Ministry of Environment and Food of Denmark
Environmental Protection Agency

Life Cycle Assessment of grocery carrier bags

Environmental Project no. 1985

February 2018

Publisher: The Danish Environmental Protection Agency

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Konceptuel ramme
Dette studie giver en livscyklusvurdering af produktion, brug og bortskaffelse ("vugge til grav") af indkøbsposer tilgængelige i danske supermarkeder i 2017. Undersøgelsen blev udført af DTU Miljø i perioden oktober - december 2017.
I øjeblikket tilbyder danske supermarkeder kunderne flere indkøbsposer i forskellige materialer (såsom genanvendeligt og ikke-genanvendeligt plast, papir og bomuld) designet til at skulle bruges flere gange inden bortskaffelse. Grundet miljøpåvirkninger fra deres fremstilling, skal disse flerbrugsposer optimalt genbruges et vist antal gange for at kompensere for miljøpåvirkningerne, hvor antallet afhænger af materialet og design.
Studiet blev bestilt af Miljøstyrelsen med det formål at identificere indkøbsposen med den bedste miljøpræstation, til brug i danske supermarkeder. Studiet har til formål at identificere et anbefalet antal genbrug af hver indkøbspose baseret på indkøbsposernes miljøpåvirkninger under hele livscyklus. Studie tog højde for, at genbrug af indkøbsposerne kan forekomme både som primær genbrug (hvor indkøbsposen genbruges til samme funktion, som den blev produceret, dvs. for at transportere dagligvarer fra supermarked til hjem) eller som erstatning af en skraldepose i affaldsbeholdere (sekundær genbrug).
De følgende indkøbsposer blev undersøgt:

- Lavdensitets polyethylen (LDPE), 4 typer; en LDPE indkøbspose med gennemsnitlige værdier, en LDPE indkøbspose med blødt håndtag, an LDPE indkøbspose med fast håndtag og en LDPE indkøbspose af genanvendt LDPE
- Polypropylen (PP), 2 typer: ikke-vævet og vævet;
- Genanvendt polyethylenterephthalat (PET);
- Polyester (af primære PET-polymerer);
- Stivelse-kompleksbundet biopolymer;
- Papir, 2 typer: ubleget og bleget;
- Bomuld, 2 typer: økologisk og konventionel;
- Komposit materiale (jute, PP, bomuld).

En undersøgelse foretaget af DTU Miljø viste, at LDPE-poser er tilgængelige for køb i alle danske supermarkeder, mens andre typer af indkøbsposer tilbydes som alternativer. Derfor blev de gennemsnitlige egenskaber ved en LDPE indkøbspose brugt som referencepose i studiet. Rapporten omhandler kun indkøbsposer til rådighed i danske supermarkeder i 2017, og omfatter ikke andre typer af poser. Rapporten fokuserer på de miljøpåvirkninger, der er forbundet med indkøbsposerne, og tager ikke stilling til hvad indførelsen af skatter, kunders holdninger eller adfærdsmæssige ændringer ville kunne have for studiet. Miljøeffekten af, at poserne smides som henkastet affald i naturen blev antaget som ubetydelige for danske forhold og blev derfor ikke inkluderet i modellen. Undersøgelsen blev kun udført for materialetyper og poser, der allerede var på markedet. Dette betyder ikke, at andre mere optimale kombinationer af materialevalg og posedesign ikke kunne være relevante for fremtidig poseproduktion (volumen, genanvendt materiale, bæreevne osv.)

Metodisk ramme
Miljøvurderingen blev udført via livscyklusvurdering (LCA), som er en standardiseret metode, der tager højde for de potentielle miljøpåvirkninger forbundet med de ressourcer, der er nødvendige for at producere, bruge og bortskaffe produktet der evalueres samt mulige emissioner der kan opstå under produktion og bortskaffelse. Når materiale- og energiressourcer genvindes, krediteres systemet med potentielt undgåede emissioner fra primær produktion af de samme ressourcer. For at sammenligne indkøbsposerne tog vi højde for, hvor mange af de

forskellige poser der var nødvendige for at kunne opfylde den funktion, der bliver leveret af en LDPE indkøbspose med gennemsnitlige egenskaber, som i studies fastsattes til:

"Transportere indkøb med et gennemsnitligt volumen på 22 liter og en gennemsnitlig vægt på 12 kg fra et dansk supermarked til hjemmet i 2017 med en (nyindkøbt) indkøbspose. Indkøbsposen er produceret i Europa og distribueret til Danske supermarkeder. Efter brug, indsamles og behandles indkøbsposen i det danske affaldshåndteringssystem"

Som vist i Tabel I var to poser nødvendige for at opfylde funktionen i tilfælde af simple LDPE, recirkulerede LDPE-, biopolymer-, papir- og økologiske bomuldsposer. For disse poser, var enten den krævede volumen eller vægtkapacitet ikke opfyldt. Poser af økologisk og konventionelt produceret bomuld blev modelleret hver for sig, for at kunne sammenligne forskellene i resultater for de to materialetyper, da økologisk bomuld har et lavere produktions udbytte end konventionelt produceret bomuld (Forster et al., 2013). Tabel I viser, at for økologisk bomuld skal der bruges to indkøbsposer, da volumen af den økologiske bomuldspose ikke var lige så stort som volumen for reference posen af LDPE.

Tabel I. Forskellige indkøbsposer vurderet i denne LCA og det antal poser der kræves for at opfylde funktionaliteten leveret af en LDPE indkøbspose med gennemsnitlige egenskaber.

Indkøbspose materiale	Indkøbspose type	Reference flow (antal poser der er nødvendige)
Plast	LDPE (gennemsnit)	1 (reference pose)
Plast	LDPE simpel	2
Plast	LDPE fast håndtag	1
Plast	LDPE genanvendt	2
Plast	PP ikke-vævet	1
Plast	PP vævet	1
Plast	PET genanvendt	1
Plast	Polyester	1
Bioplast	Biopolymer	2
Papir	Papir, ubleget	2
Papir	Papir, bleget	2
Tekstil	Bomuld økologisk	2
Tekstil	Bomuld konventionelt	1
Komposit	Jute, PP, bomuld	1

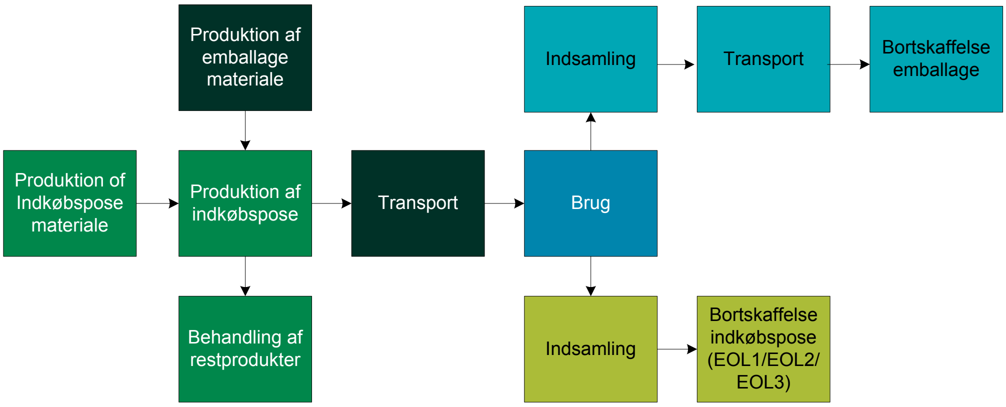
Miljøvurderingen blev for hver indkøbspose udført for forskellige bortskaffelsesmuligheder: forbrænding (EOL1); genanvendelse (EOL2); og genbrug som skraldepose inden forbrænding (EOL3). For alle indkøbsposer blev der taget højde for miljøpåvirkningen af produktion (antages at produceres i Europa), emballage ved fremsendelse til butik, transport til Danmark samt brug og bortskaffelse (som kunne forekomme i Danmark eller i Europa). Den generelle struktur af de inkluderede scenarier, og processer der tages i betragtning, er vist i Figur I.

Miljøvurderingen blev udført for en række anbefalede miljøpåvirkninger (Europa-Kommissionen, 2010): klimaforandringer; ozonnedbrydning; human toksicitet (kræft og ikke-kræftvirkninger); fotokemisk ozondannelse; ioniserende stråling; partikelforurening; terrestrisk forsuring; terrestrisk eutrofiering; marin eutrofiering; ferskvands eutrofiering; økosystems toksicitet; ressourceforbrug fossilt og abiotisk; samt brug af vandressourcer.

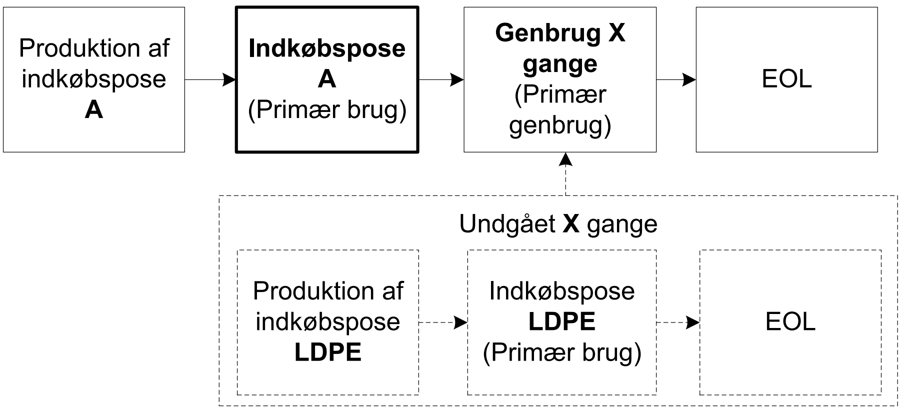
For hver indkøbspose blev beregnet det antal genbrug der var nødvendigt for at tilsvare referenceposen af LDPE. Dette blev gjort per indkøbspose, livscyklus og påvirkningskategori under forudsætning af, at X gange genbrug af en indkøbspose erstatter en tilsvarende anvendelse X gange af referenceposen, dvs. for hver gang en pose genbruges undgås den fulde livscyklus af referenceposen. Et grafisk eksempel for primært genbrug er vist i Figur II. Ved at tage udgangspunkt i vugge-til-grav LCA-resultatet for alternativ indkøbspose A som LCIA[1] $_A$ og vugge- til- grav LCA-resultatet for den gennemsnitlige LDPE indkøbspose som $LCIA_{LDPE}$, blev antallet af genbrugsgange x beregnet som følger:

$$x = \frac{LCIA_A - LCIA_{LDPE}}{LCIA_{LDPE}}$$

LCA-studiet er baseret på offentligt tilgængelige livscyklusdata (LCI) og data fra eksisterende studier af indkøbsposer. I udførelsen af studiet var der nogle databegrænsninger og antagelser, for eksempel med hensyn til valget af referencepose, modellering af materialeproduktionen og indkøbsposeproduktionen. En følsomhedsanalyse blev udført for de kritiske antagelser og valg der blev foretaget.



Figur I. Generel struktur for alle indkøbspose scenarier vurderet i denne LCA. "EOL" henviser til de tre forskellige bortskaffelses scenarier. EOL1: forbrænding, EO2: genanvendelse, EOL3: genbrug som skraldepose.



Figur II. Generel modellering af primær genbrug. Eksemplet illustrerer den primære genbrug X gange af en generisk "indkøbspose A". Genbruget X gange tillader en undgået produktion, brug og bortskaffelse X gange af en reference indkøbspose af LDPE.

[1] LCIA = life cycle impact assessment

Resultater og anbefalinger
LCA-undersøgelsen gav en række resultater, som kan være nyttige til optimering af brugen og bortskaffelsen af indkøbsposer til rådighed for køb i Danmark. Resultaterne refererer til de reference flows der er præsenteret i Tabel I.

Hvad er den mest fordelagtige bortskaffelsesmulighed for hver type af indkøbspose?
Når indkøbsposen er genbrugt så mange gange som muligt, er det bedre at genbruge indkøbsposen som en skraldepose, end blot at smide posen i restaffaldet, og dette er bedre end at aflevere posen til genanvendelse. Genanvendelse kan potentielt give større fordele i tilfælde af tunge plastposer, såsom poser af PP, PET og polyester. Sekundær genbrug som skraldepose er mest gavnlig for lette indkøbsposer, såsom poser af LDPE, papir og biopolymer. Når genbrug som skraldepose ikke er muligt, for eksempel når posen let prikkes hul i, rives i stykker eller bliver fugtig, som for papir- og biopolymerposer, er forbrænding den mest foretrukne løsning ud fra et miljømæssigt synspunkt. Tabel II giver et resumé af de opnåede resultater for hver bærerpose.

Tabel II. Oversigt over den mest foretrukne bortskaffelsesmulighed for hver af de indkøbsposer, der vurderes.

Indkøbspose materiale	Foretrukken bortskaffelsesmetode efter genbrug som indkøbspose
Plast, LDPE	Genbrug som skraldepose
Plast, PP	Genanvendelse, genbrug som skraldepose hvis muligt, ellers forbrændes
Plast, genanvendt PET	Genanvendelse, genbrug som skraldepose hvis muligt, ellers forbrændes
Plast, polyester PET	Genbrug som skraldepose hvis muligt, ellers forbrændes
Biopolymer	Genbrug som skraldepose hvis muligt, ellers forbrændes
Papir	Genbrug som skraldepose hvis muligt, ellers forbrændes
Tekstil	Genbrug som skraldepose hvis muligt, ellers forbrændes
Komposit	Genbrug som skraldepose hvis muligt, ellers forbrændes

Hvilken indkøbspose giver de laveste miljøpåvirkninger?
Generelt har LDPE-indkøbsposer, som er poser der altid kan købes i danske supermarkeder, de laveste miljøpåvirkninger for de fleste miljøindikatorer (Tabel III). LDPE-indkøbsposer med stift håndtag havde den laveste miljøpåvirkning i flertallet af de miljøpåvirknings kategorier der var inkluderet i dette LCA studie. Indkøbsposer, der kan give en lignende lav miljøpåvirkning er ublegede papir- og biopolymerposer, men for et lavere antal miljøindikatorer. Såkaldt tunge indkøbsposer, såsom poser af PP, PET, polyester, bleget papir og tekstilposer, skal genbruges flere gange for at opveje deres miljøproduktionsomkostninger. For poser af samme materiale havde vævede PP-indkøbsposer lavere belastning end ikke-vævede PP-poser, ubleget papir havde lavere påvirkning end bleget papir, og konventionelt bomuld havde lavere påvirkning end økologisk bomuld.

Hvor mange gange skal indkøbsposer mindst genbruges?
For alle indkøbsposer skal de genbruges så mange gange som muligt før bortskaffelse. Tabel IV rapporterer antal gange indkøbsposen skal genbruges for at reducere de miljømæssige konsekvenser, der er forbundet med alle de alternative indkøbsposer i forhold til LDPE-indkøbsposen. Derfor refererer de tal, der er angivet i Tabel IV, til det mindste antal gange en pose skal genbruges. Det beregnede antal genbrug varierer, hvis kun én miljøindikator er observeret eller hvis alle miljøindikatorer tages i betragtning. Det beregnede antal genbrug kan være i overensstemmelse med den mulige levetid for PP, PET og polyester indkøbsposer, men kan overstige levetiden for bleget papir-, komposit- og bomuldsposer, især hvis man tager alle miljøindikatorer i betragtning. For LDPE-indkøbsposer var det nødvendige antal genbrug forholdsvis ens for de forskellige miljøpåvirkningskategorier.

Tabel III. Indkøbsposer med den laveste miljøpåvirkning for alle de vurderede miljøindikatorer. Rækkefølgen, som poserne er anført i, svarer til placering i forhold til deres LCA-resultater med lavest påvirkning først. Kun de tre laveste effekter er angivet. Resultaterne refererer til det reference flow der er anført i Tabel I.

Miljøpåvirknings indikator	Indkøbspose med lavest påvirkning
Klimaforandringer	Papir ubleget, biopolymer, LDPE
Ozonnedbrydning	LDPE
Human toksicitet, kræft	Papir ubleget, LDPE
Human toksicitet, ikke-kræft	Komposit, PP, LDPE
Fotokemisk ozondannelse	LDPE
Ioniserende stråling	LDPE
Partikelforurening	LDPE
Terrestrisk forsuring	LDPE
Terrestrisk eutrofiering	LDPE
Ferskvands eutrofiering	LDPE
Marin eutrofiering	PP, LDPE
Økosystems toksicitet	LDPE
Ressourceforbrug, fossilt	Papir ubleget, LDPE
Ressourceforbrug, abiotisk	PP, LDPE
Ressourceforbrug, vandressourcer	LDPE, biopolymer

For indkøbsposer af PP, PET, biopolymer og papir var det nødvendige antal genbrug højere i nogle kategorier end andre. Slutteligt fandtes det, at det meget høje antal genbrug for indkøbsposer af bomuld og kompositmateriale primært skyldtes kategorien ozonnedbrydning der var væsentligt højere end de andre kategorier, for hvilken datasættet for produktion af bomuldsposen havde en væsentligt højere påvirkning end LDPE-posen.

Følsomhedsanalysen af data og antagelser fremhævede vigtigheden af valget af reference flow, hvilket var afgørende for det beregnede antal genbrug for poser af økologisk bomuld. Valget af reference flow afhænger af opfyldelsen af funktionen udtrykt af den funktionelle enhed beskrevet ovenfor. Specielt viste resultaterne betydningen af indkøbsposens design, som bør fokusere på maksimering af volumen og bærekapacitet, samtidig med at mængden af materiale der anvendes minimeres og dermed også vægten af indkøbsposen.

Vores endelige anbefalinger er følgende[2]:

- **LDPE-pose, simpel**: Kan genbruges direkte som skraldepose i forhold til klimaforandringer, skal genbruges mindst 1 gang til indkøb når der tages højde for alle andre indikatorer. Genbrug som skraldepose, forbrænding.

[2] Antallet af gange poserne skal genbruges for "alle indikatorer" henviser til det højeste antal blandt dem, der beregnes for hver påvirkningskategori. For lette indkøbsposer (LDPE, PP, PET ...) skyldes det høje antal en gruppe af påvirkningskategorier med samme høje værdier. Omvendt er det for komposit- og bomuldsposer ozonnedbrydning der er grunden til det meget høje antal gange poserne skal genbruges. Hvis der ses bort fra ozonnedbrydning, falder det nødvendige antal gange poserne skal genbruges fra 50 til 1400 for konventionel bomuld, fra 150 til 3800 for økologisk bomuld og fra 0 til 740 for kompositmaterialeposen hvilket primært skyldes brugen af vandressourcer, men ferskvands- og terrestrisk-eutrofiering har lignende høje værdier. Resultater for det nødvendige antal gange poserne skal genbruges for hver påvirkningskategori, minimum-maksimum intervaller og gennemsnitligt antal genbrug fremgår af bilag C.

Tabel IV. Beregnet antal primære genbrug nødvendigt for hver indkøbspose, med den optimale bortskaffelse af indkøbsposen, for at give den samme miljømæssige ydeevne som den gennemsnitlige LDPE indkøbspose med bortskaffelse som skraldepose inden forbrænding. Resultaterne refererer til det reference flow der er anført i Tabel I.

	LDPE gennemsnitspose, genbrug som skraldepose	
	Klimaforandring	Alle indikatorer
LDPE simpel, genbrug som skraldepose	0	1
LDPE fast håndtag, genbrug som skraldepose	0	0
LDPE genanvendt, genbrug som skraldepose	1	2
PP, ikke-vævet, genanvendelse	6	52
PP, vævet, genanvendelse	5	45
Genanvendt PET, genanvendelse	8	84
Polyester PET, genanvendelse	2	35
Biopolymer, genbrug som skraldepose og forbrænding	0	42
Ubleget papir, genbrug som skraldepose og forbræn-ding	0	43
Bleget papir, genbrug som skraldepose og forbrænding	1	43[3]
Økologisk bomuld, genbrug som skraldepose og for-brænding	149	20000
Konventionelt bomuld, genbrug som skraldepose og forbrænding	52	7100
Komposit, genbrug som skraldepose og forbrænding	23	870

- **LDPE-pose, fast håndtag**: Kan genbruges direkte som skraldepose i forhold til alle indikatorer. Genbrug som skraldepose, forbrænding.
- **LDPE-pose, genanvendt**: Genbrug til indkøb mindst 1 gang i forhold til klimaforandringer, mindst 2 gange når der tages højde for alle indikatorer. Genbrug som skraldepose, forbrænding.
- **PP-pose, ikke-vævet**: Genbrug til indkøb mindst 6 gange i forhold til klimaforandringer, mindst 52 gange når der tages højde for alle indikatorer. Bortskaffes med genanvendelige materialer, ellers genbrug som skraldepose hvis det er muligt, forbrænding.
- **PP-pose, vævet:** Genbrug til indkøb mindst 5 gange i forhold til klimaforandringer, mindst 45 gange når der tages højde for alle indikatorer. Bortskaffes med genanvendelige materialer, ellers genbrug som skraldepose hvis det er muligt, forbrænding.
- **PET-pose:** Genbrug til indkøb mindst 8 gange i forhold til klimaforandringer, mindst 84 gange når der tages højde for alle indikatorer; bortskaffes med genanvendelige materialer, genbrug som skraldepose hvis muligt, forbrænding.
- **Polyesterpose:** Genbrug til indkøb mindst 2 gange i forhold til klimaforandringer, mindst 35 gange når der tages højde for alle indikatorer; bortskaffes med genanvendelige materialer, ellers genbrug som skraldepose hvis muligt, forbrænding.
- **Biopolymerpose:** Hvis muligt genbrug direkte som skraldepose i forhold til klimaforandringer, skal genbruges mindst 42 gange til indkøb når der tages højde for alle andre indikatorer. Genbrug som skraldepose hvis muligt, forbrænding.
- **Ubleget papirpose**: Hvis muligt genbrug direkte som skraldepose i forhold til klimaforandringer, skal genbruges mindst 43 gange når der tages højde for alle andre indikatorer. Genbrug som skraldepose hvis muligt, forbrænding.

[3] Den højeste værdi for bleget papir er sat til minimum at være den samme som ubleget papir.

- **Bleget papirpose:** Genbrug til indkøb mindst 1 gang i forhold til klimaforandringer, mindst 43 gange når der tages højde for alle indikatorer. Genbrug som skraldepose hvis det er muligt, ellers forbrænding.
- **Økologiske bomuldspose**: Genbrug til indkøb mindst 149 gange for klimaændringer, mindst 20000 gange når der tages højde for alle indikatorer. Genbrug som skraldepose hvis det er muligt, ellers forbrænding.
- **Traditionelle bomuldspose:** Genbrug til indkøb mindst 52 gange i forhold til klimaforandringer, mindst 7100 gange når der tages højde for alle indikatorer. Genbrug som skraldepose, hvis det er muligt, ellers forbrænding.
- **Kompositpose:** Genbrug til indkøb mindst 23 gange i forhold til klimaforandringer, mindst 870 gange når der tages højde for alle indikatorer. Genbrug som skraldepose, hvis det er muligt, ellers forbrænding.

