitivity analysis.*

4 Conclusions

This LCA study took a "cradle-to-pavement" approach and quantified the carbon footprint of bio-extended bituminous binders used for pavement decarbonisation. The results indicated that using the investigated bio-oil as a bitumen extender slightly increases the fossil GWP of asphalt pavements up to the construction phase of the life cycle, by about 1%. Among the analysed processes, HMA mixing is the largest source of fossil carbon emissions within the system boundaries.

By the biogenic carbon accounting, the impact of biogenic carbon flow could be analysed by both the "-1/+1" and "-1/+X" approaches. For the pavement structures with two asphalt layers using bio-extended bituminous binders (Cases B and E), the biogenic GWP reduction due to the inward transfer of biogenic carbon accounted for around 50% of the initial fossil GWP. However, the impacts of the outward transfer and eventual emission of biogenic carbon from the studied system at the end-of-life stage vary depending on the approach adopted for the analysis. Using the "-1/+1" approach, the GWP returns to the initial fossil GWP level, achieving a net zero biogenic carbon balance. Meanwhile, employing the "-1/+X" approach resulted in a significant reduction in Cases B and E, with the total GWP still being around 50% of the initial fossil GWP level. This reduction depends on the biogenic carbon content in the pavement structure.

To facilitate fair comparisons between the cases with and without PMB, the average annual GWP was assessed for the studied pavement structures over their whole service life taking into account the effects of PMB on pavement durability, and a sensitivity analysis was carried out for verifying the result reliability. The results indicate that both the absolute GWP levels and the effect of PMB on average annual GWP are variable, depending on the input data. When the "-1/+1" approach is adopted, two of the three analysed cases showed a lower average annual GWP of asphalt pavements with PMB while one analysed case showed almost unchanged average annual GWP. All analysed cases confirmed that the biogenic carbon accounting by the "-1/+X" approach reduces the total and average annual GWP significantly for the cases with biogenic components.

Lastly, this study has its limitations. (1) The LCI in this study considered only traditional fossil fuels and electricity energy sources. No fossil-free energy such as renewable energy that has been increasingly popular in Sweden and Europe was considered. (2) No reclaimed asphalt was taken into account. Bio-based binders have proven effects (Cavalli et al. 2018) on the performance of pavements with reclaimed asphalt. (3) The use and end-of-life stages were not fully included in this study due to data availability. This limited the system boundary to "cradle to pavement" excluding the use phase and end-of-life phase (only biogenic carbon accounting was included). (4) This study focused on carbon emission impacts whereas the bio-based material may have other impacts to quantify, such as land use change, in order to inform sustainable design and procurement. (5) The unit inventory (Unit 4 of the LCA model) can be expanded to include more temporal and spatial dimensions for the supply chain, as previous work by other researchers (Moretti et al. 2022) found the trade-off between environmental impacts and the variation in results when the energy mix in supply chain is changed. Future studies will need to consider these important aspects.

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Data Availability

Data generated or analysed during this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare there are no competing interests.

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