Det understreges, at hvis reference LDPE-posen genbruges til indkøb, øges det nødvendige antal gange de andre poser skal genbruges proportionalt. Resultaterne opnået for det minimale antal genanvendelses gange er beregnet for at bidrage til en videre diskussion mellem interessenterne om den forventede effektive levetid for hver indkøbspose i forhold til det beregnede antal gange poserne skal genbruges. Selvom det beregnede antal genbrug kan være i overensstemmelse med den funktionelle levetid for PP, PET og polyester indkøbsposer, kan den overgå levetiden for bleget papir-, komposit- og bomuldsindkøbsposer, især når man tager alle miljøindikatorer i betragtning.

Resumé af det kritiske review

Reviewere

En kritisk gennemgang i henhold til ISO 14040/14044 blev udført af Line Geest Jakobsen og Trine Lund Neidel fra COWI A/S i Januar 2018

Review processen

Reviewet involverede følgende faser:

- COWI udførte det første review i januar 2018
- DTU svarede på de spørgsmål der blev stillet af COWI, og rettede rapporten i forhold de kommentarer der var enighed om i reviewet fra januar 2018
- COWI evaluerede de rettelser der var lavet, og sammenfattede den endelige review kommentar.

Det kritiske review er vedhæftet i fulde i Appendix D. Hovedpunkterne fremhævet i det kritiske review er angivet nedenfor.

LCA-rapporten er blevet gennemgået med hensyn til overholdelse af de internationale standarder ISO 14040 og 14044. Rapporten viste sig i overordnet at overholde standarderne. Forfatterne anfører, at rapporten ikke er i overensstemmelse med standarden, da et review med inddragelse af et ekspertpanel ikke blev gennemført i projektfaserne.

Metoden valgt til fastsættelse af den funktionelle enhed og reference flow blev verificeret ved en følsomhedsanalyse. Resultaterne af følsomhedsanalysen viste, at valget af reference flow har stor indflydelse på bæreposer med høje miljøpåvirkninger forbundet med produktion og poser med et lavere volumen end det, der udtrykkes i den funktionelle enhed (hovedsageligt økologisk bomuld). Forfatterne tilføjede en dedikeret sektion om indkøbspose design, hvor de giver kommentarer til den indflydelse som indkøbspose design har på resultaterne.

Det kritiske review understregede, at særlig opmærksomhed skal tillægges datakvalitetsvurdering og at kritiske antagelser skal være tydeligt klargjort. Forfatterne tilføjede dedikerede afsnit om datakvalitetsvurdering, kritiske antagelser samt hvilken indflydelse data og antagelser har på resultaterne. Miljøpåvirkningen som udvalgte kritiske antagelser havde på resultaterne blev vurderet med en følsomhedsanalyse.

Efter det første kritisk review, tilføjede forfatterne yderligere specifikationer på indkøbstyperne (for eksempel polyester polymertypen), justerede sprog og grammatisk fejl og tilføjede yderligere detaljer for at forbedre den overordnede forståelse af rapporten.

Executive summary - English

Conceptual framework
This study provides the life cycle environmental impacts of the production, use and disposal ("cradle-to-grave") of grocery carrier bags available for purchase in Danish supermarkets in 2017. The study was carried out by DTU Environment in the period October – December 2017.

Currently, Danish supermarkets provide multiple-use carrier bags of different materials (such as recyclable and non-recyclable plastic, paper and cotton) designed for a multiple number of uses. In order to compensate the environmental impacts arising from their manufacturing phase, these multiple-use carrier bags need to be reused a number of times.

This study was commissioned by the Danish Environmental Protection Agency (Miljøstyrelsen) with the aim to identify the grocery carrier bag with the best environmental performance to be provided in Danish supermarkets. Moreover, the Miljøstyrelsen aimed at identifying a recommended number of reuse times for each carrier bag based on their life cycle environmental impacts. The project took into account that reuse of the carrier bag could occur both as primary reuse (where the carrier bag is reused for the same function for which it was produced, i.e. for carrying grocery shopping from the supermarket to the home), or replacing other products as waste bin liners (secondary reuse).

The following types of carrier bags were studied:

- Low-density polyethylene (LDPE), 4 types: an LDPE carrier bag with average characteristics, an LDPE carrier bag with soft handle, an LDPE carrier bag with rigid handle and a recycled LDPE carrier bag;
- Polypropylene (PP), 2 types: non-woven and woven;
- Recycled polyethylene terephthalate (PET);
- Polyester (of virgin PET polymers);
- Starch-complexed biopolymer;
- Paper, 2 types: unbleached and bleached;
- Cotton, 2 types: organic and conventional;
- Composite (jute, PP, cotton).

A survey conducted by DTU Environment showed that LDPE bags are always available for purchase in all Danish supermarkets, while other carrier bag types are provided as alternatives. Therefore, the average characteristics of the LDPE carrier bag were taken as reference. The report considers only carrier bags available in Danish supermarkets in 2017 and it does not include personal bags or other carriers. The report focuses on the environmental impacts connected to the carrier bags, and does not consider the introduction of taxes, customers' attitude or behavioural changes. The effects of littering were considered negligible for Denmark and not considered. The study was only done for material types already on the market, and the functionality of these bags. This does not mean that other more optimal combinations could not be relevant for future bag production (volume, recycled material, carrying capacity etc.).

Methodological framework
The environmental assessment of the carrier bag alternatives was carried out with Life Cycle Assessment (LCA), which is a standardized methodology that takes into account the potential environmental impacts associated with resources necessary to produce, use and dispose the

product, and also the potential emissions that may occur during its disposal. When material and energy resources are recovered, the system is credited with the avoided potential emissions that would have been necessary in order to produce these resources. In order to compare the carrier bags, we took into account how many of the different types were necessary in order to fulfil the function provided by an LDPE carrier bag with average characteristics, which was:

"Carrying one time grocery shopping with an average volume of 22 litres and with an average weight of 12 kilograms from Danish supermarkets to homes in 2017 with a (newly purchased) carrier bag. The carrier bag is produced in Europe and distributed to Danish supermarkets. After use, the carrier bag is collected by the Danish waste management system".

As shown in Table I, two bags were necessary to fulfil the function in the case of simple LDPE, recycled LDPE, biopolymer, paper, and organic cotton bags. For these bags, either the volume or weight holding capacity required was not fulfilled. Organic and conventional cotton bags were modelled separately in order to differentiate the results for the different types of material, since organic cotton production has a lower yield than conventional cotton (Forster et al., 2013). Table I shows that organic cotton required two carrier bags, since the volume of the organic cotton bag did not fulfil the volume requirements expressed in the functional unit.

Table I. Carrier bag alternatives considered for this LCA study and number of bags required to fulfil the functionality provided by an LDPE carrier bag with average characteristics.

Material carrier bag	Type carrier bag	Reference flow (number of bags needed)
Plastic	LDPE (average)	1 (reference bag)
Plastic	LDPE simple	2
Plastic	LDPE rigid handle	1
Plastic	LDPE recycled	2
Plastic	PP non-woven	1
Plastic	PP woven	1
Plastic	PET recycled	1
Plastic	Polyester	1
Bioplastic	Biopolymer	2
Paper	Paper, unbleached	2
Paper	Paper, bleached	2
Textile	Cotton organic	2
Textile	Cotton conventional	1
Composite	Jute, PP, cotton	1

The environmental assessment of each carrier bag was carried out taking into consideration different end-of-life options: incineration (EOL1), recycling (EOL2), and reuse as waste bin bag (EOL3) before being incinerated. For all carrier bag alternatives, the assessment took into account impacts arising from production of the carrier and its packaging (assumed to occur in Europe), transportation to Denmark, use, and disposal (which could occur in Denmark or within Europe). The general structure of the processes taken into account is shown in Figure I. The environmental assessment was carried out for a range of recommended environmental impacts (European Commission, 2010): climate change, ozone depletion, human toxicity cancer and non-cancer effects, photochemical ozone formation, ionizing radiation, particulate matter, terrestrial acidification, terrestrial eutrophication, marine eutrophication, freshwater

eutrophication, ecosystem toxicity, resource depletion, fossil and abiotic, and depletion of water resource.
The number of primary reuse times for each carrier bag, end-of-life scenario and impact category was calculated assuming that a reuse X times of a carrier bag allowed avoiding the corresponding use X times of the reference LDPE carrier bag with average characteristics, or more simply, for every time a bag is reused it avoids the full life cycle of the reference bag. A representation of primary reuse is provided in Figure II. Considering the cradle-to-grave LCA result for and alternative carrier bag A as $LCIA_A$ and the cradle-to-grave LCA result for the average LDPE carrier bag as $LCIA_{LDPE}$, the number of reuse times x was calculated as follows:

$$x = \frac{LCIA_A - LCIA_{LDPE}}{LCIA_{LDPE}}$$

The LCA study was based on publicly available LCI data and data from existing LCA studies on grocery carrier bags. The study presented some data limitations and assumptions, for example regarding the choice of reference flow, the modelling of material production and carrier bag manufacture. A sensitivity analysis was performed on critical assumptions and choices made.

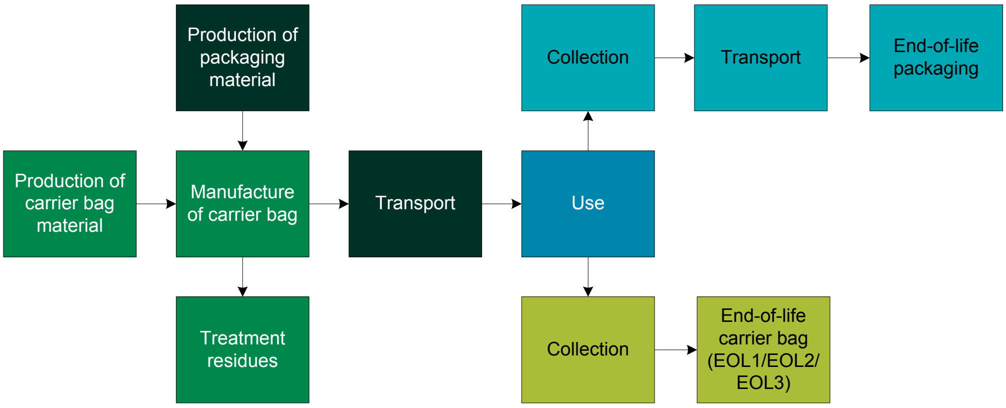


Figure I. General structure for all carrier bag scenarios assessed in this LCA study. "EOL" refers to three different end-of-life options. EOL1: incineration, EO2: recycling, EOL3: reuse as waste bin bag.

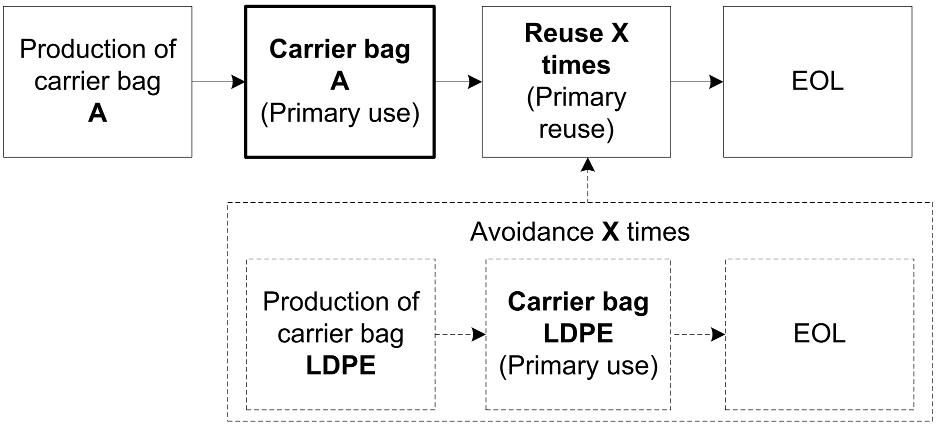


Figure II. Generic modelling of primary reuse. The example portrays the primary reuse X times of a generic "carrier bag A". The reuse X times allows avoiding X times the production, use and disposal of the reference LDPE carrier bag.

Findings and recommendations
The LCA study provided a number of findings that can be useful for optimizing the use and disposal of the carrier bags available for purchase in Denmark. The results are referred to the reference flows presented in Table I.

Which is the most preferable disposal option for each type of carrier bag?
After reusing the carrier bag as many times as possible, reusing the carrier bag as a waste bin bag is better than simply throwing away the bag in the residual waste and it is better than recycling. Recycling can potentially offer benefits in the case of heavy plastic bags, such as PP, PET and polyester. Reuse as a waste bin bag is most beneficial for light carrier bags, such as LDPE, paper and biopolymer. When reuse as a waste bin bag is not feasible, for example when the bag can easily be punctured, torn, or wetted, as in the case of paper and biopolymer bags, incineration is the most preferable solution from an environmental point of view. Table II provides a summary of the results obtained for each carrier bag.

Table II. Overview of the most preferable end-of-life option for each of the carrier bag types assessed.

Carrier bag material	Preferable end-of-life after normal reuse
Plastic, LDPE	Reuse as waste bin bag
Plastic, PP	Recycle, reuse as waste bin bag if possible, else incinerate
Plastic, recycled PET	Recycle, reuse as waste bin bag if possible, else incinerate
Plastic, polyester PET	Reuse as waste bin bag if possible, else incinerate
Biopolymer	Reuse as waste bin bag if possible, else incinerate
Paper	Reuse as waste bin bag if possible, else incinerate
Textile	Reuse as waste bin bag if possible, else incinerate
Composite	Reuse as waste bin bag if possible, else incinerate

Which is the carrier bag providing the lowest environmental impacts?
In general with regards to production and disposal, LDPE carrier bags, which are the bags that are always available for purchase in Danish supermarkets, are the carriers providing the overall lowest environmental impacts for most environmental indicators (Table III). In particular, LDPE carrier bags with rigid handle provided in general the lowest environmental impacts in the majority of the impact categories included in this LCA study. Carrier bags alternatives that can provide a similar performance are unbleached paper and biopolymer bags, but for a lower number of environmental indicators. Heavier carrier bags, such as PP, PET, polyester, bleached paper and textile bags need to be reused multiple times in order to lower their environmental production cost. Between the same bag types, woven PP carrier bags provided lower impacts than non-woven PP bags, unbleached paper resulted more preferable than bleached paper, and conventional cotton over organic cotton.

How many times should the carrier bags be reused?
For all carrier bags, reuse as many times as possible before disposal is strongly encouraged. Table IV reports the number of calculated primary reuse times necessary to lower the environmental impacts associated with all carrier bag alternatives to the levels of the LDPE carrier bag. Therefore, the numbers reported in Table IV refer to minimum number of reuse times. The number of calculated reuse times varies if only one environmental indicator is observed, or if all environmental indicators are taken into account. The calculated number of reuse times might be compliant with the lifetime of PP, PET and polyester carrier bags, but might surpass the lifetime of bleached paper, composite and cotton carriers, especially considering all environmental indicators. The number of calculated reuse times was rather uniform across impact categories for LDPE carrier bags. For PP, PET, biopolymer and paper carrier bags, some

impact categories presented higher reuse times than others. Lastly, the very high number of reuse times scored by cotton and composite bags is primarily due only to the ozone depletion impact category, for which the cotton production dataset provides larger impacts than the reference LDPE carrier bag.

Table III. Carrier bags providing the lowest environmental impacts for all the environmental indicators considered. The order in which the bags are listed corresponds to the raking of their LCA results starting from the lowest impact. Only the three lowest scoring bags are listed. The results refer to the reference flow provided in Table I.

Environmental indicator	Carrier bags providing lowest impacts
Climate change	Paper unbleached, biopolymer, LDPE
Ozone depletion	LDPE
Human toxicity, cancer effects	Paper unbleached, LDPE
Human toxicity, non-cancer effects	Composite, PP, LDPE
Photochemical ozone formation	LDPE
Ionizing radiation	LDPE
Particulate matter	LDPE
Terrestrial acidification	LDPE
Terrestrial eutrophication	LDPE
Freshwater eutrophication	LDPE
Marine eutrophication	PP, LDPE
Ecosystem toxicity	LDPE
Resource depletion, fossil	Paper unbleached, LDPE
Resource depletion, abiotic	PP, LDPE
Water resource depletion	LDPE, biopolymer

Table IV. Calculated number of primary reuse times for the carrier bags in the rows, for their most preferable disposal option, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration. The results refer to the reference flow provided in Table I.

	LDPE average, reused as waste bin bag	
	Climate Change	All indicators
LDPE simple, reused as waste bag	0	1
LDPE rigid handle, reused as waste bag	0	0
Recycled LDPE, reused as waste bag	1	2
PP, non-woven, recycled	6	52
PP, woven, recycled	5	45
Recycled PET, recycled	8	84
Polyester PET, recycled	2	35
Biopolymer, reused as waste bag or incinerated	0	42
Unbleached paper, reused as waste bag or incinerated	0	43
Bleached paper, reused as waste bag or incinerated	1	43[4]
Organic cotton, reused as waste bag or incinerated	149	20000

[4] The highest value for bleached paper is set to as minimum be equal to the value for unbleached paper.

Conventional cotton, reused as waste bag or incinerated	52	7100
Composite, reused as waste bag or incinerated	23	870

The sensitivity analysis on data and assumptions highlighted the importance of the choice of reference flow, which was determining for the calculated number of reuse times for organic cotton. The reference flow choice depends on the fulfilment of the function expressed by the functional unit. In particular, the results showed the importance of the carrier bags design, which should be focused on maximizing volume and weight holding capacity, while minimizing the amount of material needed and the final weight of the carrier bag.
Our final recommendations are the following[5]:

- **Simple LDPE bags**: Can be directly reused as waste bin bags for climate change, should be reused at least 1 time for grocery shopping considering all other indicators; finally reuse as waste bin bag.
- **LDPE bags with rigid handle**: Can be directly reused as waste bin bags considering all indicators; finally reuse as waste bin bag.
- **Recycled LDPE bags**: Reuse for grocery shopping at least 1 time for climate change, at least 2 times considering all indicators; finally reuse as waste bin bag.
- **PP bags, non-woven**: Reuse for grocery shopping at least 6 times for climate change, at least 52 times considering all indicators; finally dispose with recyclables, otherwise reuse as waste bin bag if possible, lastly incinerate.
- **PP bags, woven**: Reuse for grocery shopping at least 5 times for climate change, at least 45 times considering all indicators; finally dispose with recyclables, otherwise reuse as waste bin bag if possible, lastly incinerate.
- **PET bags**: Reuse for grocery shopping at least 8 times for climate change, at least 84 times considering all indicators; finally dispose with recyclables, otherwise reuse as waste bin bag if possible, lastly incinerate.
- **Polyester bags**: Reuse for grocery shopping at least 2 times for climate change, at least 35 times considering all indicators; finally dispose with recyclables, otherwise reuse as waste bin bag if possible, lastly incinerate.
- **Biopolymer bags**: Can be directly reused as waste bin bags for climate change, should be reused at least 42 times for grocery shopping considering all other indicators. Finally, reuse as waste bin bag if possible, otherwise incinerate.
- **Unbleached paper bags**: Can be directly reused as waste bin bags for climate change, should be reused at least 43 times considering all other indicators. Finally, reuse as waste bin bag if possible, otherwise incinerate.
- **Bleached paper bags**: Reuse for grocery shopping at least 1 time for climate change, at least 43 times considering all indicators; reuse as waste bin bag if possible, otherwise incinerate.
- **Organic cotton bags**: Reuse for grocery shopping at least 149 times for climate change, at least 20000 times considering all indicators; reuse as waste bin bag if possible, otherwise incinerate.
- **Conventional cotton bags**: Reuse for grocery shopping at least 52 times for climate change, at least 7100 times considering all indicators; reuse as waste bin bag if possible, otherwise incinerate.

[5] The number of times for "all indicators" refers to the highest number of reuse times among those calculated for each impact category. For light carrier bags (LDPE, PP, PET...) the high numbers of reuse times are given by a group of impact categories with similar high values. Conversely, for composite and cotton the very high number of reuse times is given by the ozone depletion impact alone. Without considering ozone depletion, the number of reuse times ranges from 50 to1400 for conventional cotton, from 150 to 3800 for organic cotton, and from 0 to 740 for the composite material bag. The highest number is due to the use of water resource, but also to freshwater and terrestrial eutrophication. Results for the number of reuse times for each impact category, minimum-maximum ranges and average number of reuse times are provided in Appendix C.

- **Composite bags**: Reuse for grocery shopping at least 23 times for climate change, at least 870 times considering all indicators; reuse as waste bin bag if possible, otherwise incinerate.

It should be considered that if the reference LDPE bag is reused for shopping, this will increase the needed number of reuse times for the other bags proportionally. The results obtained on the minimum number of reuse times are intended to raise the discussion among the stakeholders on the effective expected lifetime of each carrier bag. While the calculated number of reuse times might be compliant with the functional lifetime of PP, PET and polyester carrier bags, it might surpass the lifetime of bleached paper, composite and cotton carriers, especially considering all environmental indicators.

Summary of the critical review

Reviewers

A critical review according to ISO 14040/14044 was performed by Line Geest Jakobsen and Trine Lund Neidel from COWI A/S in January 2018.

Review process

The review process involved the following phases:
- COWI conducted the first review in January 2018.
- DTU answered to the questions raised by COWI and corrected the report according to the outcomes of the review in January 2018.
- COWI evaluated the corrections and compiled a final review statement.

The critical review from COWI can be found in full in Appendix D. The main points highlighted in the critical review are provided below.

The LCA report has been reviewed with respect to compliance with the ISO 14040 and 14044 International Standards. The report was found to comply with the standards to a large extent. The authors state that the report does not comply with the standard because an exchange with a panel of experts was not made during the project phases.

The method chosen for selecting the functional unit and reference flow was verified with a sensitivity analysis. The results of the sensitivity analysis showed that the choice of reference flow influenced heavily the carrier bags with high impacts connected to production and with a lower volume than the one expressed in the functional unit (mainly organic cotton). The authors added a dedicated section on carrier bag design where they provide comments on the influence of the carrier bag design on the results.

The critical review highlighted that specific attention should have been dedicated to data quality assessment and to the clear statement of critical assumptions. The authors added dedicated sections on data quality assessment, critical assumption and on the influence on data and assumptions on the results. The influence of selected critical assumptions on the results was assessed with a sensitivity analysis.

After the review, the authors added further specifications on the carrier bag types (e.g. polyester polymer type), adjusted language and typos, and added further details for improving the overall understanding of the report.

Preface

This study provides the life cycle environmental impacts associated with the production, use and disposal of selected grocery carrier bags available in Danish supermarkets in 2017.

The commissioner of the LCA is the Danish Environmental Protection Agency (Miljøstyrelsen). The LCA was conducted by DTU Environment in the period October – December 2017, using the EASETECH LCA model developed by DTU Environment for the environmental assessment of waste management systems and environmental technologies. The LCA was conducted for assessing and comparing the environmental impacts associated with the grocery carrier bags currently available in Danish supermarkets.

The LCA has been conducted according to the requirements outlined in DS/EN ISO International Standards 14040 and 14044; however, the report is not intended to strictly comply with the standard. The report is intended for internal decision support at the Danish Environmental Protection Agency as part of a wider range of assessments aiming at investigating possible options for grocery carrier bags available in Danish supermarkets. The report has undergone a peer review process outside the project group in January 2018 by Line Geest Jakobsen and Trine Lund Neidel from COWI A/S.

The report was prepared by Valentina Bisinella, Paola Federica Albizzati, Thomas Fruergaard Astrup, and Anders Damgaard from DTU Environment.

DTU, February 2018

List of Abbreviations

General

EOL	End-of-life (as: “treatment”, “waste management” or “disposal”)
EOL1	Incineration
EOL2	Source segregation of recyclables and recycling
EOL3	Reuse as a waste bin bag before incineration
HDPE	High-density polyethylene
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Low-density polyethylene
PE	Persons equivalents (normalized LCA results)
PET	Polyethylene terephthalate
PP	Polypropylene
W	Waste bin bag

Carrier bag scenarios

LDPEavg	LDPE carrier bag, average characteristics (between LDPEs and LDPEh)
LDPEs	LDPE carrier bag, simple
LDPEh	LDPE carrier bag, rigid handle
LDPErec	Recycled LDPE carrier bag
PP	Non-woven PP carrier bag
PPwov	Woven PP carrier bag
PETrec	Recycled PET carrier bag
PETpol	Polyester carrier bag
BP	Starch-complexed biopolymer carrier bag
PAP	Unbleached craft paper carrier bag
PAPb	Bleached craft paper carrier bag
COTorg	Organic cotton carrier bag
COT	Conventional cotton carrier bag
COM	Composite carrier bag (jute, PP, cotton)

Acronyms for the impact categories assessed by the LCA

CC	Climate change
OD	Ozone depletion
HTc	Human toxicity, cancer effects
HTnc	Human toxicity, non-cancer effects
POF	Photochemical ozone formation
IR	Ionizing radiation
PM	Particulate matter
TA	Terrestrial acidification
TE	Terrestrial eutrophication
ME	Marine eutrophication
FE	Freshwater eutrophication
ET	Ecosystem toxicity
RDfos	Resource depletion, fossil
RD	Resource depletion, abiotic
Water	Water resource depletion

Key definitions

Primary reuse	Reuse for the same function for which the product was produced. For example, the function of grocery carrier bags is to contain and transport groceries and goods from the supermarkets to the homes. Primary reuse of a carrier bag would be reusing it for carrying goods and groceries from the supermarkets to the homes.
Secondary reuse	Reuse fulfilling a different function than the one for which the product was produced. For example, grocery carrier bags are produced to contain and transport groceries and goods from the supermarkets to the homes. Secondary reuse of a carrier bag could be used as a waste bin bag, bag for laundry, etc. Any reuse that does not entail carrying goods and groceries from the supermar-kets to the homes.
Single-use carrier bag	Lightweight carrier bags intended to be used for one shopping trip from the supermarkets to the homes.
Multiple-use carrier bag	Durable carrier bags intended to be used for multiple shopping trips from the supermarkets to the homes.
Grocery carrier bag	Bag product, usually light, resistant and capacious, with the primary function of containing and transporting goods and groceries from the supermarkets to the homes.
Lightweight plastic carrier bags	Single-use plastic carriers, commonly made of low-density or high-density polyethylene plastic (LDPE or HDPE) with thickness below 50 microns (European Commission, 1994).
Very lightweight plastic carrier bags	Small plastic carrier bags with thickness below 15 microns (European Commission, 1994), which are available supermarkets free of charge as primary packaging for loose food.

1. Introduction and objectives

This study was commissioned by the Danish Environmental Protection Agency (Miljøstyrelsen) in order to assess the life cycle environmental impacts of the production, use and disposal of different grocery carrier bags available for purchase in supermarkets in Denmark in 2017. This Section provides the background on grocery carrier bags in Denmark and the aim of the study.

1.1 Background

Carrier bags are used in supermarkets in order to carry grocery shopping and other items sold at supermarkets from the shops to the homes. Grocery carrier bags are considered a form of packaging and have been addressed in the European Parliament and Council Directive 94/62/EC on packaging and packaging waste (European Commission, 1994). The Directive, which is currently in force, aims at limiting the production of packaging waste and promoting recycling, reuse and other forms of waste recovery. Lightweight plastic carrier bags are single-use plastic carriers6, commonly made of low-density or high-density polyethylene plastic (LDPE or HDPE). These carriers are single-use in the sense that they are usually only used for one shopping trip (European Commission, 2011). The environmental concerns associated with plastic carrier bags include the use of non-renewable resources for production (such as crude oil), the environmental impacts of their disposal and the effects of littering. In particular, the Directive aimed at reducing the large consumption of single-use carrier bags in order to ultimately reduce the amounts to be disposed.

Since 1993, Denmark has taken action against single-use plastic carrier bags by introducing a tax on retailers. Currently, Danish supermarkets provide multiple-use carrier bags of different materials (such as recyclable and non-recyclable plastic, paper and cotton) which can be bought by customers at the cash register. These types of multiple-use carrier bags are designed for a multiple number of uses and are intended to last longer, therefore requiring more resources in their production and potentially more environmental impacts than a single-use carrier bag. In order to compensate the impacts arising from their manufacturing phase, multiple-use carrier bags need to be reused a number of times. However, due to the functionality issue or customer attitude, if the reusable bags are thrown away before their desired number of use, the environmental impacts may surpass those of single-use bags. Moreover, reuse of the carrier bag can occur both as primary reuse (where the carrier bag is reused for the same function for which it was produced, i.e. for carrying grocery shopping from the supermarket to the home), or replacing other products as waste bin liners (secondary reuse).

1.2 Aim of the study

The aim of this study is to identify the multiple-use carrier bag alternative with the best environmental performance to be provided in Danish supermarkets. In order to do so, the study aims to assess the environmental impacts associated with production, distribution, use and disposal of the multiple-use carrier bags available for purchase in Danish supermarkets in 2017, for a range of environmental impacts. Three end-of-life options were taken into account for the disposal. In particular, the study wishes to:

- Identify the best disposal option for each carrier bag type within the identified end-of-life options;

[6] "Lightweight plastic carrier bags" shall mean plastic carrier bags with thickness below 50 microns (European Commission, 1994).

- Identify the multiple-use carrier bag alternative with the best environmental performance for each of the investigated impact categories;
- Define the number of times a multiple-use carrier bag would need to be reused in order to provide a better environmental performance than another carrier bag alternative, for a range of environmental indicators.

The study aims to obtain the number of reuse times taking into consideration primary and secondary reuse, as well as separate collection and recycling of the material, between the disposal options.

The environmental assessment of the carrier bag alternatives is carried out with Life Cycle Assessment (LCA), a standardized methodology for quantifying environmental impacts of providing, using and disposing of a product or providing a service throughout its life cycle (ISO, 2006). LCA takes into account the potential environmental impacts associated with resources necessary to produce, use and dispose the product, and also the potential emissions that may occur during its disposal. When material and energy resources are recovered, the system is credited with the avoided potential emissions that would have been necessary in order to produce these resources. The LCA will be carried out with the EASETECH model developed at DTU Environment (Clavreul et al., 2014). The goal definition of the LCA and the LCA methodology are provided in a dedicated Section.

The LCA modelling includes the actual multiple-use carrier bag options currently available for purchase in Danish supermarkets, which were identified by a dedicated survey. In particular, the modelling takes into account the material of the carrier bag, for example including whether the material is virgin or recycled, recyclable or non-recyclable. The study will assess whether a large variation exists within carrier-bag types, in terms of weight, volume, thickness, and carrying capacity.

The present study only considers carrier bags available for purchase in Danish supermarkets in 2017. Small very lightweight plastic carrier bags[7], which are available in Danish supermarkets free of charge as primary packaging for loose food, were excluded from the scope of this study, since they were not included in the 94/62/EC measures. This study does not include the assessment of other types of carriers, such as personal bags or bags provided by other retailers. The report does not consider behavioural changes or consequences of introducing further economic measures. The study does not take into account economic consequences for retailers and carrier bag producers. The environmental assessment does not take into account the effects of littering.

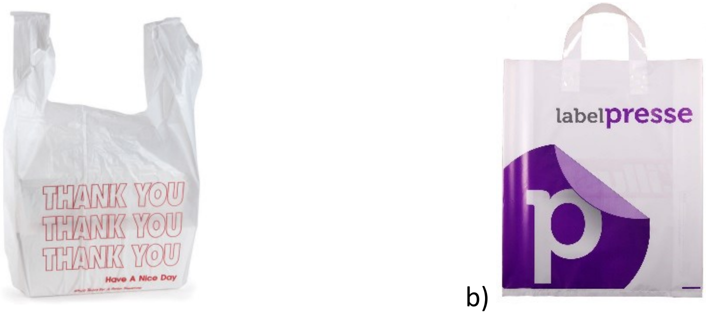
[7] "Very lightweight plastic carrier bags" shall mean plastic carrier bags with thickness below 15 microns (European Commission, 1994).

2. Carrier bags

2.1 Carrier bag types

Carrier bags are provided in supermarkets with the function to carry goods and groceries from the supermarkets to the homes. Carrier bags must therefore be robust and large enough to hold a certain amount of items, while at the same time being economically convenient. Carrier bags can be made of plastic materials of fossil origin, such as low- or high-density polyethylene (LDPE/HDPE), polypropylene (PP), polyethylene terephthalate (PET) and polyester. Alternative plastic materials composed of carbon of biogenic origin can also be used, such as polyester-complexed starch biopolymer. Other materials used for carrier bags are paper and textiles. A few types of carrier bags are described below. All the bags analysed in this report are intended to be used multiple times.

- **Low-density polyethylene (LDPE) bags**
  Plastic bags formed from an LDPE plastic melt, which is blown and sealed to form a bag. Figure 1 provides two examples of LDPE carrier bag: one with simple handle, one with a rigid handle.



a) b)

Figure 1. Examples of LDPE carrier bags with (a) simple handle (Paxonplastic, 2018) and (b) rigid handle (C-bags, 2018).

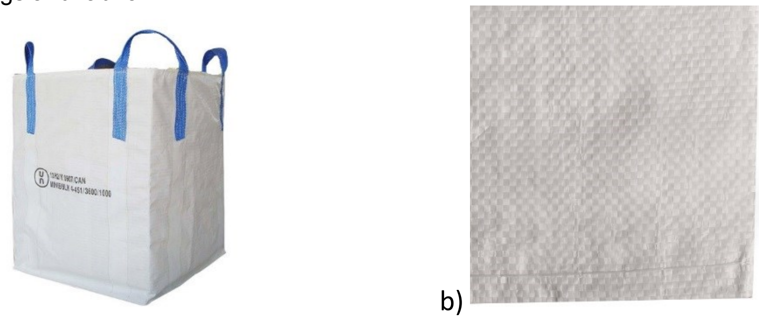
- **Non-woven polypropylene (PP) bags**
  Plastic bags formed from molten filament of PP, which is spun bonded. Non-woven PP bags are stronger, more durable and generally larger in volume than LDPE carrier bags and are intended to be reused many times (Edwards and Fry, 2011). Figure 2 provides an example of non-woven PP bags and of the fabric type.

a)

b)

Figure 2. Examples of non-woven PP bags (a) (Indiamart, 2018) and (b) detail of the non-woven PP fabric (Bharatcottons, 2018).

- **Woven polypropylene (PP) bags**
  Plastic bags obtained from weaving PP fibres. Just like non-woven PP bags, these bags are usually stronger and more durable than LDPE carrier bags. Figure 3 provides an example of woven PP bags and fabric.



a) b)

Figure 3. Example of a woven PP bag (a) (Indiamart, 2018b) and (b) detail of the woven PP fabric (Bagsupplies, 2018).

- **Recycled polyethylene terephthalate (PET) bags**
  Plastic bags obtained from weaving molten fibres from recycled PET pellets. Strong and durable, intended for multiple-use. An example is provided in Figure 4.

Figure 4. Example of recycled PET bag (Customgrocerybags, 2018).

- **Polyester bags**
  Plastic bags obtained from weaving polyester fibres. These polyester fibres are obtained from processing other polymer types, such as PP or PET, and are usually thinner and lighter than the original polymers, resulting in a very light and foldable multiple-reuse bag. An example is provided in Figure 5.

Figure 5. Example of a polyester carrier bag (Aliexpress, 2018).

- **Biopolymer bags**
  Biopolymer bags are usually composed by either polylactic acid (PLA) or starch polyester blends, which are compostable materials able to decompose in in aerobic environments that are maintained under specific controlled temperature and humidity conditions (ASTM, 2018). An example is provided in Figure 6. These carrier bags are usually less resistant than LDPE bags. The biodegradability of these polymers is debated in the scientific community. Most of the materials are only biodegradable in full scale facilities (compost or anaerobic) run at high enough temperatures, and there can still be partial plastic parts left at the end of treatment, In most natural environments only a small part of the plastic will degrade (Emadian et al., 2017)

Figure 6. Example of biopolymer bags (Ecostoviglie, 2018).

- **Paper bags**
  Carrier bags obtained from craft paper, which is glued to form the bag. This type of carrier bag has become less used since the 1970s, replaced by plastic bags that do not tear when wet (Edwards and Fry, 2011). An example is provided in Figure 7.

Figure 7. Example of a paper bag (Natuerlich-verpacken, 2018).

- **Textile bags**
  Bags made of woven cotton or jute, intended to be reused many times. Textile bags can be made of organic or conventional textiles. Figure 8 provides an example of a cotton bag.

Figure 8. Example of cotton carrier bag (Amazon, 2018).

- **Composite bags**
  Bags made of multiple material types, such as textile and plastic. An example is provided in Figure 9 below, where plastic handles are attached to a jute bag.

Figure 9. Example of composite bag (Topcottonbags, 2018).

2.2 Carrier bags available in Denmark

Since this study focuses on the multiple-use carrier bag alternatives available for purchase in Danish supermarkets in 2017, we have conducted a survey in order to identify the carrier bag alternatives on which to carry out the environmental assessment. The survey was conducted in September – October 2017 as part of a Master thesis project work at DTU Environment (Alonso Altonaga, 2017).

The survey involved collecting all types of carrier bags available in Danish supermarkets. The survey involved a total of 19 retailers: Fakta, Fakta Q, Superbrugsen, Dagli' Brugsen, Irma, Kvickly, Netto, Føtex food, Føtex, Bilka, 7-eleven, Rema 1000, Lidl, Aldi, Meny, Spar, Min købmand, Let-Køb, and Løvbjerg. The material of each carrier bag was identified based on the labelling on the carrier bag and it was verified with material analysis via infrared spectroscopy. The number of number of carrier bags surveyed per material type was reported. Then, we analysed the weight, volume, thickness and weight holding capacity (measured as tensile strength at the point where the material started to stretch or broke) for each of the carrier bags.

Table 1 shows the material and the material type of the carrier bags available for purchase in Danish supermarkets in 2017, with detail on the retailers providing each type of bag. For each type of carrier bag, Table 2 provides the number of items identified by the survey, the average weight of the bag, the average volume, the average thickness and average weight holding capacity.

The total number of carrier bag types available in Danish supermarkets which was identified in the project was 40. The virgin LDPE plastic bag was identified as the most commonly available bag in Danish supermarkets with 23 items. In particular, the survey indicated that an LDPE carrier bag can always be found for purchase in all supermarkets, regardless of the retail chain they belong to. Two retailers provided also LDPE bags made of recycled LDPE, on top of virgin LDPE plastic bags. Both virgin and recycled LDPE grocery carrier bags were found in two versions: one with a rigid handle (of the same material; "LDPE rigid handle" in Table 2) and a simple type, with a handle of the same thickness of the bag ("LDPE simple" in Table 2). The same retailer often provided both types of LDPE carrier bags. All remaining types of carrier bags were considerably less abundant, scoring a total of 1 to 3 items. This reflects the fact that some retailers provided other types of carrier bags as an alternative to the most common LDPE carrier bag. The material types of such carrier bag types were woven and non-woven PP, recycled PET, polyester of virgin PET fibres, biodegradable plastic, craft paper, cotton (organic and conventional). One bag type presented composite characteristics, with jute, PP and cotton materials combined. Often the alternatives to LDPE were heavier, multiple-use-oriented carrier bags, as in the case on woven and non-woven PP, recycled PET and cotton bags. Nine supermarkets provided at least one alternative to the LDPE carrier bag. Irma was the supermarket with the largest number of alternative options for the choice of carrier bag.

Table 1. Material and material type of the multiple-use carrier bags available for purchase in Danish supermarkets in 2017, subdivided by retailer. (*) indicates that the LDPE carrier bags are available both as virgin plastic and recycled plastic.

Material	Type	Fakta	Fakta Q	Superbrugsen	Dagli Brugsen	Irma	Kvickly	Netto	Føtex food	Føtex	Bilka	7-eleven	Rema 1000	Lidl	Aldi	Meny	Spar	Min købmand	Let-Køb	Løvbjerg
Plastic	LDPE simple				X	X	X	X		X	X	X	X	X*	X*				X	X
Plastic	LDPE rigid handle	X	X	X		X	X	X	X	X			X	X*		X	X	X		X
Plastic	PP non-woven	X					X								X					
Plastic	PP woven							X			X			X						
Plastic	PET recycled					X														
Plastic	Polyester, PET												X							
Bioplastic	Biopolymer			X																
Paper	Paper					X														
Textile	Cotton organic					X														
Textile	Cotton conventional				X	X														
Composite	Jute, PP, cotton														X					

The carrier bags identified in the survey varied in terms of weight, volume, thickness and weight holding capacity, as presented in Table 2. We could identify a direct correlation between thickness and weight of the bag. The larger the thickness, the more material was employed and the heavier the carrier bag. Table 2 indicates that LDPE and biopolymer plastic bags presented the lowest average thickness and weight. When the LDPE carrier bag was equipped with a rigid handle, the overall average weight of the carrier bag was larger (highlighted in grey and italics in Table 2). Paper carrier bags presented the second-lowest average thickness and weight. On the other hand, woven and non-woven PP, recycled PET, PET polyester, cotton and composite carrier bags presented considerably larger weight. The average weight holding capacity generally follows the same trend of weight of the bag and thickness, with thicker bags generally providing a larger holding capacity, with exception of paper bags. On the other hand, the volume of the bag was not related to weight or thickness. Simple LDPE bags presented the lowest volume, followed by biopolymer, organic cotton and LDPE bags with rigid handle. The largest volumes were recorded for woven PP and recycled PET bags

After the first draft of the report was provided to Miljøstyrelsen and stakeholders, the stakeholders in the project group highlighted that another conventional cotton bag was available for purchase from one of the retailers. This cotton bag presents a larger volume (31 litres) and lower weight (120 grams), which would change the average weight of the cotton bag presented in Table 2 to 195 grams and a volume of 28 litres. The latter average characteristics were not included in the modelling, but were used in the discussion of the results.

Overall, the survey allowed identifying important aspects that need to be taken into account when carrying out the LCA of carrier bag alternatives:

- LDPE carrier bags are the most common type of carrier bag and the carrier bag type that can always be found in Danish supermarkets. Therefore, the LCA study should take this car-

rier bag as baseline and compare how many times the other carrier bags should be reused in order to reach a similar environmental performance.
- The carrier bags have considerable differences in weight, and bags with larger weight are likely to have larger environmental impacts due to the larger amount of material required to manufacture the grocery carrier bag.
- The bags have different characteristics and cannot all cover the same functionality. The functional unit has to be tailored in a way that a fair comparison is provided.

Table 2. Survey results of the grocery carrier bags.

Material	Type	Number of items	Average weight (g)	Average volume (L)	Average thickness (mm)	Average weight holding capacity (kg)
Plastic	LDPE	23	24.2	22.4	0.04	12.0
Plastic	*LDPE simple*	*10*	*17.9*	*19.2*	*0.04*	*10.5*
Plastic	*LDPE rigid handle*	*13*	*29.0*	*24.8*	*0.05*	*13.2*
Plastic	LDPE recycled	3	24.9	21.7	0.05	10.7
Plastic	*LDPE recycled, simple*	*1*	*14.7*	*15.0*	*0.04*	*8.0*
Plastic	*LDPE recycled, rigid handle*	*2*	*30.0*	*25.0*	*0.05*	*12.0*
Plastic	PP non-woven	2	137.0	29.0	0.50	36.0
Plastic	PP woven	3	118.7	36.7	0.35	41.0
Plastic	PET recycled	2	159.0	42.0	0.60	45.0
Plastic	PET polyester	1	48.0	32.0	0.10	45.0
Bioplastic	Biopolymer	1	18.2	22.0	0.04	12.0*
Paper	Paper	1	44.7	23.0	0.12	12.0*
Textile	Cotton organic	1	252.0	20.0	1.40	50.0
Textile	Cotton conventional	2	232.0	27.0	0.93	50.0
Composite	Jute, PP, cotton	1	282.0	32.0	0.70	50.0

* The average weight holding capacity was 12 kg, but the samples of these types of carrier bags presented the highest variation of weight holding capacity. For example, the bags were easily torn if containing items with sharp edges.

3. LCA Methodology

The LCA carried out for this study was conducted according to the requirements outlined in the International Standards 14040 and 14044 (ISO, 2006a, 2006b). The present Section provides a detailed description of the LCA methodology utilized for the study: the goal of the LCA, functional unit and reference flow, the system boundaries, the choices for the modelling approach for addressing multi-functionality, the modelling tools, data requirements, impact assessment method, assumptions and limitations.

The final receiver of the study is the Danish Environmental Protection Agency and the study might ultimately be used for internal decision support at the Danish Environmental Protection Agency as part of a wider range of assessments aiming at investigating possible options for grocery carrier bags. This means that even if the report could be disclosed to third parties, the report does not strictly comply with the standard. The reason for this lack of compliance is that the report has undergone external peer review by COWI A/S, but not by a panel of experts throughout the development of the project as required by the standard.

The contract for the project did not budget for extensive data collection, which means that there were pre-specified limitations on the amount of data that could be gathered for the study. Therefore, most of the data used are based on publicly available LCI data and data from existing LCA studies on grocery carrier bags.

3.1 LCA goal definition

The goal of this study was to provide the Danish Environmental Protection Agency with the potential life cycle environmental impacts associated with a range of alternative types of multiple-use carrier bags. The aim of the study was to:

- identify the best disposal option for each carrier bag type within the identified end-of-life options;
- identify the multiple-use carrier bag alternative with the best environmental performance for each of the investigated impact categories;
- identify the number of times each multiple-use bag would need to be reused to lower the environmental impacts connected to its production and in comparison to other carrier bag alternatives, based on different reuse and disposal options.

The carrier bag alternatives investigated were those available for purchase in Danish supermarkets in 2017. The comparative analysis was carried out with respect to a range of environmental impacts and taking into account three different end-of-life options: incineration, recycling, and secondary reuse as a waste bin bag before being incinerated. The number of reuse times was calculated as primary reuse, i.e. complying with the function for which the carrier bag was produced. The scenarios are described in detail in Section 4.

The target audience of the LCA is the Danish Environmental Protection Agency. The study might ultimately be used for internal decision support at the Danish Environmental Protection Agency as part of a wider range of assessments aiming at investigating possible options for managing waste grocery carrier bags.

3.2 Functional unit

The role of the functional unit definition in LCA is to ensure that the environmental assessment of the products is based on a fair basis for comparison, in this case the fulfilment of the same functionality. This is particularly important in the case of carrier bags, where different types and materials can provide different functionalities in terms of number of uses, resistance to puncturing and tearing, resistance to water, weight holding capacity, and so on. As explained in Section 2, different carrier bag types have different weight, and carrier bags intended to last longer, with larger thickness and weight, commonly require more resources for their production and therefore are likely to provide larger environmental impacts than lighter bags on a bag-to-bag comparison.

Previous LCA studies on carrier bags have compared different carrier bag types based functional unit such as “carrying grocery shopping to the home for a defined amount of time (and amount of items) in a defined year” (i.e. Environment Agency, 2011; Environment Australia, 2002). These studies calculated the number of each type of bag required to fulfil the defined function, where the impacts associated with multiple-use carrier bags were “discounted”, meaning that the environmental impacts associated with these bags were divided by the number of reuse times expected for that type of bag (Edwards and Fry, 2011).

For this study, we defined a functional unit that allowed a fair basis for comparison for the grocery carrier bags, but that also allowed to identify the number of required reuse times on the basis of the environmental impacts associated with each bag, instead of using initial assumptions on the potential carrier bag reuse time and overall lifetime. Then, the calculated number of reuse times based on environmental performance is intended to raise the discussion among the stakeholders on the effective expected lifetime of each carrier bag. The functional unit chosen for this study was:

Carrying one time grocery shopping with an average volume of 22 litres and with an average weight of 12 kilograms from Danish supermarkets to homes in 2017 with a (newly purchased) carrier bag. The carrier bag is produced in Europe and distributed to Danish supermarkets. After use, the carrier bag is collected by the Danish waste management system.

The functional unit chosen corresponds to carrying grocery shopping home for one shopping with a virgin LDPE carrier bag with average characteristics. The volume and the weight for the grocery shopping specified in the functional unit correspond to the average volume and weight holding capacity of the carrier bag always available in all Danish supermarkets, which is virgin LDPE. Ideally, the customer at the Danish supermarket could buy this type of bag for every shopping. This type of functional unit allows comparing different types of carrier bags as if they were all bought at the same time for one shopping. The volume and weight chosen allow comparing the other bag types to the most common carrier bag options: some carrier bags will not fulfil the volume or weight holding requirement, therefore needing a purchase of two instead of one.

The carrier bags considered for this study are assumed to be produced in Europe and distributed to Danish supermarkets. After being used, the bags are collected within the Danish waste management system, which handles also the packaging required for the distribution of the bags.

The number of reuse times for the carrier bag alternatives will be calculated as: how many times would this alternative carrier bag type need to be reused in order to provide a better environmental performance than an average virgin LDPE carrier bag, while fulfilling the same function? The functional unit defined for this study did not cover prevention strategies, nor consumer behaviour or behavioural changes. The functional unit does not target a specific group or age of customers and does not cover typical or average shopping preferences or behaviour.

3.2.1 Reference flow

The reference flow was calculated for each bag type, and it corresponded to the number of carrier bags required to fulfil the functional unit. According to the definition provided by the functional unit, this depended mainly on the volume of the bag and its weight holding capacity. Volume and weight holding capacity were considered only, since we observed a direct correlation between thickness and weight holding capacity. The reference flow for each carrier bag type is provided below in Table 3. The average virgin LDPE plastic was taken as a reference.

The reference flow for each bag subtype in Table 3 was calculated taking into consideration both volume and weight holding capacity as conditions that had to be fulfilled at the same time. This means that, for each carrier bag, if the volume and/or the weight holding capacity were lower than the ones specified in the functional unit, we assumed that the customers would need to buy two bags instead of one in order to comply for the same functionality (a grocery shopping of the volume of 22 litres and/or a weight of 12 kilograms). When a bag was required two times, it was modelled by multiplying by two the average weight and volume provided in Table 2. In the cases of biopolymer and paper carrier bags, the weight holding capacity surveyed was in average compliant with the virgin LDPE carrier bag, but provided the highest variance between the samples. For example, the weight that these types of bags were capable of holding varied greatly in the tested samples, especially if the items placed in the bags for the survey had sharp angles, which tore the bags much more easily than for other carrier bag types (Alonso Altonaga, 2017). For these reasons, the weight holding capacity for the reference flow was considered not respected, and that two bags would be required to carry the same weight. The reference flow for each carrier bag also differed for the material composition used for the LCA modelling. Further details are provided in the Life Cycle Inventory (LCI; Appendix A).

Table 3. Required reference flow for each carrier bag

Material	Type	Volume enough?	Weight holding capacity enough?	Reference flow (number of bags needed)
Plastic	LDPE	-	-	**1 (reference bag)**
Plastic	*LDPE simple*	*No*	*No*	***2***
Plastic	*LDPE rigid handle*	*Yes*	*Yes*	***1***
Plastic	LDPE recycled	No	No	**2**
Plastic	*LDPE recycled, simple*	*No*	*No*	***2***
Plastic	*LDPE recycled, rigid handle*	*Yes*	*Yes*	***1***
Plastic	PP non-woven	Yes	Yes	**1**
Plastic	PP woven	Yes	Yes	**1**
Plastic	PET recycled	Yes	Yes	**1**
Plastic	Polyester	Yes	Yes	**1**
Bio-plastic	Biopolymer	No	No	**2**
Paper	Paper	Yes	No	**2**
Textile	Cotton organic	No	Yes	**2**
Textile	Cotton conventional	Yes	Yes	**1**
Composite	Jute, PP, cotton	Yes	Yes	**1**

3.3 System boundaries

The time horizon of the impacts in this LCA was 100 years. The geographical scope was Europe. The temporal scope was 2017. The LCA was a “cradle-to-grave” LCA, meaning that for each carrier bag were taken into account the environmental impacts of all its life-cycle stages, from production of the carrier bag material, manufacturing of the carrier bag and distribution, to use and end-of-life.

The system boundaries included production of energy and material resources required for the production of the carrier bags, as well as production of the packaging used for the distribution of the bags. These required resources were production of electricity and heat, production of the main carrier bag material (such as LDPE) and ancillary materials (such as ink, glue). In accordance with the project partners, the production of the carrier bags and the packaging for distribution was set to occur in Europe. Production of the carrier bag material and other ancillary materials could occur anywhere in the world, as the materials were assumed to be retrieved from the market. The carrier bags were assumed to be distributed to Danish supermarkets by road transportation and using cardboard packaging. Production of transportation fuel was included in the assessment.

The assessment assumed zero emissions arising from the use phase. The LCA included the production of energy and material resources required to collect, treat and manage the carrier bag once it was collected by the Danish waste management system. In particular, the assessment took into account direct emissions occurring to air, water and soil during the waste management phase, as well as avoided processes (*i.e.* avoided production of primary materials and energy substituted by the residues). The waste management processes were set to occur partly in Denmark (collection, transport and incineration) and partly in other European countries (transport, recycling and final disposal of rejects).

Capital goods, as the construction of facilities and production of machineries and transportation were not included. In accordance with the project partners, the system boundaries do not include small very lightweight plastic carrier bags and other types of carriers, such as personal bags or bags provided by other retailers. The report does not consider behavioural changes or consequences of introducing further economic measures. The study does not take into account economic consequences for retailers and carrier bag producers. The environmental assessment does not take into account the effects of littering.

3.4 Modelling approach and allocation of multi-functionality

The LCA involved consequences that resulted in additionally installed (or additionally decommissioned) equipment/capacity outside the boundary of the foreground systems. The modelling approach used was consequential LCA. Multi-functionality in the model was addressed by system expansion. This means that co-products generated along with the main service provided by the scenarios, *i.e.* treatment of the residues, were assumed to displace those products in the market that were likely to react to changes in demand/supply induced by the investigated scenarios. These technologies were referred to as “marginal technologies” and are discussed in detail in Appendix B. Examples are the energy produced from the incineration of the waste, and recovered material from the recycling processes.

The marginal energy technologies were chosen with the project partners and are described in detail in Appendix B. The energy marginal technologies have a future outlook and were defined for the period 2020 – 2030. Since the study is going to support decisions that will occur in a 10 year period, using a future marginal energy was assumed to represent the effects of such choices in the future waste management system.

3.5 Modelling of primary reuse

Each of the carrier bags can be reused multiple times. When the carrier bag for grocery shopping is used again to provide the same function, this is called primary reuse (reuse for the same function for which the product is produced).

Primary reuse has been modelled as illustrated in Figure 10. We assumed that reuse X times of a carrier bag allowed avoiding the corresponding use X times of another carrier bag. This means that the avoided use of another carrier bag avoids the environmental life cycle impact associated with its production and disposal. Disposal is indicated below generically as “EOL” (end-of-life). The three end-of-life options taken into account for this study are described in Section 4.

This configuration allows calculating the number of times a type of carrier bag would need to be reused in order to provide a better environmental performance the carrier bag taken as reference, which was LDPE. Considering the cradle-to-grave LCA result for the carrier bag A as $LCIA_A$ and the cradle-to-grave LCA result for the reference LDPE carrier bag as $LCIA_{LDPE}$, the number of reuse times x is calculated as follows:

$$LCIA_A - xLCIA_{LDPE} = LCIA_{LDPE} \qquad \text{(Eq. 1)}$$

$$x = \frac{LCIA_A - LCIA_{LDPE}}{LCIA_{LDPE}} \qquad \text{(Eq. 2)}$$

The number of times depends on the difference between the two LCIA results, based on the LCIA result set as reference.

The results for these calculations were provided for this report as a matrix, which represents in the rows the alternative carrier bags, and in the column the carrier bag taken as reference. The numbers in the cells provide the number of times an alternative carrier bag needs to be reused in order to provide a better alternative than the carrier bag used as reference in the column (Figure 11).

The avoided bag can in practice also be reused, and if this was the case then the reuse number X would proportionally be as many times higher as it was reused. The resulting reuse numbers calculated with equation 2 should therefore be seen as a minimum reuse number that could be higher.

Edwards and Fry (2011) performed a similar assessment, but calculating the number of reuse times simply performing a ratio between the carrier bag alternative and the reference carrier bag. Such calculation differs from the method adopted for the present study by providing the number of reuse times, instead of the number of times the bag is used in total (Eq. 2).

3.6 Modelling of secondary reuse

Secondary reuse, i.e. reuse to provide for a function different than the one for which the product was produced, was assumed as substituting a waste bin bag (production and disposal). The function of the substituted waste bin bag is to hold waste with an average volume of 22.4 litres before being incinerated. The substituted waste bin bag was assumed to be an LDPE waste bin bag; the average volume was obtained after a survey of three different types of LDPE waste bin bags purchasable in Danish supermarkets in 2017.

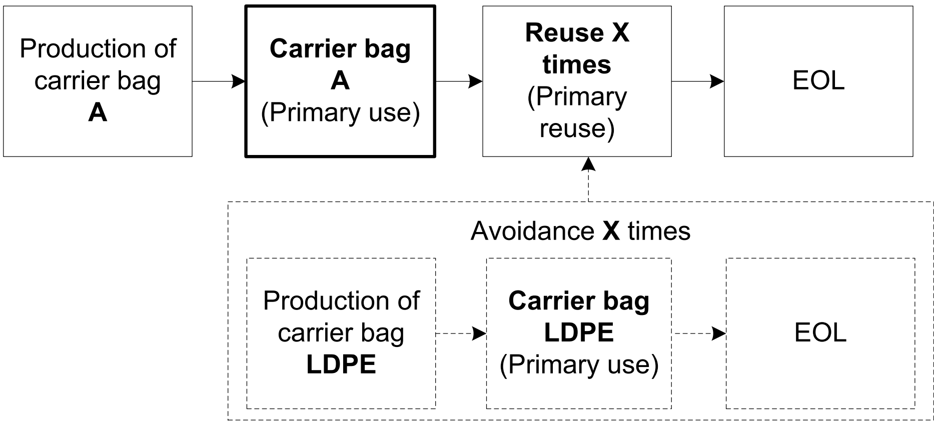


Figure 10. Generic modelling for the primary reuse. The example portrays the primary reuse X times of a generic "carrier bag A". The reuse X times allows avoiding X times the production, use and disposal of the reference LDPE carrier bag.

	LDPE carrier bag , EOL1
Carrier bag A, EOL1	**X times**
Carrier bag C, EOL1	**X times**
Carrier bag D, EOL1	**X times**

X: *number of times a carrier bag type in the rows needs to be reused in order to provide the environmental performance of the carrier bag type in the column*

Figure 11. Example of the result table that will illustrate the calculated number of primary reuse times. For each carrier bag alternative in the rows, the cells provide the number of times the carrier bag alternative needs to be reused in order to provide the environmental performance of the reference carrier bag in the column, for a defined impact category.

The conceptual model for secondary reuse is illustrated in Figure 12. A carrier bag produced and purchased for grocery shopping is reused one time in order to hold waste as a waste bin bag before being collected with residual waste and sent to incineration. The number of avoided waste bin bags (Y) was assumed to depend on the volume of the carrier bag. For example, carrier bags with a larger volume than an average LDPE waste bin bag were assumed to be able to contain more waste. The calculated avoided waste bin bags for each carrier bag type are provided in Table 4.

It is noteworthy that PP, polyester, paper, cotton and composite bags cannot fully provide for the same function as an LDPE waste bin bag. This is due to the material characteristics of the bags, which are water permeable, while LDPE is not. Therefore, the secondary reuse of these carrier bags has to be taken into account with due discussion. Moreover, biopolymer carrier bags may have a lower holding capacity and lower resistance to puncturing and tearing, which should also be taken into account for the discussion of the results.

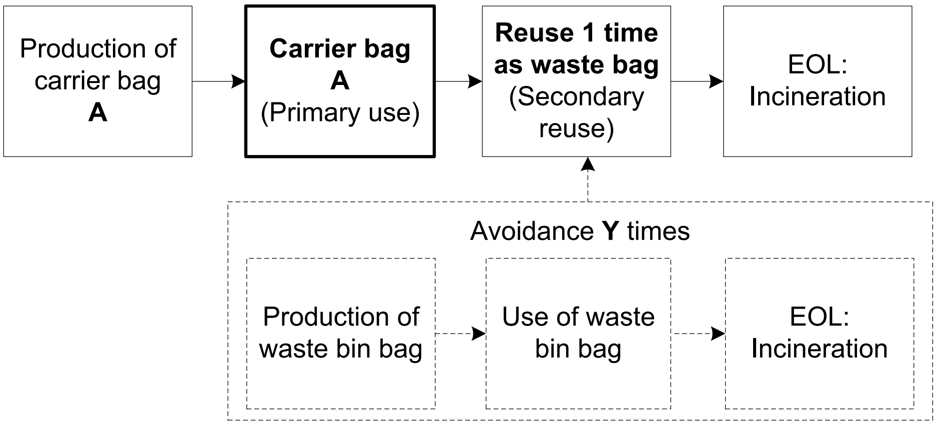


Figure 12. Generic modelling for the secondary reuse. The example portrays the secondary avoided number Y of produced as disposed waste bin bags for the secondary reuse of one carrier bag A.

Table 4. Number of avoided waste bin bags per carrier bag alternative.

Material	Type	Reference flow (number of bags needed)	Volume available (L)	Y: number of avoided waste bin bags (fraction)
Plastic	LDPE	1 (reference bag)	22.4	**1.0**
Plastic	*LDPE simple*	2	38.4	**1.7**
Plastic	*LDPE rigid handle*	1	24.8	**1.1**
Plastic	LDPE recycled	2	43.3	**1.9**
Plastic	*LDPE recycled, simple*	2	30.0	**1.3**
Plastic	*LDPE recycled, rigid handle*	2	50.0	**2.2**
Plastic	PP non-woven	1	29.0	**1.3***
Plastic	PP woven	1	36.7	**1.6***
Plastic	PET recycled	1	42.0	**1.9***
Plastic	Polyester	1	32.0	**1.4***
Bioplastic	Biopolymer	2	44.0	**2.0***
Paper	Paper	2	46.0	**2.1***
Textile	Cotton organic	2	40.0	**1.8***
Textile	Cotton conventional	1	27.0	**1.2***
Composite	Jute, PP, cotton	1	32.0	**1.4***

* The indicated carrier bag alternatives cannot fully provide for the LDPE waste bin bag functionality due to their water permeability; the biopolymer bag could be less resistant to tearing.

3.7 Modelling tools

The study was carried out with the waste-LCA model EASETECH (Clavreul et al., 2014), which was developed at DTU Environment and used for this assessment. EASETECH allows modelling of the flow of material in the LCA as a mix of material fractions (e.g. plastic, paper, etc.) and tracking their physico-chemical properties (e.g. energy content, fossil carbon, etc.) throughout the modelled life-cycle steps. The tracking of the material composition on top of the conventional mass flow-based LCA allows consumption and production of resources to be based on the physico-chemical properties of the functional unit, and especially to express emissions occurring during the end-of-life phases as a function of its chemical composition (e.g. fossil carbon emitted during incineration).

3.8 LCIA methodology and types of impacts

The impact categories for the impact assessment phase were selected among those recommended by the European Commission (European Commission, 2010). Since the LCA study might ultimately be used to support decisions, we decided to provide a comprehensive set of indicators. Previous LCA studies on grocery carrier bags have focused only on climate change, especially for the calculation of primary reuse times. The selected impact categories were: climate change, ozone depletion, human toxicity cancer and non-cancer effects, photochemical ozone formation, ionizing radiation, particulate matter, terrestrial acidification, terrestrial eutrophication, freshwater eutrophication, ecosystem toxicity, resource depletion, fossil and abiotic. We also took into account depletion of water resource.

Results are presented as characterized impacts following the characterization references in Table 5. Since characterization for the depletion of water resource is highly dependent on the geographical location, we decided to present inventory results as litres of water resource used. The LCIA results presented in this LCA study are relative and do not predict impacts on category endpoints, nor threshold levels, safety margins or risk levels.

3.9 Data requirements

In order to carry out this LCA study, inventory data on the emissions connected to the production of primary materials and energy required for the production of the different carrier bag types were needed. Moreover, we required data on material and energy consumption for the manufacturing of the carrier bags, as well as material needed for packaging and distribution. Data on waste management technologies for the end-of-life of the carrier bags were also needed.

The project did not focus on extensive data collection and was intended to be based on existing inventories for resources and data in the literature. For this reason, the study was mostly based on data available in the Ecoinvent database, version 3.4. Ecoinvent datasets were used for inventories for all materials and energy resources required for production, distribution, use and disposal. In order to be consistent with the modelling approach of the study, we used the consequential version of the database. Data on the material and energy resources required for the production of the carrier bags was obtained from a literature review of existing LCA studies on the environmental performance of supermarket carrier bags. Additional data on the material composition and on the waste management technologies were obtained from the library of the LCA model EASETECH. In general, EASETECH data and process models were used in order to model waste incineration when it was taking place in Denmark, as well as recycling in Europe. Management of rejects from recycling outside Denmark was modelled using generic waste management processes for Europe.

Each X in Table 6 shows the data available from LCI databases, literature sources and EASETECH at the beginning of this LCA study. Data for each scenario is further specified in Appendix A.

3.9.1 Production and distribution

Physico-chemical composition data for carrier bags products, which were needed for modelling incineration emissions, were obtained from the EASETECH library. The physico-chemical composition for the biopolymer bag was obtained by modifying EASETECH data according to physico-chemical characteristics of biopolymers from existing studies in the literature (Razza, 2014).

Table 5. Characterization (midpoint) references utilized in the project. The impact category "Depletion of abiotic resources" follows the ILCD recommended characterization factors.

Impact Category	Acronyms	LCIA method	Reference year	Units
Climate change	CC	ILCD2011, Climate change w/o LT; midpoint; GWP100; IPPC2007	2011	kg CO_2 eq.
Ozone depletion	OD	ILCD2011, Ozone depletion w/o LT, ODP w/o LT	2011	kg CFC-11 eq.
Human toxicity, cancer effects	HTc	ILCD2011, Human toxicity, cancer effects, w/o LT, USEtox	2011	CTUh
Human toxicity, non-cancer effects	HTnc	ILCD2011, Human toxicity, non-cancer effects w/o LT, USEtox	2011	CTUh
Particulate matter/Respiratory inorganics	PM	ILCD2011, Particulate matter w/o LT, from Humbert 2009, PM	2011	kg PM2.5 eq.
Ionizing radiation, human health	IR	ILCD2011, Ionising radiation human health w/o LT, IRP100 w/o LT, ReCiPe 1.05 midpoint (H)	2011	kBq U235 eq. (to air)
Photochemical ozone formation, human health	POF	ILCD2011, Photochemical ozone formation, human health w/o LT, POCP	2011	kg NMVOC eq.
Terrestrial acidification	TA	ILCD2011, Terrestrial acidification, Accumulated Exceedance	2011	mol H+ eq.
Eutrophication terrestrial	TE	ILCD2011, Eutrophication Terrestrial, Accumulated Exceedance	2011	mol N eq.
Eutrophication freshwater	FE	ILCD2011, Eutrophication Freshwater, FEP ReCiPe 1.05 midpoint (H)	2011	kg P eq.
Eutrophication marine	ME	ILCD2011, Eutrophication Marine w/o LT, ReCiPe2008 1.05	2011	kg N eq.
Ecotoxicity freshwater	ET	ILCD2011, Ecotoxicity freshwater w/o LT, USEtox	2011	CTUe
Resources, depletion of abiotic resources, fossil	RDfos	CML 2001, Depletion of abiotic resources, fossil - updated 2016	2016	MJ
Resources, depletion of abiotic resources (reserve base)	RD	CML 2001, Depletion of abiotic resources, elements (reserve base) - updated 2016	2016	kg Sb eq.

The manufacturing process of the carrier bag was set to occur in Europe. Inventories of emissions related to the production of primary materials and energy required for the carrier bags manufacturing phase were retrieved from the Ecoinvent database (v3.4, consequential), with exception of recycled LDPE, PET polyester, organic cotton and composite. It was assumed that primary materials and energy were retrieved from the market, therefore Ecoinvent "market" inventories were utilized when available. These inventories take into account production shares in different locations in the world. Market inventories were utilized also for the energy (electricity and heat) required for the manufacturing of the carrier bags, but with a European focus. Cotton bags are assumed to be manufactured in Europe, but the cotton used for the manufacturing is assumed to be retrieved from the market. The dataset used for cotton production (Ecoinvent, version 3.4, consequential) is based on a global average based on inputs from China, India, Latin America, and Turkey.

Data on the energy and material requirements (such as amount of electricity, ancillary materials, and packaging) for most of the carrier bag manufacturing processes were available from literature. Specific data was missing for woven PP, PET, polyester, organic cotton and composite carrier bags. Transportation data was available as far as fuel consumption is concerned, but data on kilometres driven was missing, since it was not possible to locate a precise geographical location for the production of the carrier bag.

3.9.2 End-of-life

On the other hand, as far as the end-of-life phase was concerned, extensive data and dedicated process models were available for incineration and recycling through the EASETECH database. Incineration in Denmark was modelled with an input-specific process in EASETECH, which took into account also direct emissions occurring from the incineration of the material. Utilized and recovered electricity and heat were the marginal energy technologies described in detail in Appendix B. The management of residues from the incineration process was also taken into account and modelled. Recycling in European countries was modelled with EASETECH and according to data available in the literature. Management of residues from the recycling process was modelled with Ecoinvent waste management processes for Europe. Ancillary materials required in the end-of-life processes were obtained from the Ecoinvent database, version 3.4, consequential.

Table 6. Data completeness assessment. Inventory of the available data at the beginning of the LCA study (without assumptions). X in the table represents available data. Please see Appendix A for details on data selected for the assessment and on the literature references used for the carrier bag manufacturing data.

Carrier bag material	Physico-chemical composition data	Material production data	Carrier bag manufacturing data	Transportation data	End-of-life: incineration	End-of-life: recycling
LDPE	X EASETECH (Riber et al., 2009)	X Ecoinvent 3.4, consequential, global market	X		X EASETECH, Ecoinvent 3.4, consequential	X EASETECH, Ecoinvent 3.4, consequential
LDPE recycled	X EASETECH (Riber et al., 2009)				X EASETECH, Ecoinvent 3.4, consequential	X EASETECH, Ecoinvent 3.4, consequential
PP non-woven	X EASETECH (Riber et al., 2009)	X Ecoinvent 3.4, consequential, global market	X		X EASETECH, Ecoinvent 3.4, consequential	X EASETECH, Ecoinvent 3.4, consequential
PP woven	X EASETECH (Riber et al., 2009)	X Ecoinvent 3.4, consequential, global market			X EASETECH, Ecoinvent 3.4, consequential	X EASETECH, Ecoinvent 3.4, consequential
PET recycled	X EASETECH (Riber et al., 2009)	X Ecoinvent 3.4, consequential, global market			X EASETECH, Ecoinvent 3.4, consequential	X EASETECH, Ecoinvent 3.4, consequential

Table 6 (continued). Data completeness assessment. Inventory of the available data at the beginning of the LCA study (without assumptions). X in the table represents available data. Please see Appendix A for details on data selected for the assessment and on the literature references used for the carrier bag manufacturing data.

Carrier bag material	Physico-chemical composition data	Material production data	Carrier bag manufacturing data	Transportation data	End-of-life: incineration	End-of-life: recycling
PET Polyester	X EASETECH (Riber et al., 2009)				X EASETECH, Ecoinvent 3.4, consequential	
Biopolymer	X EASETECH (Razza, 2014; Riber et al., 2009)	X Ecoinvent 3.4, consequential, global market	X		X EASETECH, Ecoinvent 3.4, consequential	Not recycled
Paper	X EASETECH (Riber et al., 2009)		X		X EASETECH, Ecoinvent 3.4, consequential	X EASETECH, Ecoinvent 3.4, consequential
Cotton organic	X EASETECH (Riber et al., 2009)				X EASETECH, Ecoinvent 3.4, consequential	Not recycled
Cotton conventional	X EASETECH (Riber et al., 2009)	X Ecoinvent 3.4, consequential, global market	X		X EASETECH, Ecoinvent 3.4, consequential	Not recycled
Composite (jute, PP, cotton)	X EASETECH (Riber et al., 2009)				X EASETECH, Ecoinvent 3.4, consequential	Not recycled

3.10 Assumptions

First of all, the present LCA study included in the assessment only the grocery carrier bag types identified in the carrier bags survey (Section 2), which are carrier bag types available in Danish supermarkets in 2017. Other carrier bags sold by other retailers, personal bags and very lightweight carrier bags were excluded from the assessment.

In order to identify the functional unit and reference flow, we did not take into consideration customers' behavioural patterns, such as tendency to buy new bags for each grocery shopping. We did not take into account whether differences could occur in shopping occurring at different times of the week (weekdays versus weekends) or the size of the family unit. Effect of taxation on customers' behaviour or choices of the supermarkets was not included.

For biopolymer and textile bags, recycling was not considered (Table 6). For biopolymers they do not recycle with other polymers, and are actually detrimental to the recycling of other plastics. In the report we did not include negative effects from consumers that mistakenly would place the biopolymer with the plastic recycling, therefore the result for biopolymer bags could be worse if this effect was included. In addition we did not include material recovery through composting for the compostable starch-biopolymer bags, since biopolymer bags are currently sorted out from organic waste management plants and sent for incineration.

Recycling of textiles was not taken into account since it mainly occurs outside the Danish waste management system, for example via charity organizations or through return schemes at retailer shops. The extent of recovery of materials can be extremely variable according to the specific collection selected, and the quality of the material collected.

3.10.1 Assumptions on missing data

In order to provide for the missing data identified in the completeness assessment (Table 6), assumptions had to be made. The assumptions are reported in the following Table 7. First of all, the material fractions used for the material composition in EASETECH were not as many as the carrier bag types identified. We used the same material fraction for each of the three types of material: plastic, paper and textiles.

Regarding the production of the primary materials required for the manufacturing of the carrier bags, it was not possible to retrieve “market” production processes from Ecoinvent for all the carrier bags materials assessed. Market inventories were not available for paper and for the LDPE selected for the modelling of the waste bin bag. For these materials, production datasets for Europe were chosen instead. A specific dataset for PET polyester production was not available, so instead a market dataset for virgin PET was used.

Moreover, Ecoinvent did not provide inventories for the production of recycled LDPE and organic cotton. For this reason, we assumed that recycled LDPE could be modelled, as a first assumption, utilizing the same dataset of virgin LDPE. For organic cotton, we modified the Ecoinvent dataset for conventional cotton production by subtracting environmental impacts connected to fertilizers and by lowering the production yield by 30 %. The yield of organic versus conventional cotton was found to range between 20 % and 40 % in the literature, 30 % according to a field test performed in India (Forster et al., 2013).

In order to model the production of composite material, we took into account the production of each single material composing the composite bag, with an assumed percent share of 80% jute, 10% PP and 10% cotton.

The available data on the manufacturing part of the carrier bags was lacking for the different PP (woven or non-woven), PET recycled, polyester PET, organic cotton and composite. We considered that the manufacturing materials and energy requirements were the same for woven and non-woven PP bags, as well as for PET and polyester PET. These types of carrier bags were found having very similar characteristics from the survey conducted on carrier bags. The same manufacturing data were used for the paper bleached and not bleached; similarly the same production data was used for cotton conventional, organic and composite bags (according to weight and materials used). We assumed that the packaging for shipping of the bags was single-wall corrugated cardboard box for all carrier bag types, as found from the conducted literature review.

We could not find literature data on the production and manufacturing of the waste bin bag. The waste bin bags surveyed for this study were thinner and of a visibly lower quality compared to the LDPE carrier bags. Due to the characteristics of the LDPE waste bin bags surveyed, we assumed that the production of such bag was less demanding in terms of energy and materials. For this reason, we decided to use the Ecoinvent dataset for the production of LDPE packaging, which included extrusion of LDPE and ancillary materials consumption. The Ecoinvent process chosen for waste bin bags production presented slightly lower overall impacts compared to the one for the production of LDPE carrier bag.

The EASETECH process models for recycling were based on literature data for recycling of plastic originating from virgin polymers, but not for recycled polymers. Therefore, we assumed that the efficiency was the same based on material type (for example, the same efficiency for all LDPE types).

As far as the environmental assessment is concerned, the LCA included the potential environmental impacts arising from the material and energy requirements for the production, use and treatment of the carrier bag, as well as the direct emissions during treatment. The LCA did not take into consideration the environmental effects of littering, nor the environmental impacts associated with the construction or decommissioning of infrastructures. Biomass was not considered a limited resource.

Table 7. Data assumptions with respect to carrier bag type and location in the modelling. X indicates where data was already present and did not require assumptions.

Carrier bag material	Physcio-chemical composition data	Material production data	Carrier bag manufacturing data	Transportation distance	End-of-life: incineration	End-of-life: recycling
LDPE	Soft plastic	X	X	Assumed	X	X
LDPE recycled	Soft plastic	Same as LDPE Ecoinvent 3.4, consequential, global market	Same as LDPE	Assumed	X	Same as LDPE
PP non-woven	Soft plastic	X	X	Assumed	X	X
PP woven	Soft plastic	X	Same as PP non-woven	Assumed	X	X
PET recycled	Soft plastic	X	Same as LDPE	Assumed	X	X
Polyester	Soft plastic	Virgin PET Ecoinvent 3.4, consequential, global market	Same as PP non-woven	Assumed	X	Same as PET
Biopolymer	Soft plastic, modified	X	X	Assumed	X	Not recycled
Paper	Paper and carton	X Ecoinvent 3.4, consequential, production in Europe	X	Assumed	X	X
Cotton organic	Textiles	Modified from cotton conventional	Same as cotton conventional	Assumed	X	Not recycled
Cotton conventional	Textiles	X	X	Assumed	X	Not recycled
Composite (jute, PP, cotton)	Textiles	Ecoinvent 3.4, consequential, global market, share between materials	Same as cotton conventional	Assumed	X	Not recycled

3.11 Data quality assessment

The information regarding volume, weight holding capacity and weight of the carrier bags was retrieved by a survey for all carrier bags available for purchase in Danish supermarkets in 2017 and is considered reliable and current.

Considering the same material composition for some carrier bags assessed in this study means that in the LCA results emissions from incineration of each material type are driven by mass rather than by different chemical composition of the bags. This will affect results mainly for the fossil carbon content of the material, which is emitted to air through incineration.

Regarding the datasets retrieved from the Ecoinvent database, the consequential version of the database is considered consistent with the goal and scope of this LCA study. The version of the database employed for this LCA was the latest available (3.4). All datasets used for this study have been tested for their environmental impacts against other datasets for similar materials and energy before being selected and implemented in the modelling. For example, we downloaded all available datasets for LDPE (market, production in various geographical locations) and verified that the dataset chosen for the modelling presented overall values in line with other similar datasets. In general, market and global datasets provided slightly higher emissions than production datasets in specific geographical locations. Therefore, the carrier bags for which only production datasets were available are likely to have slightly lower emissions than using market datasets. Assuming that the carrier bag manufacturers retrieve materials and energy from the market, our preference was always for the market datasets. When not available, we used production datasets, preferably for Europe.

Specific manufacturing data for recycled LDPE, woven PP, recycled PET, polyester, bleached paper, organic cotton and textile carrier bags were missing and available data from the most similar carrier bags manufacturing process was assumed instead. These assumptions are not considered limiting for the results since past LCAs on grocery carrier bags have evidenced that most of the production impacts were ascribable to the production of the carrier bag material (Edwards and Fry, 2011; Kimmel and Cooksey, 2014).

The data utilized to model material and energy requirements during the manufacturing processes were retrieved from a series of well-documented LCA studies. For our references, we gave priority to reviewed LCA studies and LCAs carried out by institutional bodies and with a similar geographical scope (Europe). The manufacturing data was obtained as a range from the values found in the literature, as reported in detail in Appendix A. When manufacturing data for specific carrier bags were missing, as in the case of PET and PP bags, we utilized data of peer-reviewed LCA studies for bags with similar characteristics.

The assumption of modelling the waste bin bag as an LDPE with lower quality was considered in line with the intended use of the bag: the LDPE carrier bags are intended for multiple uses, while the waste bin bag is intended for single use. Moreover, selecting a process with slightly lower impacts for the production of the waste bin bag allows being more conservative regarding the results, since lower benefits will arise from the saving of a waste bin bag.

The assumed transportation distances, which were the same for all the assessed carrier bags, reflect that transportation could occur to be as far as southern Europe. This was considered conservative, since the exact locations of the recycling plants were not known.

Data for end-of-life is considered technologically reliable. EASETECH allows modelling waste management as input-specific and allows following the material flow. Values characterizing the end-of-life processes are based on peer-reviewed literature and are extensively reported in Appendix A. Regarding the missing data for the recycling of recycled polymer, the recovery efficiencies could be lower if the quality of the polymer sent to recycling was lower, but we did not have data to substantiate assumptions on lower recovery rates and higher residues production for recycled polymers.

3.11.1 Critical assumptions

Overall, the present LCA study involved a series of assumptions. The following assumptions were considered critical for the outcomes of the study:

- The reference flow was calculated assuming that two bags were required when one carrier bag could not provide for the same volume and weight holding capacity of an average LDPE carrier bag, which was taken as reference. The study assumes that the customers of Danish supermarkets would need to buy another bag of the same type in order to provide for the same functionality (rounding). For some carrier bags this assumption could result in a large overcapacity.
- The recycled LDPE carrier bag was modelled using the same production dataset of virgin LDPE. This modelling choice, due to unavailability of data, is considered to be conservative. Recycled LDPE is expected to provide lower environmental impacts than virgin LDPE, as it can be observed for recycled HDPE and recycled PET in comparison with virgin HDPE and virgin PET (please see Appendix B).
- The yield of organic cotton farming was assumed 30 % lower than conventional cotton. For the modelling, this implies that 30 % more impacts are considered for the production of organic cotton than conventional cotton. The yield was found to vary in the literature between 20 % and 40 % and according to the geographical location (Forster et al., 2013). Since the Ecoinvent dataset for cotton production is not linked to a specific geographical location, but is based on a global average, 30 % was considered as average value. The selected value influences the contribution of the production process to the overall impacts related to the organic cotton carrier bag.
- Although the functional unit is based on carrier bags available for purchase in Danish supermarkets in 2017, the study is assumed to support decisions that will occur in a 10 year period, using a future marginal energy is assumed to well represent the effects in the future waste management system. Using a non-future marginal energy would have entailed having coal in the energy mix, and would have provided higher savings from energy recovery in the incineration process.
- Recycling was not considered for biopolymer and textile bags. Considering recycling feasible would mean allowing for the recovery of these materials through separate collection and re-processing, therefore lowering the impacts connected to the production of the carrier bags.
- Reuse as waste bin bag was modelled for all carrier bags included in the study, even if some carrier bags may not be able to provide for the same functionality of an LDPE waste bin bag.

Some of these critical assumptions were considered for sensitivity analysis, as explained in the Life Cycle Interpretation Section.

3.12 Cut-offs

As presented in the scope Section, the assessment did not include construction and decommissioning of infrastructure, buildings, machinery (capital goods), or analyses of existing capacities/new capacities requirements.

3.13 Limitations

The assumptions and cut-offs listed above were not considered limiting for the results of the assessment. First of all, the choice of the functional unit and reference flow was intentional for the calculation of the number of primary reuse times, regardless of the consumers' behavioural patterns. Nevertheless, a different reference flow will be taken into consideration for a sensitivity analysis of the results.

The choice of limiting the scope of the LCA to grocery carrier bags and not to personal bags and bags sold from other retailers was necessary in order to provide a specific assessment of the carrier bags available for purchase in Danish supermarkets, and to provide specific guidance to retailers on the choice of the carrier bags based on their environmental performance.

The choice of using the same material fractions for plastic bags, paper bags and textile bags will influence only the impacts that are modelled in EASETECH as a function of the material composition. In the case of the scenarios modelled in this assessment, the choice of material fractions will influence the emissions to atmosphere during incineration. Therefore, identifying the fossil and non-fossil carbon content and the content of metals emitted to air of the material fractions can cover the input-dependent part of the results.

Finally, littering effects were considered negligible for Denmark. Littering was mentioned in Environment Australia (2002) as an effect of wind blowing on landfills and as a result of missed environmental education.

3.14 Life Cycle Interpretation

The Life Cycle Interpretation part of this study comprises the analysis of the results, which are provided both as characterized and normalized impacts, and the discussion of such results. The analysis of the results was carried out with respect to the three main aims stated in the goal of the study: (1) identification of the best disposal option for each type of bag, (2) identification of the carrier bag with the best environmental performance, and (3) identification of the required number of primary reuse times based on the environmental assessment. The comparison of results was carried out per impact category and without employing any weighting.

1. Identification of the best disposal option for each type of bag
   For each type of carrier bag and impact category at a time, we examined the characterized results for each of the end-of-life scenarios. The LCIA for each bag was assessed with a contribution analysis, which identified the parts of the LCA model contributing the most to the final results. We also provided a dedicated contribution analysis to the carrier bag manufacturing part. This part of the interpretation of the results provided indication of the most preferable disposal option for each carrier bag type based on the results of the environmental assessment.

2. Identification of the carrier bag with the best environmental performance
   For each impact category, we identified the carrier bag alternative and the end-of-life scenario that provides the best environmental performance, as well as whether the identified environmental performance was significantly better than the one provided by the other carrier bag alternatives. The optimal end-of-life scenario identified in (1) was taken into account for the discussion of the results.

3. Identification of the number of primary reuse times
   As explained in the Section on modelling of primary reuse, we provided the calculated number of primary reuse times required by a carrier bag alternative to provide a better environmental performance than a reference carrier bag. The number of reuse times was calculated for each impact category and differences were discussed.

The results were discussed with respect to the goal and scope of the study, as well with respect to the limitations and considerations about data quality.

The discussion of the results was supported by additional calculations carried out as scenario analysis. A scenario analysis is a sensitivity analysis that takes into account the variation in the final result that occurs with differences in the initial assumptions taken. In particular, the variation in the results obtained was observed with respect to:

- different reference flow: not rounded to two bags but based on fractions that fulfil the weight and volume criteria;
- secondary reuse allowed for all carrier bag types versus only carrier bags that can fully provide for the waste bin bag functionality;
- 25 % lower impacts associated to virgin LDPE production.

3.15 Critical review

This LCA study includes a critical review, carried out by Line Geest Jakobsen and Trine Lund Neidel from COWI A/S in January 2018. The aim of the critical review is to assess the compliance of the LCA study with the ISO standard and to increase the clarity and usefulness of the result.

Although this LCA might be used to support decisions and that the comparative assertion might ultimately be disclosed to the public, there are pre-defined limitations to the study regarding the fact that the critical review was not conducted while the project was being carried out and by a panel of interested parties. For this reason, the report does not fully comply with the ISO standard. The critical review is provided in Appendix D and the main outcomes are summarized in the Executive Summary.

3.16 Format of the report

The format of the report is:

- Short executive summary in Danish (8 pages);
- Short executive summary in English (7 pages);
- Technical LCA report.

4. Scenarios

The following Section presents the scenarios that have been assessed by this LCA study. First of all, we selected a number of alternatives from the carrier bags identified from the survey. Then, scenarios were obtained by associating each carrier bag alternative with three different end-of-life scenarios. The scenarios are described referring to their main technological features. However, as anticipated in the scope section, the system boundaries also include upstream processes and emissions to air, water and soil related to material and energy requirements for the presented technologies, as well as substituted energy and products. A detailed description of the material and energy processes used in the present study is provided in the LCI (Appendix A).

4.1 Carrier bag alternatives

The selected carrier bag alternatives are provided in Table 8. The virgin LDPE type was selected as reference, since it represents the carrier bag that can always be found for purchase at the cash register in all Danish supermarkets. This carrier bag alternative has been named "LDPEavg" scenario and it constitutes an average between simple and rigid handle LDPE carrier bags. Scenarios "LDPEs" and "LDPEh", on the average simple and rigid handle LDPE carrier bags, respectively, were considered as well. The rigid handle carrier bag requires more material for its production, but has larger volume and might result in a different environmental performance when compared in terms of the functional unit. "LDPErec" was considered for recycled LDPE in general, since the survey could only find three items for this bag and since the simple and rigid handle model both do not show any difference with respect to the functional unit considered.

Table 8. Required reference flow for each carrier bag

Scenario name	Material	Type	Reference flow (number of bags needed)
LDPEavg	Plastic	LDPE	1 (reference bag)
LDPEs	*Plastic*	*LDPE simple*	*2*
LDPEh	*Plastic*	*LDPE rigid handle*	*1*
LDPErec	Plastic	LDPE recycled	2
-	Plastic	*LDPE recycled, simple*	*2*
-	Plastic	*LDPE recycled, rigid handle*	*2*
PP	Plastic	PP non-woven	1
PPwov	Plastic	PP woven	1
PETrec	Plastic	PET recycled	1
PETpol	Plastic	Polyester	1
BP	Bioplastic	Biopolymer	2
PAP	Paper	Paper, unbleached	2
PAPb	Paper	Paper, bleached	2
COTorg	Textile	Cotton organic	2
COT	Textile	Cotton conventional	1
COM	Composite	Jute, PP, cotton	1
W	Plastic	LDPE	1

Scenarios “PP” and “PPwov” consider non-woven and woven PP, respectively. “PETrec” represents recycled PET carrier bags, while “PETpol” refers to PET polyester. The “BP” scenario models a biopolymer bag, which was assumed to be starch-complexed biopolymer (i.e. a so-called compostable bag, as explained in Section 2). For the paper carrier bag, an additional scenario was added to the carrier bag “PAP”: we introduced the scenario, “PAPb”, in order to include also the effect of utilizing bleached paper instead of unbleached paper.

“COTorg” and “COT” scenarios model organic and conventional cotton, respectively. The difference between the two scenarios lies in the fact that organic cotton will require less fertilizers to be produced, but will also have a lower yield. It was estimated that the yield was 30 % lower, as previously seen in Section 3. “COM” scenario models the composite bag case, where the carrier bag is made of a mix of materials: jute, PP, and cotton.

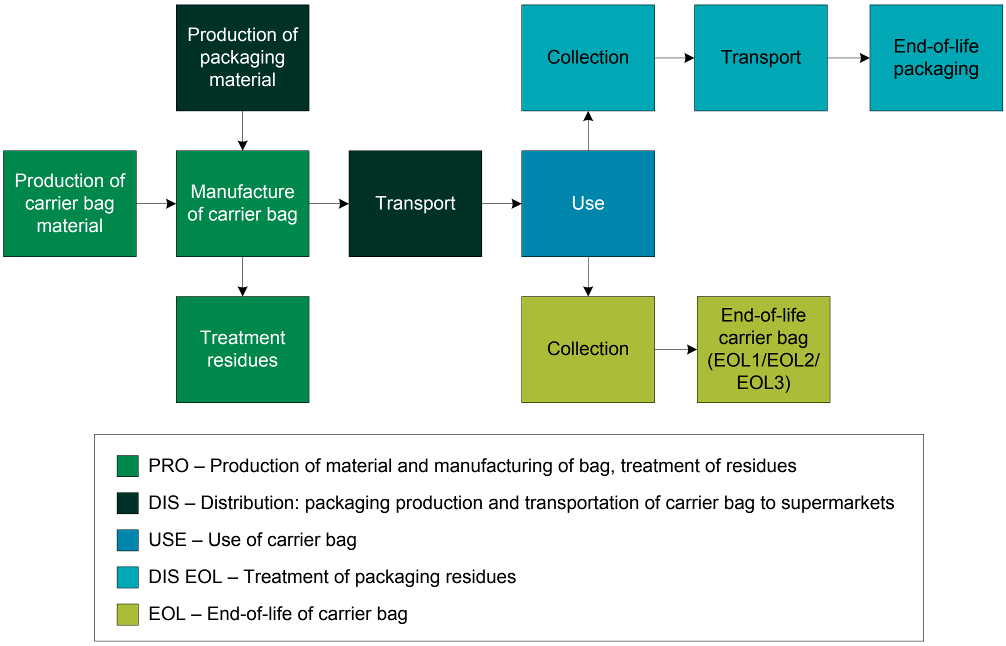


Figure 13. General common structure for all carrier bag scenarios assessed in this LCA study. The colour scales assigned to the different parts of the cradle to grave model will be used also for the contribution analysis.

After being used by the customer, the carrier bag had three different end-of-life options (end-of-life, orange): ending up in the residual waste collection and being incinerated (EOL1); being separately collected within similar materials waste stream and sent to recycling (EOL2); or being reused as a waste bin bag one time before ending up in the residual waste stream and being incinerated (EOL3). The following Sections illustrate the different end-of-life options.

4.2 End-of-life scenarios

This Section introduces the three main end-of-life scenarios considered for this project and indicates which carrier bags are associated with which end-of-life scenarios.

4.2.1 Incineration: EOL1

The carrier bag is produced and provided in Danish supermarkets. Here it is purchased and used for its primary function, which is carrying grocery shopping from the supermarkets to homes (primary use). After being used, the carrier bag is disposed in the residual waste, collected and ultimately incinerated in Denmark. The electricity and heat produced during the incineration process allows for avoiding the production of the same amount of electricity and heat from other resources. This scenario will be further referred to as "EOL1". The main features of the EOL scenario are provided in Figure 14 below. The colour scale is the same as Figure 13. Details are provided in Appendix A.

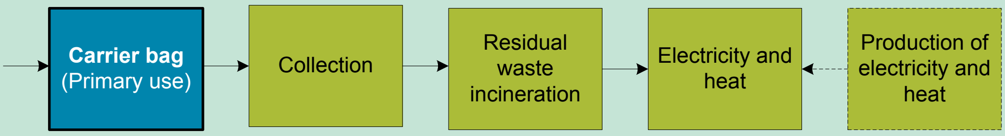


Figure 14. General EOL1 scenario structure. Dashed lines indicate substituted energy.

4.2.2 Recycling of material: EOL2

After being used for its primary function, the carrier bag is disposed with separately collected waste material of the same type. The separately collected waste is sorted and sent to material recycling, which is assumed to occur in Europe, but not in Denmark. The recycled secondary material allows avoiding the production of the same amount of material from primary resources. The residues from the recycling process are incinerated, allowing for the production of electricity and heat, which substitute the production of the same amount of electricity and heat from other resources. This scenario will be further referred to as "EOL2". The main features of the scenario are provided in Figure 15. The colour scale is the same as Figure 13. Details are provided in Appendix A.

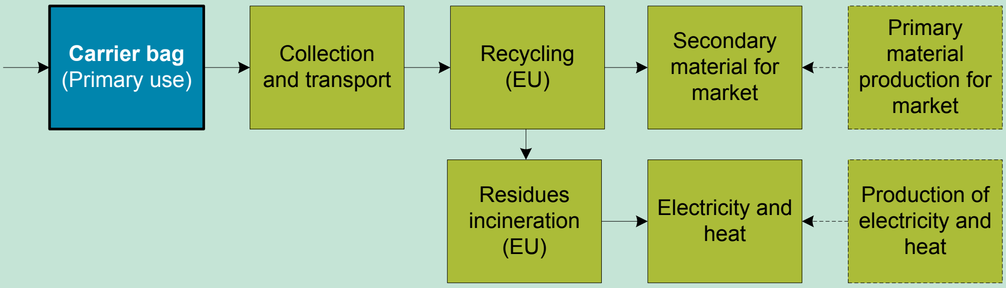


Figure 15. General EOL2 scenario structure.

4.2.3 Reuse as waste bin bag: EOL3

The carrier bag is produced and provided in Danish supermarkets. Here it is purchased and used for its primary function, which is carrying grocery shopping from the supermarkets to homes (primary use). After being used, the carrier bag is reused for another function, which is collecting residual waste (secondary reuse). The carrier bag used as a waste bin bag allows avoiding the production and disposal of a traditional waste bin bag. In both cases, the electricity and heat produced during the incineration process allow for avoiding the production of the same amount of electricity and heat from other resources. This scenario will be further referred to as "EOL3". The main features of the scenario are provided in Figure 16. The colour scale is the same as Figure 13. Details are provided in Appendix A.

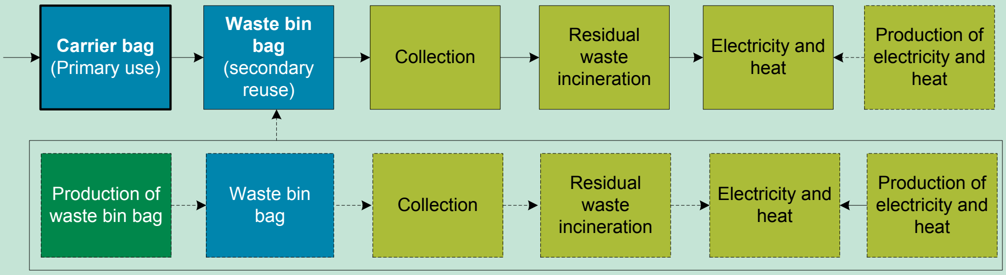


Figure 16. General EOL3 scenario structure.

Table 9 indicates which carrier bags alternatives are associated with which end-of-life scenario. EOL1 occurs for all carrier bag options, while recycling was not supposed to occur for biopolymer, cotton and composite bags. Recycling of polyester could only be assumed.

Table 9. Disposal options considered for each type of carrier bag included in the LCA study. X in the Table indicates where an end-of-life scenario in the column is considered viable and modelled for the corresponding carrier bag alternative in the row. * indicates functionality not fully provided.

Carrier bag alternative	EOL1	EOL2	EOL3
LDPEavg	X	X	X
LDPEs	X	X	X
LDPEh	X	X	X
LDPErec	X	X	X
PP	X	X	X*
PPwov	X	X	X*
PETrec	X	X	X*
PETpol	X	X	X*
BP	X		X*
PAP	X	X	X*
PAPb	X	X	X*
COTorg	X		X*
COT	X		X*
COM	X		X*
W	X		

As introduced in the previous section, recycling of biopolymer and textiles was not considered feasible in this study. The exclusion of recycling for textiles and biopolymers means that carrier bags of these materials will only be tested for EOL1 and EOL3.

The secondary reuse as a waste bin bag was modelled for all carrier bag options. However, as previously explained in Section 3, the functionality of an LDPE waste bin bag cannot be fully provided by bags that are permeable to water, such as PP, polyester, paper, cotton and composite. Moreover, biopolymer bags may present a higher chance of puncturing and tearing. EOL3 for these carrier bag types was calculated and then further discussed in the discussion section.

4.3 Carrier bag scenarios

For all carrier bag scenarios, the manufacturing stage was assumed to occur in Europe. The produced carrier bags were distributed with single-wall corrugated cardboard packaging, and transported from their place of production in Europe to Denmark, where they were put into use in supermarkets. The packaging was assumed to be separately collected with cardboard packaging, and to be transported abroad (Europe) for recycling. The carrier bag alternatives were tested for the end-of-life scenarios as shown in Table 9. For EOL1 and EOL3, residual waste was collected and incinerated in Denmark. For EOL2, the carrier bags were separately collected and sorted (30 % sorted out as residues) in Denmark, then transported and recycled in Europe.

4.3.1 LDPE carrier bags: LDPEavg, LDPEs, LDPEh, LDPErec

LDPE carrier bags include virgin LDPE carrier bags (LDPEavg, LDPEs, LDPEh), and recycled LDPE carrier bags (LDPErec). The bags were associated with the same material composition (soft plastic, Riber et al., 2009) and to the same manufacturing data; the scenarios differed for the weight associated with each bag and the number of bags required to fulfil the function expressed in the functional unit. The scenarios included the production of LDPE required for the manufacturing of the bag, as well as ancillary materials and energy. The manufacturing of the carrier bag produced around 5 % residues of LDPE from the initially required mass, which were assumed to be incinerated. Recycling of LDPE in EOL2 (9.7 % residues) was assumed to substitute LDPE production as granulate in Europe with a market response of 90 %. Residues were assumed to be incinerated in Europe.

4.3.2 PP carrier bags: PP, PPwov

PP carrier bags include non-woven (PP) and woven (PPwov) carrier bags. The bags were associated with the same material composition (soft plastic, Riber et al., 2009) and to the same manufacturing data; the scenarios differed for the weight associated with the carrier bags. The scenarios included the production of PP required to manufacture the bags, as well as energy and material requirements. 5 % of PP was assumed to be lost during production and to be incinerated. Recycling of PP in EOL2 (9.7 % residues) was assumed to substitute PP production as granulate in Europe with a market response of 90 %. Residues were assumed to be incinerated in Europe.

4.3.3 Recycled PET carrier bags: PETrec

Recycled PET carrier bags were associated with the material composition of soft plastic (Riber et al., 2009) and to the manufacturing consumption data of PP bags, due to the similarity in shape and structure. The scenario included the production of recycled PET. During manufacturing, 5 % of material was assumed to be lost as residues, which were incinerated. The recycling process in EOL2 (24.5 % residues) was assumed to produce recycled PET and to substitute recycled PET granulate, amorphous, in Europe with a market response of 81 %. Residues were assumed to be incinerated in Europe.

4.3.4 Polyester carrier bags: PETpol

Polyester carrier bags were also assumed representable by the material fraction soft plastic (Riber et al., 2009). The scenario included production of PET polyester, which was assumed ascribable to that of virgin PET. Due to the characteristics of the bag observed in the survey, energy and materials needed for manufacturing were assumed the same as PP carrier bags.

The manufacturing process was assumed to produce 5 % residues, which were incinerated. The recycling process in EOL2 was assumed to be similar to that of PET, with 24.5 % residues produced and with a market response for recycled polyester of 81 %. Residues were assumed to be incinerated in Europe.

4.3.5 Starch-complexed biopolymer bags: BP

The material composition for starch-complexed biopolymer bags was obtained from Razza, (2014). The scenario included production of the biopolymer and manufacturing of the carrier bag. The Ecoinvent dataset for the production of starch-complexed biopolymer does not take into account carbon storage. Residues (1 %) were assumed to be incinerated. The recycling scenario was not considered for this type of carrier bags, and should be avoided as it can be detrimental to recycling of other plastic types.

4.3.6 Paper bags: PAP, PAPb

Paper carrier bags comprise unbleached (PAP) and bleached (PAPb) craft paper bags. Both scenarios were associated with the material composition of paper and carton containers (Riber et al., 2009) and to the same energy and material requirements for manufacturing. The scenarios differed for the material production process associated with unbleached and bleached craft paper. Production was assumed to produce 5 % residues, which were incinerated. Recycling in EOL2 (9 % residues) was assumed to produce craft liner for cardboard production, with a market substitution in Europe of 90 %. Residues were assumed to be incinerated.

4.3.7 Cotton bags: COTorg, COT

Cotton bags comprise organic (COTorg) and conventional (COT) cotton. Both carrier bag types were modelled as textiles materials (Riber et al., 2009). The scenarios differed for the weight associated with the carrier bag, the number of bags required to fulfil the functional unit and for the cotton production data. Organic cotton production was modelled by subtracting fertilizers production data from conventional cotton production data and by lowering the yield by 30 %. Residues from production (1 %) were assumed to be landfilled. The recycling scenario was not considered for this type of carrier bag. If the bags were recycled it would lower the impact of using the cotton bags. It would though be important what material the cotton would substitute for the overall performance.

4.3.8 Composite bags: COM

The carrier bag composed of jute, PP and cotton was associated with the material fraction textiles (Riber et al., 2009). The material production data of jute, PP and cotton was included in the production inventory, as well as materials and energy requirements (assumed the same as those of the cotton bags). Based on the survey, we assumed that the composition of the bag was 80% jute, 10% PP and 10% cotton. Residues from production (1 %) were assumed to be landfilled. The recycling scenario was not considered for this type of carrier bag.

4.3.9 LDPE waste bin bag

The LDPE waste bin bag production and disposal via incineration was modelled in order to be used as avoided production in EOL3. The bag was modelled as soft plastic material (Riber et al., 2009) and its production was associated with the process of extrusion of plastic, due to the simplicity of the carrier bag. 5 % residues during production were assumed to be incinerated.

5. Life Cycle Impact Assessment

5.1 Results for each carrier bag

This Section presents the characterized result scores for each carrier bag type and end-of-life scenario. The characterized result scores are presented in Tables 10 – 12 below, one for each end-of-life scenario. The LCIA results are relative and do not predict impacts on category end-points, nor threshold levels, safety margins or risk levels. In order to facilitate the interpretation of the results, results for the same type of carrier bags have been grouped and discussed in detail in dedicated paragraphs. The results are subdivided according to the contribution of production, distribution, use, and end-of-life of packaging and carrier bag to the overall results. The colour scale of the contribution analysis in the following figures in this Section follows the same colour scale of Figure 4 in Section 4. The contribution analyses for materials and energy requirements in the manufacturing phase for each carrier bag are provided in table format.

Table 10. Characterized result scores for all carrier bag types, for the EOL1 end-of-life option (incineration). Results are provided per reference flow (see Table 8).

Scenario	Impact category														
	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD	Water
	kg CO_2 eq	kg CFC11eq	CTUh	CTUh	kg PM2.5 eq	kBq U235 eq	kg NM VOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq	L
LDPEavg	1.1E-01	1.2E-09	1.3E-09	-1.1E-08	1.6E-05	6.0E-04	2.0E-04	1.1E-04	8.7E-05	-5.6E-07	2.3E-05	7.1E-02	1.7E+00	1.9E-06	4.4E-02
LDPEs	1.7E-01	1.7E-09	2.0E-09	-1.7E-08	2.3E-05	8.9E-04	2.9E-04	1.7E-04	1.3E-04	-8.3E-07	3.4E-05	1.1E-01	2.5E+00	2.7E-06	6.5E-02
LDPEh	1.3E-01	1.4E-09	1.6E-09	-1.3E-08	1.9E-05	7.3E-04	2.3E-04	1.4E-04	1.0E-04	-6.8E-07	2.8E-05	8.6E-02	2.0E+00	2.2E-06	5.3E-02
LDPErec	2.3E-01	2.7E-09	2.8E-09	-2.3E-08	3.5E-05	1.3E-03	4.1E-04	2.5E-04	2.0E-04	-8.7E-07	5.0E-05	1.5E-01	3.5E+00	3.8E-06	5.3E-02
PP	6.5E-01	5.0E-08	2.6E-09	-5.4E-08	1.1E-04	8.7E-03	9.3E-04	5.8E-04	9.6E-04	1.1E-05	1.8E-04	2.7E-01	1.0E+01	2.3E-06	7.8E-01
PP	5.6E-01	4.4E-08	2.2E-09	-4.7E-08	9.4E-05	7.5E-03	8.1E-04	5.0E-04	8.3E-04	9.9E-06	1.5E-04	2.3E-01	9.0E+00	2.0E-06	6.8E-01
PET	7.7E-01	6.4E-08	7.0E-09	-1.6E-08	2.7E-04	1.4E-02	9.6E-04	1.1E-03	1.9E-03	3.8E-05	2.2E-04	5.1E-01	1.2E+01	2.1E-05	1.4E+00
PET	2.6E-01	2.2E-08	2.4E-09	-5.3E-09	9.8E-05	4.6E-03	3.3E-04	4.0E-04	6.9E-04	1.4E-05	8.9E-05	1.7E-01	4.1E+00	7.3E-06	4.7E-01
BP	9.0E-02	1.5E-08	2.3E-09	3.1E-08	1.2E-04	3.8E-03	3.4E-04	7.4E-04	1.4E-03	1.6E-05	2.4E-04	1.3E-01	2.9E+00	5.1E-06	2.2E-02
PAP	6.0E-02	1.2E-08	1.5E-09	8.9E-08	1.7E-04	6.2E-03	3.5E-04	4.2E-04	1.1E-03	1.7E-05	1.4E-04	2.0E-01	1.2E+00	3.8E-05	3.4E-01
PAP	1.8E-01	2.7E-08	1.6E-09	2.4E-09	2.9E-04	3.7E-03	4.6E-04	5.8E-04	1.4E-03	8.1E-06	1.7E-04	1.3E-01	3.6E+00	5.1E-06	2.4E-01
COM	1.8E+00	1.2E-06	4.3E-08	-1.8E-07	2.9E-03	4.0E-02	4.8E-03	1.1E-02	3.4E-02	2.4E-04	2.5E-03	4.4E+00	2.9E+01	3.2E-05	5.5E+00
COTorg	1.1E+01	2.8E-05	4.9E-07	1.6E-06	1.1E-02	3.8E-01	2.5E-02	5.7E-02	1.4E-01	1.4E-03	9.7E-03	3.3E+01	2.0E+02	4.4E-04	7.6E+01
COT	3.9E+00	1.0E-05	1.7E-07	5.6E-07	3.8E-03	1.3E-01	8.7E-03	2.0E-02	4.9E-02	4.8E-04	3.4E-03	1.2E+01	7.2E+01	1.6E-04	2.7E+01
W	3.9E-02	-2.4E-10	1.9E-10	-4.1E-09	6.1E-06	1.9E-04	6.9E-05	3.8E-05	4.1E-05	-1.6E-07	7.5E-06	2.0E-02	6.0E-01	2.6E-07	2.4E-02

Table 11. Characterized result scores for all carrier bag types, for the EOL2 end-of-life option (recycling). Results are provided per reference flow (see Table 8).

Scenario	Impact category														
	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD	Water
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kg PM2.5 eq	kBq U235 eq	kg NM VOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq	L
LDPEavg	8.2E-02	5.6E-09	1.3E-09	-4.3E-10	3.0E-05	1.7E-03	1.7E-04	1.7E-04	2.7E-04	7.9E-07	3.3E-05	9.1E-02	1.3E+00	2.1E-06	8.6E-02
LDPEs	1.2E-01	8.3E-09	1.9E-09	-6.4E-10	4.4E-05	2.6E-03	2.6E-04	2.5E-04	4.0E-04	1.2E-06	4.9E-05	1.3E-01	2.0E+00	3.1E-06	1.3E-01
LDPEh	9.8E-02	6.7E-09	1.6E-09	-5.2E-10	3.6E-05	2.1E-03	2.1E-04	2.0E-04	3.3E-04	9.5E-07	3.9E-05	1.1E-01	1.6E+00	2.6E-06	1.0E-01
LDPErec	1.7E-01	1.2E-08	2.7E-09	-5.6E-10	6.5E-05	3.6E-03	3.6E-04	3.7E-04	5.8E-04	1.9E-06	7.0E-05	1.9E-01	2.8E+00	4.4E-06	9.6E-02
PP	5.0E-01	7.5E-08	3.2E-09	1.2E-08	2.1E-04	1.5E-02	9.8E-04	1.2E-03	2.4E-03	1.9E-05	2.6E-04	4.0E-01	8.9E+00	4.1E-06	1.0E+00
PP	4.4E-01	6.5E-08	2.8E-09	1.0E-08	1.9E-04	1.3E-02	8.5E-04	1.0E-03	2.1E-03	1.6E-05	2.3E-04	3.5E-01	7.7E+00	3.5E-06	9.0E-01
PET	6.6E-01	8.7E-08	6.4E-09	3.0E-08	3.3E-04	1.7E-02	1.2E-03	1.6E-03	3.1E-03	3.4E-05	3.0E-04	8.7E-01	1.2E+01	1.7E-05	1.3E+00
PET	2.1E-01	2.8E-08	2.0E-09	9.4E-09	1.1E-04	5.5E-03	3.7E-04	5.1E-04	1.0E-03	1.1E-05	1.1E-04	2.9E-01	3.6E+00	5.2E-06	4.1E-01
BP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PAP	1.1E-01	1.9E-08	1.7E-09	9.7E-08	2.5E-04	8.1E-03	4.4E-04	6.5E-04	1.6E-03	1.8E-05	1.6E-04	2.6E-01	2.2E+00	3.7E-05	1.6E+00
PAP	2.3E-01	3.3E-08	1.8E-09	1.1E-08	3.7E-04	5.6E-03	5.5E-04	8.0E-04	1.9E-03	8.9E-06	1.9E-04	1.8E-01	4.6E+00	4.8E-06	1.5E+00
COM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
COTorg	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
COT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 12. Characterized result scores for all carrier bag types, for the EOL3 end-of-life option (secondary reuse as a waste bin bag). Results are provided per reference flow (see Table 8).

Scenario	Impact category														
	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD	Water
	kg CO2 eq	kg CFC11 eq	CTU h	CTU h	kg PM2.5 eq	kBq U235 eq	kg NM VOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq	L
LDPE	7.2E-02	1.4E-09	1.1E-09	-7.1E-09	9.6E-06	4.2E-04	1.3E-04	7.5E-05	4.6E-05	-4.1E-07	1.6E-05	5.2E-02	1.1E+00	1.6E-06	2.0E-02
LDPE	9.8E-02	2.2E-09	1.6E-09	-9.5E-09	1.3E-05	5.7E-04	1.7E-04	1.0E-04	5.8E-05	-5.6E-07	2.1E-05	7.2E-02	1.5E+00	2.3E-06	1.7E-02
LDPE	9.1E-02	1.7E-09	1.4E-09	-8.9E-09	1.2E-05	5.2E-04	1.6E-04	9.3E-05	5.9E-05	-5.0E-07	1.9E-05	6.4E-02	1.4E+00	1.9E-06	-5.7E-02
LDPE	1.6E-01	3.1E-09	2.4E-09	-1.5E-08	2.4E-05	9.4E-04	2.7E-04	1.7E-04	1.2E-04	-5.6E-07	3.5E-05	1.1E-01	2.4E+00	3.3E-06	2.9E-02
PP	6.0E-01	5.1E-08	2.3E-09	-4.9E-08	1.0E-04	8.5E-03	8.4E-04	5.3E-04	9.0E-04	1.2E-05	1.7E-04	2.4E-01	9.6E+00	2.0E-06	7.6E-01
PP	5.0E-01	4.4E-08	1.9E-09	-4.0E-08	8.4E-05	7.2E-03	6.9E-04	4.4E-04	7.6E-04	1.0E-05	1.4E-04	2.0E-01	8.0E+00	1.6E-06	6.5E-01
PET	6.9E-01	6.5E-08	6.7E-09	-8.5E-09	2.6E-04	1.3E-02	8.3E-04	1.0E-03	1.8E-03	3.9E-05	2.0E-04	4.7E-01	1.1E+01	2.0E-05	1.4E+00
PET	2.1E-01	2.2E-08	2.1E-09	5.4E-10	8.9E-05	4.3E-03	2.4E-04	3.5E-04	6.3E-04	1.4E-05	7.8E-05	1.4E-01	3.2E+00	6.9E-06	4.5E-01
BP	1.3E-02	1.5E-08	2.0E-09	3.9E-08	1.0E-04	3.5E-03	2.0E-04	6.6E-04	1.3E-03	1.7E-05	2.2E-04	9.5E-02	1.7E+00	4.6E-06	-2.6E-02
PAP	-2.1E-02	1.3E-08	1.1E-09	9.7E-08	1.6E-04	5.8E-03	2.0E-04	3.5E-04	1.0E-03	1.7E-05	1.2E-04	1.6E-01	-1.4E-02	3.7E-05	2.9E-01
PAP	1.1E-01	2.7E-08	1.2E-09	9.7E-09	2.7E-04	3.3E-03	3.4E-04	5.1E-04	1.3E-03	8.4E-06	1.6E-04	9.5E-02	2.5E+00	4.7E-06	1.9E-01
COM	1.7E+00	1.2E-06	4.3E-08	-1.8E-07	2.9E-03	4.0E-02	4.7E-03	1.1E-02	3.4E-02	2.4E-04	2.5E-03	4.4E+00	2.8E+01	3.2E-05	5.5E+00
COTorg	1.1E+01	2.8E-05	4.9E-07	1.6E-06	1.1E-02	3.8E-01	2.5E-02	5.7E-02	1.4E-01	1.4E-03	9.7E-03	3.3E+01	2.0E+02	4.4E-04	7.6E+01
COT	3.8E+00	1.0E-05	1.7E-07	5.7E-07	3.8E-03	1.3E-01	8.6E-03	2.0E-02	4.8E-02	4.8E-04	3.4E-03	1.2E+01	7.1E+01	1.6E-04	2.7E+01

5.1.1 LDPE bags: LDPEavg, LDPEs, LDPEh, LDPErec, W

The performance of LDPE carrier bags can be described with the results associated with scenario LDPEavg for LDPE carrier bags with average characteristics. The contribution of production, distribution and end-of-life to the results was proportionally the same for scenarios LDPEs, LDPEh and LDPErec, which differed for the weight of carrier bag and number of carrier bags needed to fulfil the function expressed in the functional unit. The results for the climate change impact category for LDPEavg and the three end-of-life options is presented in Figure 8, with results subdivided according to production, distribution, use and end-of-life for the packaging and the carrier bag (contribution analysis). A dedicated contribution analysis for the production phase for the average virgin LDPE carrier bag is presented in Table 13.
For EOL1, LDPE bags presented net impacts for the climate change impact category. 70 % of the impacts were related to the production of the carrier bag, of which 71 % were solely related to the LDPE material production. The second largest contribution to the climate change impacts was connected to the incineration process, where the fossil carbon in the LDPE was released to the atmosphere through air emissions. In this case, the recovery of electricity and heat from the incineration process lead to less savings in fossil carbon emissions than the direct emissions. Further climate change impacts were linked to the distribution phase, mostly from the transportation of the carrier bag.

EOL2 presented net climate change impacts as well, but with a lower magnitude than EOL1. The production and distribution phases led to the same climate change impacts as EOL1, but the recycling of LDPE at end-of-life provided climate change savings, which were mainly ascribable to the recovery of LDPE as secondary material for the market and consequent avoided LDPE production. Moreover, less fossil carbon was incinerated and released to atmosphere. EOL3 presented lower climate change impacts than EOL1 and EOL2. The reduced net contribution of the production and distribution phases presented in Figure 8 are due to the subtracted impacts connected to the waste bin bag that was avoided with the secondary reuse of the LDPE carrier bag. Emissions of carbon fossil to atmosphere were also lower due to the prevented emissions that would have occurred with incineration of the waste bin bag.

Table 13. Contribution analysis for the production (PRO) processes, which included the manufacturing of the virgin LDPE carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 average LDPE carrier bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials						
			Virgin LDPE production	Electricity	Heat	Calcium carbonate	Titanium dioxide	Ink	Management residues
CC	kg CO_2 eq	8.0E-02	71%	5%	8%	6%	7%	2%	2%
OD	kg CFC11 eq	3.0E-09	12%	19%	30%	10%	26%	3%	0%
HTC	CTUh	1.6E-09	37%	3%	-1%	2%	60%	1%	-1%
HTNC	CTUh	9.7E-10	76%	73%	-79%	28%	58%	5%	-61%
PM	kgPM2.5 eq	4.1E-05	73%	9%	-2%	3%	16%	3%	-3%
IR	kBq U235 eq	5.5E-04	20%	97%	-28%	7%	8%	2%	-6%
POF	kg NMVOC	3.0E-04	87%	3%	1%	2%	8%	1%	-2%
TA	mol H+ eq	3.2E-04	83%	6%	0%	3%	12%	2%	-6%
TE	mol N eq	5.3E-04	89%	6%	0%	4%	3%	3%	-5%
FE	kg P eq	5.7E-07	24%	80%	-38%	47%	37%	18%	-68%
ME	kg N eq	5.3E-05	80%	5%	1%	4%	9%	5%	-3%
ET	CTUe	6.6E-02	56%	2%	-1%	3%	34%	1%	5%
RD fos	MJ	2.2E+00	85%	4%	6%	2%	4%	1%	-3%
RD	kg Sb eq	1.9E-06	5%	0%	0%	11%	81%	2%	0%
Water	L	3.8E-02	7%	122%	-33%	9%	5%	-2%	-7%

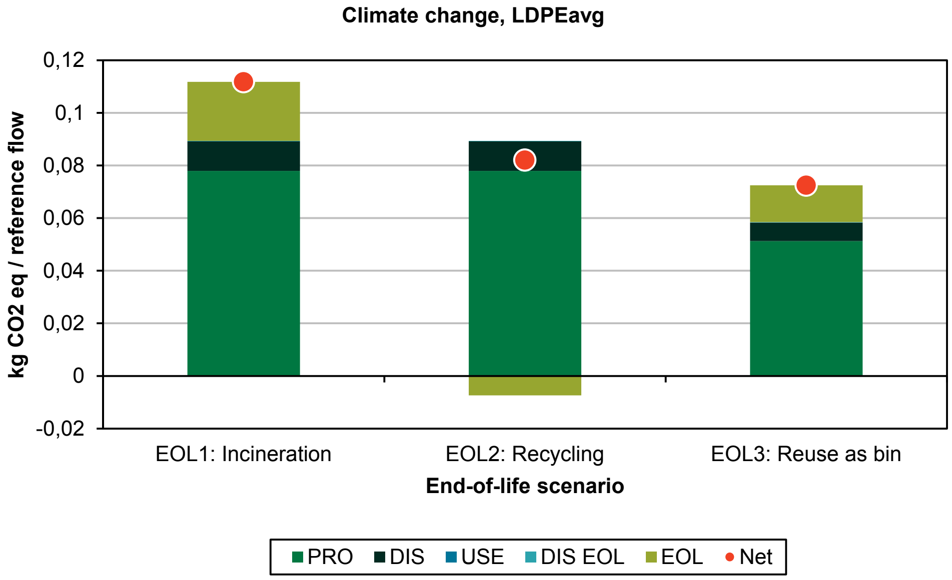


Figure 17. Characterized results for the climate change impact category and the three end-of-life options, expressed as kg CO_2 equivalents per reference flow, for the LDPE carrier bag LDPEavg. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

Overall, the climate change results indicate that recycling an LDPE carrier bag provides lower impacts than incinerating it. Secondary reuse as waste bin bag, however, results in more benefits than recycling. This trend in the impacts could be observed also for a few other impact categories, which are: photochemical ozone formation, human toxicity, cancer effects and resource depletion, fossil.

The remaining impact categories also provided overall net impacts, with exception of human toxicity, non-cancer effects, and freshwater eutrophication. In these cases savings were associated with the recovery of electricity and heat in the incineration process. Contrarily to the climate change impact category, recycling never provided a better result than incineration for these impact categories. This was mostly due to the energy requirements for the recycling process and the transportation distances to the sorting and recycling facilities and the less energy recovered in the incineration process. Reusing the LDPE carrier bag as a waste bin bag before incineration always provided a better environmental performance than incineration and recycling. For all end-of-life options, the management and recycling of the cardboard packaging used for distribution of the carrier bags did not provide a high contribution to the results, with exception of water use.

Regarding the contribution analysis for the production phase of average virgin LDPE carrier bag provided in Table 13 (common to EOL1, EOL2 and EOL3), the LDPE material production data largely contributed to the impacts in most of the impact categories, together with energy consumption. Negative scores in some impact categories are due to the use of a consequential database. Depending on the way consequential modelling is applied in Ecoinvent, the production of some intermediate exchanges can result in the decrease of production of another, to which is assigned a negative sign. For example, in the case of market for heat from natural gas that was used for this project, utilization of this heat source may lead to the avoided use of other heat sources, with a negative net impact.

The trend observed for LDPEavg in the results for all impact categories was similarly observed for all the LDPE carrier bags. Differences were due to the weight of the different carrier bag types and the number of bags necessary to fulfil the function. Figure 9 shows the climate change characterized results for all the LDPE carrier bag options (LDPEavg, LDPEs, LDPEh, LDPErec) and for the waste bin bag (W, also LDPE) for EOL1. Although some carrier bags had lower weight than the other options to which they are compared, LDPEs and LDPErec provided higher impacts because more than one bag was required in order to provide for the functionality expressed in the functional unit. Between LDPE carrier bags, LDPEh (LDPE with rigid handle) provided the best environmental performance for climate change. As previously explained in the assumptions paragraph, it was not possible to model LDPErec with recycled LDPE data, so the virgin LDPE production data was used instead.

The trend observed for LDPEavg in the results for all impact categories was similarly observed for all the LDPE carrier bags. Differences were due to the weight of the different carrier bag types and the number of bags necessary to fulfil the function. Figure 9 shows the climate change characterized results for all the LDPE carrier bag options (LDPEavg, LDPEs, LDPEh, LDPErec) and for the waste bin bag (W, also LDPE) for EOL1. Although some carrier bags had lower weight than the other options to which they are compared, LDPEs and LDPErec provided higher impacts because more than one bag was required in order to provide for the functionality expressed in the functional unit. Between LDPE carrier bags, LDPEh (LDPE with rigid handle) provided the best environmental performance for climate change. As previously explained in the assumptions paragraph, it was not possible to model LDPErec with recycled LDPE data, so the virgin LDPE production data was used instead.

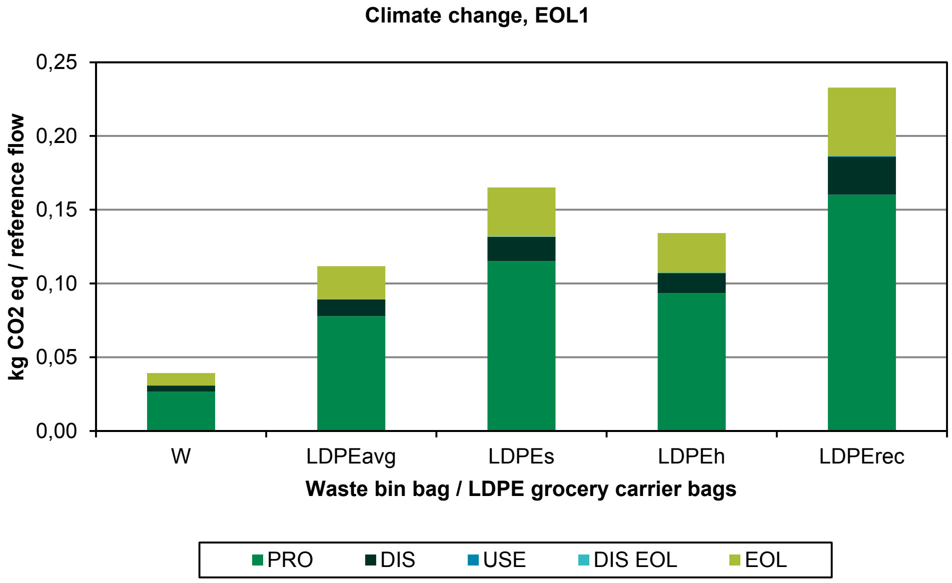


Figure 9. Characterized results for the climate change impact category, incineration end-of-life option (EOL1) expressed as kg CO_2 equivalents per reference flow, for the LDPE carrier bags LDPEavg, LDPEs, LDPEh, LDPErec and for the LDPE waste bin bag (W). PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

5.1.2 PP bags: PP, PPwov

The environmental performance of PP carrier bags can be described by the characterized results associated with PP (non-woven PP carrier bag). The results for PPwov presented the same contribution analysis, with slightly lower magnitude, since PPwov presented a slightly lighter weight and consequently required less material and energy for its production.

As observed for the LDPE carrier bags, climate change results presented overall net impacts. The impacts in EOL1 (and EOL2) were mainly associated with the production of the carrier bag, of which 69 % were associated with the production of PP (Figure 10). Emissions were also related to the release of fossil carbon to atmosphere during incineration and transportation. Recycling of PP presented lower impacts than incineration, for the recovery of material and lower fossil carbon release to atmosphere. EOL3 presented reduced impacts with respect to EOL1 for the savings associated with the avoided use and disposal of the waste bin bag, but with a small difference. The mass of avoided LDPE was proportionally lower than in the case of LDPE carrier bags, therefore it could not reduce the production and distribution impacts as in the case of LDPE carrier bags. As a consequence, recycling resulted as more beneficial disposal option than secondary reuse. PP carrier bags were considerably heavier than the waste bin bag, so could proportionally substitute more primary produced PP than avoiding the production of the LDPE waste bin bag. The same trend could be observed for the impact category resource depletion, fossil.

All the remaining impact categories presented net impacts, with exception of human toxicity, non-cancer effects. Savings for the latter impact category were associated with the recovery of electricity and heat in the incineration process. However, for all impact categories different than climate change, recycling was never more beneficial than incineration, and reuse as a waste bin bag always provided the overall best environmental performance, even if with only a slight difference with incineration. It is worth underlining that PP carrier bags may also not fully provide for the functionality of an LDPE waste bin bag due to their permeability to water.

Table 14 provides the contribution analysis for the production phase for the PP carrier bag. Similarly to LDPE, the production of PP contributes largely to the impacts of the production phase, but to a lower extent. Other processes contributing to the impacts of production are electricity, heat and cotton, necessary for the cotton threads.

Table 14. Contribution analysis for the production (PRO) processes, which included the manufacturing of the virgin PP carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 PP bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials						
			PP production	Electricity	Heat	Water	Cotton thread	Ink	Management residues
CC	kg CO_2 eq	4.5E-01	66%	12%	7%	0%	4%	8%	4%
OD	kg CFC11 eq	6.0E-08	3%	13%	7%	0%	72%	4%	0%
HTC	CTUh	3.5E-09	55%	16%	-3%	0%	21%	9%	1%
HTNC	CTUh	1.3E-08	23%	73%	-27%	0%	20%	10%	1%
PM	kgPM2.5 eq	2.4E-04	59%	22%	-1%	0%	7%	14%	0%
IR	kBq U235 eq	8.1E-03	8%	91%	-9%	0%	7%	4%	0%
POF	kg NMVOC	1.4E-03	81%	8%	1%	0%	3%	7%	0%
TA	mol H+ eq	1.6E-03	71%	15%	0%	0%	5%	9%	0%
TE	mol N eq	3.3E-03	69%	14%	0%	0%	6%	11%	0%
FE	kg P eq	1.7E-05	40%	37%	-6%	0%	12%	16%	0%
ME	kg N eq	3.4E-04	63%	11%	1%	0%	4%	21%	0%
ET	CTUe	2.2E-01	59%	9%	-2%	0%	22%	10%	3%
RD fos	MJ	1.3E+01	79%	9%	4%	0%	2%	5%	0%
RD	kg Sb eq	2.2E-06	10%	0%	1%	0%	31%	57%	0%
Water	L	7.1E-01	2%	94%	-9%	0%	16%	-3%	0%

5.1.3 Recycled PET carrier bags: PETrec

Characterized climate change results for recycled PET carrier bags are provided in Figure 11 below. Recycled PET carrier bags showed a similar trend with respect to previously examined fossil carbon-based carrier bags: overall net climate change impacts, which was governed by the carrier bag production phase (80 %, Table 15).

Although PET bags were large in volume and could potentially substitute the highest fraction of waste bin bags (Table 4), the difference between EOL1 and EOL3 was small, due to the proportionally lower weight of the avoided waste bin bag with respect to the PET bag. Recycling the PET carrier bag provided lower environmental impacts than EOL1 and EOL3 due to the recovery of recycled PET material and lower carbon fossil emissions generated during the incineration phase. Recycling provided an environmentally better result than incineration and secondary reuse also for human toxicity, cancer effects, freshwater eutrophication, resource depletion and water consumption.

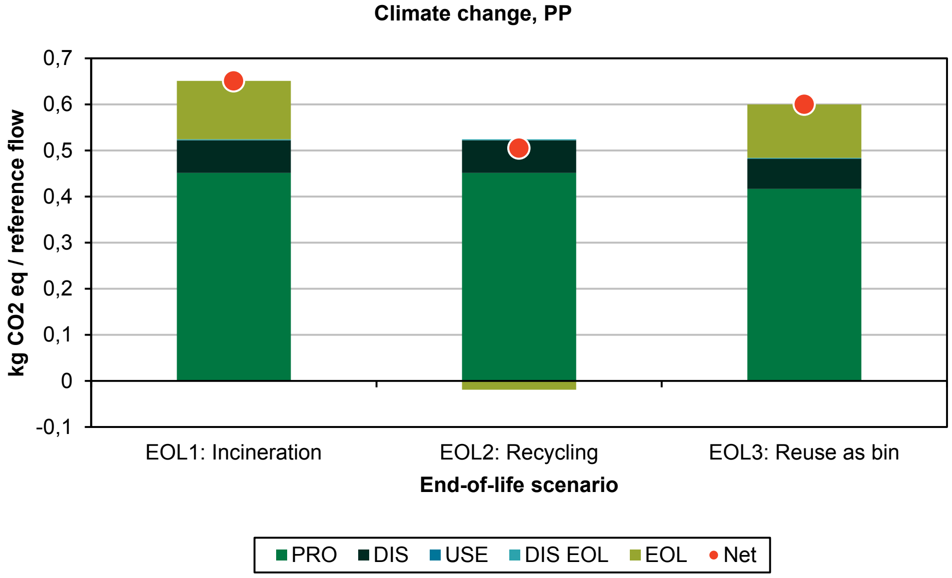


Figure 10. Characterized results for the climate change impact category and the three end-of-life options, expressed as kg CO_2 equivalents per reference flow, for the PP carrier bag PP. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

For the remaining impact categories, recycling was worse than incineration, and reuse as waste bin bag before incineration provided only slightly better environmental results. Savings occur for the human toxicity, non-cancer effects impact category due to the energy recovered during incineration.

Table 15. Contribution analysis for the production (PRO) processes, which included the manufacturing of the recycled PET carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 recycled PET bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials						
			Recycled PET production	Electricity	Heat	Ink	Cotton thread	Water	Management residues
CC	kg CO_2 eq	5.8E-01	80%	10%	5%	1%	3%	0%	1%
OD	kg CFC11 eq	7.4E-08	25%	11%	6%	1%	58%	0%	0%
HTC	CTUh	8.0E-09	85%	7%	-1%	1%	9%	0%	-1%
HTNC	CTUh	5.2E-08	86%	19%	-7%	1%	5%	0%	-3%
PM	kgPM2.5 eq	4.0E-04	83%	13%	-1%	2%	4%	0%	-1%
IR	kBq U235 eq	1.3E-02	47%	55%	-5%	0%	4%	0%	-1%
POF	kg NMVOC	1.5E-03	88%	8%	1%	1%	3%	0%	-1%

Table 15. (continued) Contribution analysis for the production (PRO) processes, which included the manufacturing of the recycled PET carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 recycled PET bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials						
			Recycled PET production	Electricity	Heat	Ink	Cotton thread	Water	Management residues
TA	mol H+ eq	2.2E-03	86%	11%	0%	1%	4%	0%	-2%
TE	mol N eq	4.3E-03	84%	11%	0%	2%	5%	0%	-2%
FE	kg P eq	4.5E-05	85%	14%	-2%	1%	5%	0%	-3%
ME	kg N eq	3.8E-04	84%	9%	1%	4%	4%	0%	-1%
ET	CTUe	4.7E-01	67%	4%	-1%	1%	10%	0%	18%
RD fos	MJ	1.4E+01	86%	8%	4%	1%	2%	0%	-1%
RD	kg Sb eq	2.1E-05	95%	0%	0%	1%	3%	0%	0%
Water	L	1.4E+00	49%	48%	-5%	0%	8%	0%	-1%

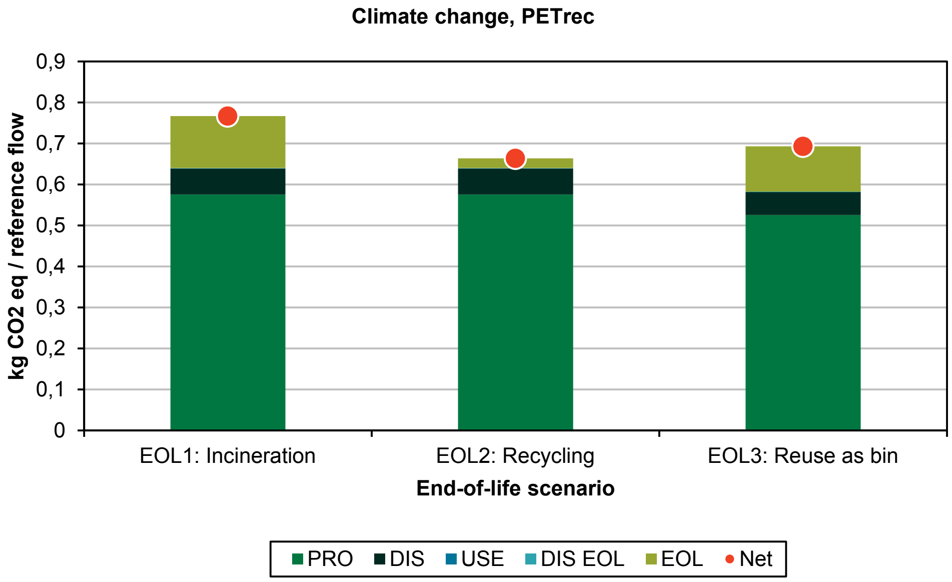


Figure 11. Characterized results for the climate change impact category and the three end-of-life options, expressed as kg CO_2 equivalents per reference flow, for the recycled PET carrier bag PETrec. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

5.1.4 Polyester bags: PETpol

In accordance with what already observed for other carrier bags, climate change impacts were mostly ascribable to the carrier bag production phase (76 % of the climate change impacts, as observed for recycled PET carrier bags). Table 16 provides the contribution analysis for the production phase.

Table 16. Contribution analysis for the production (PRO) processes, which included the manufacturing of the virgin PET polyester carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 PET polyester bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials						
			Virgin PET production	Electricity	Heat	Ink	Cotton thread	Water	Management residues
CC	kg CO_2 eq	2.0E-01	76%	9%	5%	6%	3%	0%	1%
OD	kg CFC11 eq	2.5E-08	23%	11%	6%	3%	58%	0%	0%
HTC	CTUh	2.7E-09	82%	7%	-1%	4%	9%	0%	-1%
HTNC	CTUh	1.7E-08	83%	19%	-7%	3%	5%	0%	-3%
PM	kgPM2.5 eq	1.4E-04	78%	12%	-1%	8%	4%	0%	-1%
IR	kBq U235 eq	4.4E-03	44%	56%	-6%	2%	4%	0%	-1%
POF	kg NMVOC	5.0E-04	84%	8%	1%	6%	3%	0%	-1%
TA	mol H+ eq	7.5E-04	81%	11%	0%	6%	4%	0%	-2%
TE	mol N eq	1.5E-03	79%	10%	0%	8%	5%	0%	-1%
FE	kg P eq	1.6E-05	81%	14%	-2%	6%	4%	0%	-2%
ME	kg N eq	1.4E-04	72%	8%	1%	16%	4%	0%	-1%
ET	CTUe	1.5E-01	63%	4%	-1%	5%	11%	0%	18%
RD fos	MJ	4.8E+00	83%	8%	4%	4%	2%	0%	-1%
RD	kg Sb eq	7.2E-06	91%	0%	0%	6%	3%	0%	0%
Water	L	4.5E-01	49%	49%	-5%	-2%	8%	0%	-1%

EOL 3 was the most favourable disposal option for climate change, while EOL1 was the worst, due to fossil carbon emissions to air during incineration. The difference between EOL1 and EOL3 results for climate change is due to the lower weight of the polyester bag with respect to the recycled PET carrier bag, which therefore substitutes less material when reused as a waste bin bag. EOL3 is the disposal option that provides the lowest impacts in most of the impact categories assessed.

5.1.5 Comparison of fossil plastic carrier bags

The following Figure 12 aims at comparing the climate change results associated with the fossil carbon-based grocery shopping bags that have been presented so far. The comparison of results highlights that the lowest climate change impacts were calculated for LDPE. This result is related to the fact that LDPE carrier bags were the lightest carrier bag alternatives that could provide for the volume and weight holding capacity of the functional unit, while requiring the least amount of material to be produced. Between LDPE carrier bags, the best environmental performance for climate change was associated with the LDPE carrier with rigid handle, since two of the simple LDPE (LDPEs) and recycled LDPE (LDPErec) would be required to provide for the same function.

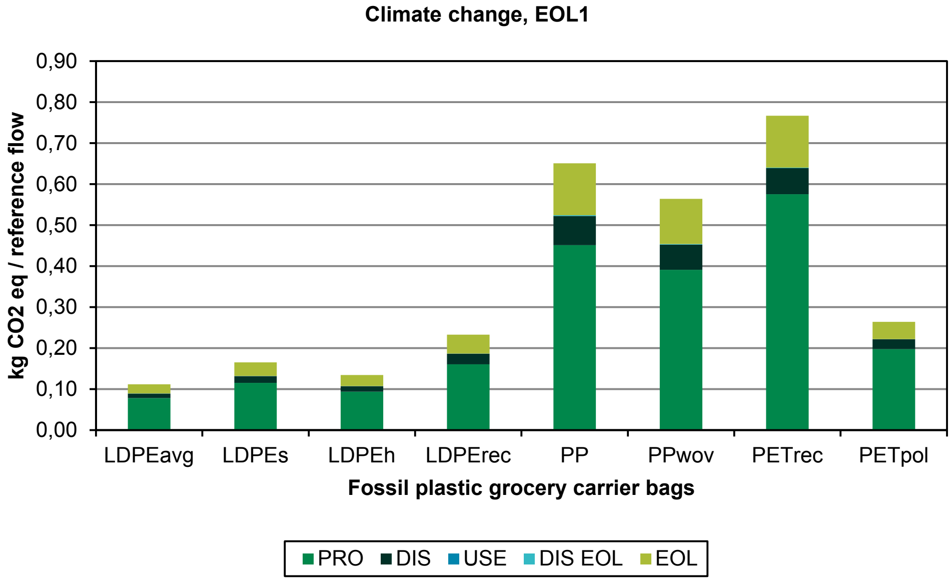


Figure 12. Characterized results for the climate change impact category, incineration end-of-life option (EOL1) expressed as kg CO_2 equivalents per reference flow, for the fossil carbon-based carrier bags LDPEavg, LDPEs, LDPEh, LDPErec, PP, PPwov, PETrec and PETpol. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

5.1.6 Biopolymer bags: BP

Climate change impacts for the starch-complexed biopolymer bags (BP) are provided in Figure 13. EOL2 scored zero impacts because recycling was not considered viable for this type of carrier bag material. Production of the carrier bag presented the highest contribution to the impacts. The contribution analysis for the production phase shown in Table 17 shows that the production of biopolymer is the process mostly contributing to the results. However, differently than for fossil carbon-based grocery shopping bags, incineration provided savings due to the considerably lower content of fossil carbon in the bag material than the previously examined bags. Secondary reuse provided considerably lower impacts than incineration, because reuse as a waste bin bag would avoid the production and disposal of a fossil carbon-based bag. For the remaining impact categories, EOL3 always provided a better performance than EOL1, but with a proportionally lower difference between the two options. Reuse of BP carrier bag as a waste bin bag might however not provide for the same functionality of the LDPE waste bin bag, since the survey carried out at DTU Environment has evidenced a lower resistance to puncturing and tearing than other bags. All impact categories provided net impacts with exception of water resource use in EOL3, where the consumption of water was lower than the water use for the waste bin bag production.

Table 17. Contribution analysis for the production (PRO) processes, which included the manufacturing of the biopolymer carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 biopolymer bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials					
			Biopolymer production	Electricity	Titanium dioxide	Water	Ink	Management residues
CC	kg CO_2 eq	4.9E-02	86%	9%	5%	0%	1%	0%
OD	kg CFC11 eq	7.2E-09	87%	8%	5%	0%	0%	0%
HTC	CTUh	1.2E-09	62%	4%	34%	0%	0%	0%
HTNC	CTUh	1.9E-08	95%	4%	1%	0%	0%	0%
PM	kgPM2.5 eq	6.3E-05	89%	6%	4%	0%	1%	0%
IR	kBq U235 eq	1.7E-03	65%	34%	1%	0%	0%	0%
POF	kg NMVOC	1.8E-04	89%	5%	5%	0%	1%	0%
TA	mol H+ eq	4.1E-04	91%	5%	4%	0%	0%	0%
TE	mol N eq	7.4E-04	94%	5%	1%	0%	1%	0%
FE	kg P eq	8.3E-06	93%	6%	1%	0%	0%	0%
ME	kg N eq	1.2E-04	95%	2%	2%	0%	1%	0%
ET	CTUe	5.5E-02	79%	3%	17%	0%	0%	0%
RD fos	MJ	1.5E+00	91%	6%	3%	0%	1%	0%
RD	kg Sb eq	2.5E-06	78%	0%	26%	0%	1%	-5%
Water	L	2.1E-03	-26%	87%	41%	3%	-13%	8%

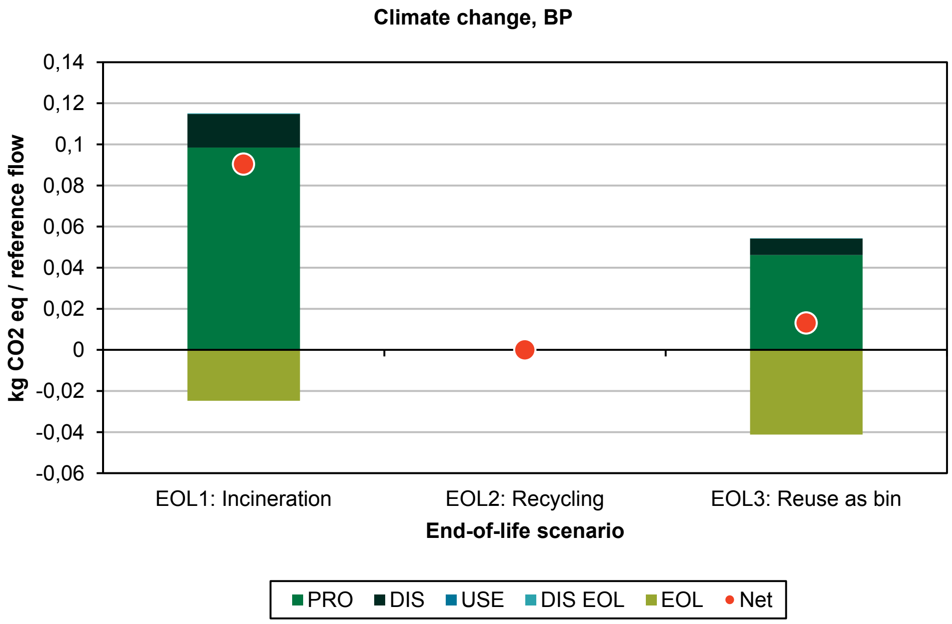


Figure 13. Characterized results for the climate change impact category and the three end-of-life options, expressed as kg CO_2 equivalents per reference flow, for the starch-complexed biopolymer carrier bag BP. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

5.1.7 Paper bags: PAP, PAPb

The environmental performance of paper carrier bags was calculated for the case of both unbleached and bleached craft paper. The characterized results for the climate change impact category for unbleached paper (PAP) are presented in Figure 14. Table 18 provides the contribution analysis for the production phase. The majority of the impacts from the production can be ascribed to craft paper production.

Table 18. Contribution analysis for the production (PRO) processes, which included the manufacturing of the paper carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 unbleached paper bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials				
			Craft paper production	Electricity	Glue	Ink	Management residues
CC	kg CO_2 eq	3.1E-02	87%	6%	2%	10%	-5%
OD	kg CFC11 eq	4.9E-09	74%	6%	16%	4%	0%
HTC	CTUh	7.1E-10	93%	3%	1%	4%	-1%
HTNC	CTUh	4.9E-08	100%	1%	0%	0%	-1%
PM	kgPM2.5 eq	8.8E-05	95%	2%	0%	3%	-1%
IR	kBq U235 eq	2.4E-03	78%	11%	11%	1%	-1%
POF	kg NMVOC	1.7E-04	91%	3%	3%	5%	-2%
TA	mol H+ eq	2.5E-04	94%	3%	2%	5%	-5%
TE	mol N eq	6.0E-04	93%	3%	1%	5%	-2%
FE	kg P eq	8.3E-06	97%	3%	0%	3%	-3%
ME	kg N eq	6.6E-05	89%	2%	1%	9%	-2%
ET	CTUe	6.9E-02	96%	1%	1%	3%	-1%
RD fos	MJ	5.9E-01	79%	7%	11%	9%	-6%
RD	kg Sb eq	1.9E-05	100%	0%	0%	1%	0%
Water	L	1.4E-01	88%	17%	-2%	-1%	-1%

As in the case of the biopolymer bag, climate change impacts for the incineration process provided net savings. The production process contributed proportionally less to the climate change impacts than in the previously examined bags. Recycling of paper provided net and higher climate change impacts than incineration, due to transportation distances, energy requirements and, mostly, to the low savings associated with avoided production of craft paper. The quality of craft paper used for paper bags was assumed to be only recyclable into paper for cardboard production.

For all the remaining impact categories with exception of resource depletion, recycling always performed worse than incineration, and secondary reuse always provided the absolute lowest impacts (saving in the case of resource depletion), provided that the paper carrier bag can provide the same functionality as a waste bin bag than the LDPE waste bin bag.

Impacts for the bleached paper bag (PAPb) were considerably higher due to the production phase of the bleached paper. Overall, the same trend between disposal options was observed, with recycling always providing larger impacts than incineration and secondary reuse. The results of the environmental assessment indicate that utilizing unbleached paper for the paper bag material is preferable than utilizing bleached paper.

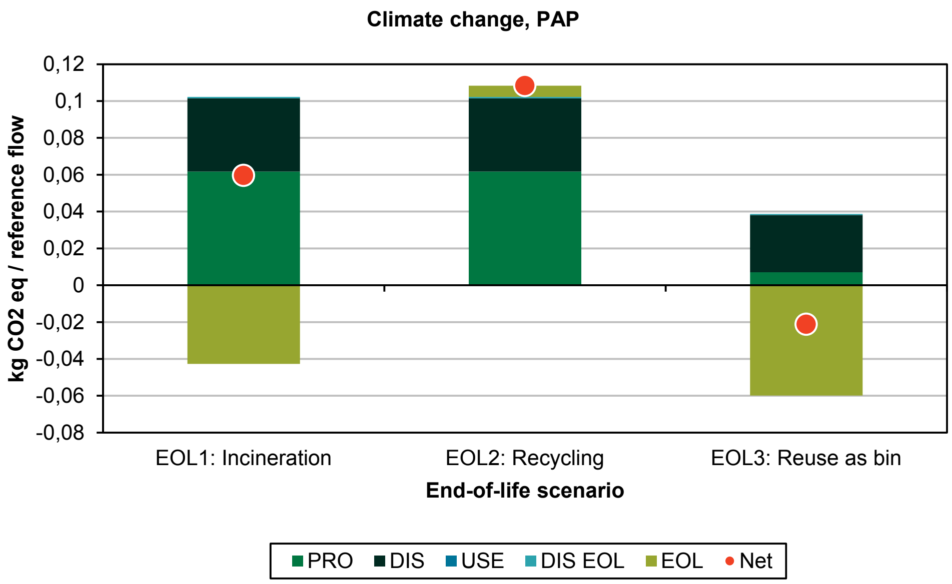


Figure 14. Characterized results for the climate change impact category and the three end-of-life options, expressed as kg CO_2 equivalents per reference flow, for the un-bleached paper carrier bag PAP. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

5.1.8 Cotton and composite bags: COTorg, COT, COM

The characterized results for the cotton bag options (COTorg, COT) and the carrier bag with composite materials (COM) are presented in the same paragraph due to their shared charac-teristics. As it is illustrated for the climate change results for organic cotton in Figure 15, these types of carrier bags presented the highest observed impacts related to their production. EOL2 scored zero in Figure 15 since recycling was not considered viable for this type of carrier bag. The same was assumed for COT and COM.

In the case of organic cotton (COTorg), production contributed to 99 % of the impact, 98 % and 96% for COT and COM scenarios, respectively. The contribution analysis for the produc-tion phase of these bags is provided in Tables 19 – 21. The high environmental cost of the cotton production can be ascribed to the energy and material required, which is responsible for 80 % of the climate change impacts. In general, the results showed very little difference be-tween EOL1 and EOL3, due to the comparatively small weight of the avoided waste bin bag in comparison to the mass (and resources required for its production) of the cotton bag. The same behaviour was observed for all impact categories, as well as for COT and COM, even if with a lower magnitude in the impacts.
The environmental impacts connected to the production of the organic cotton bag (COTorg) were considerably higher than those of the conventional cotton bag (COT). This is due to the fact that organic cotton production does not involve the use of synthetic chemicals such as

fertilizers and pesticides, which lowers the yield of the cultivation. Eventually, more resources and land are required to produce the same amount of cotton than in conventional cotton cultivation processes.

Table 19. Contribution analysis for the production (PRO) processes, which included the manufacturing of the organic cotton carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 organic cotton bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials				
			Cotton production	Electricity	Heat	N fertiliser	Management residues
CC	kg CO_2 eq	5.4E+00	99%	0%	1%	0%	0%
OD	kg CFC11 eq	1.4E-05	100%	0%	0%	0%	0%
HTC	CTUh	2.4E-07	100%	0%	0%	0%	0%
HTNC	CTUh	8.7E-07	101%	0%	-1%	0%	0%
PM	kgPM2.5 eq	5.5E-03	100%	0%	0%	0%	0%
IR	kBq U235 eq	1.9E-01	100%	0%	0%	0%	0%
POF	kg NMVOC	1.3E-02	100%	0%	0%	0%	0%
TA	mol H+ eq	2.9E-02	100%	0%	0%	0%	0%
TE	mol N eq	7.0E-02	100%	0%	0%	0%	0%
FE	kg P eq	6.8E-04	100%	0%	0%	0%	0%
ME	kg N eq	4.9E-03	100%	0%	0%	0%	0%
ET	CTUe	1.6E+01	100%	0%	0%	0%	0%
RD fos	MJ	1.0E+02	99%	0%	1%	0%	0%
RD	kg Sb eq	2.2E-04	100%	0%	0%	0%	0%
Water	L	3.8E+01	100%	0%	0%	0%	0%

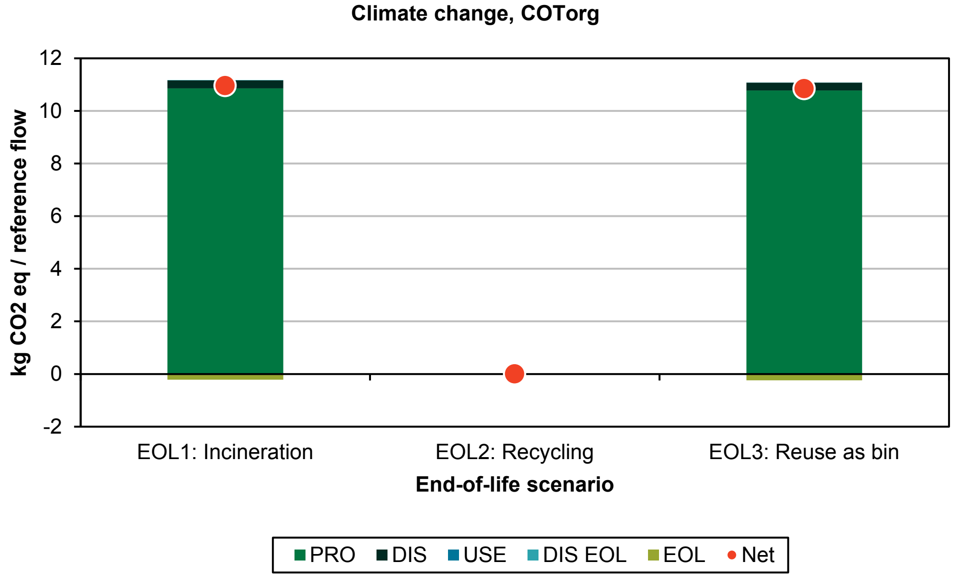


Figure 15. Characterized results for the climate change impact category and the three end-of-life options, expressed as kg CO_2 equivalents per reference flow, for the organic cotton carrier bag COTORG. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

Table 20. Contribution analysis for the production (PRO) processes, which included the manufacturing of the conventional cotton carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 conventional cotton bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials			
			Cotton production	Electricity	Heat	Management residues
CC	kg CO_2 eq	3.9E+00	99%	0%	1%	0%
OD	kg CFC11 eq	1.0E-05	100%	0%	0%	0%
HTC	CTUh	1.7E-07	100%	0%	0%	0%
HTNC	CTUh	6.2E-07	101%	0%	-1%	0%
PM	kgPM2.5 eq	3.9E-03	100%	0%	0%	0%
IR	kBq U235 eq	1.3E-01	101%	0%	-1%	0%
POF	kg NMVOC	8.9E-03	100%	0%	0%	0%
TA	mol H+ eq	2.1E-02	100%	0%	0%	0%
TE	mol N eq	5.0E-02	100%	0%	0%	0%
FE	kg P eq	4.8E-04	100%	0%	0%	0%
ME	kg N eq	3.5E-03	100%	0%	0%	0%
ET	CTUe	1.1E+01	100%	0%	0%	0%
RD fos	MJ	7.2E+01	99%	0%	1%	0%
RD	kg Sb eq	1.6E-04	100%	0%	0%	0%
Water	L	2.7E-01	100%	0%	0%	0%

Table 21. Contribution analysis for the production (PRO) processes, which included the manufacturing of the composite carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 composite bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials					
			Jute production	Cotton production	PP production	Electricity	Heat	Management residues
CC	kg CO_2 eq	1.7E+00	68%	27%	3%	0%	2%	0%
OD	kg CFC11 eq	1.2E-06	3%	97%	0%	0%	0%	0%
HTC	CTUh	4.3E-08	52%	48%	1%	0%	0%	0%
HTNC	CTUh	-1.2E-07	158%	-62%	0%	0%	4%	0%
PM	kgPM2.5 eq	3.0E-03	84%	16%	1%	0%	0%	0%

Table 21. (continued) Contribution analysis for the production (PRO) processes, which included the manufacturing of the composite carrier bag and the management of residues obtained during production. The Table presents the characterized result for each impact category, with the percent contribution given by the processes involved. Results provided for 1 composite bag.

Impact category	Unit	Result score (PRO)	Contributing processes: energy and ancillary materials					
			Jute production	Cotton production	PP production	Electricity	Heat	Management residues
IR	kBq U235 eq	3.6E-02	59%	44%	0%	0%	-3%	0%
POF	kg NMVOC	5.0E-03	74%	21%	5%	0%	0%	0%
TA	mol H+ eq	1.1E-02	77%	21%	2%	0%	0%	0%
TE	mol N eq	3.5E-02	82%	17%	1%	0%	0%	0%
FE	kg P eq	2.4E-04	76%	24%	1%	0%	-1%	0%
ME	kg N eq	2.6E-03	82%	16%	2%	0%	0%	0%
ET	CTUe	4.2E+00	67%	33%	1%	0%	0%	0%
RD fos	MJ	3.0E+01	62%	29%	7%	0%	3%	0%
RD	kg Sb eq	3.1E-05	39%	61%	0%	0%	0%	0%
Water	L	5.1E+00	39%	62%	0%	0%	-2%	0%

5.2 Overview

The aim of the following Figures 16 and 17 is to provide a comparison between the climate change results for the EOL1 disposal scenarios of all carrier bag alternatives. Cotton and composite bags were left out of Figure 16 in order to visualize the results for the remaining carrier bags, which would be out scaled otherwise, as shown in the following Figure 17.

The lowest climate change impacts were provided by LDPE carrier bags with rigid handle, paper bags and biopolymer bags, with slight differences in results. Heavier PP, PET, polyester and bleached paper carrier bags provided higher impact scores. The highest absolute impacts were scored by organic cotton bags, mostly for the environmental cost of the organic cotton production.

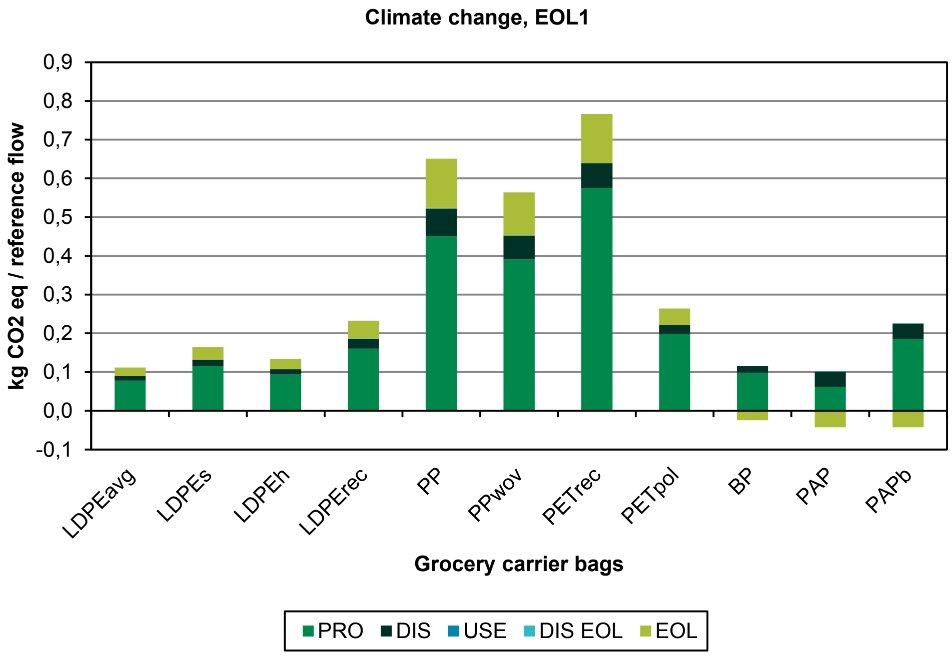


Figure 16. Characterized results for the climate change impact category, incineration end-of-life option (EOL1) expressed as kg CO_2 equivalents per reference flow, for the carrier bags LDPEavg, LDPEs, LDPEh, LDPErec, PP, PPwov, PETrec, PETpol, BP, PAP, PAPb. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result.

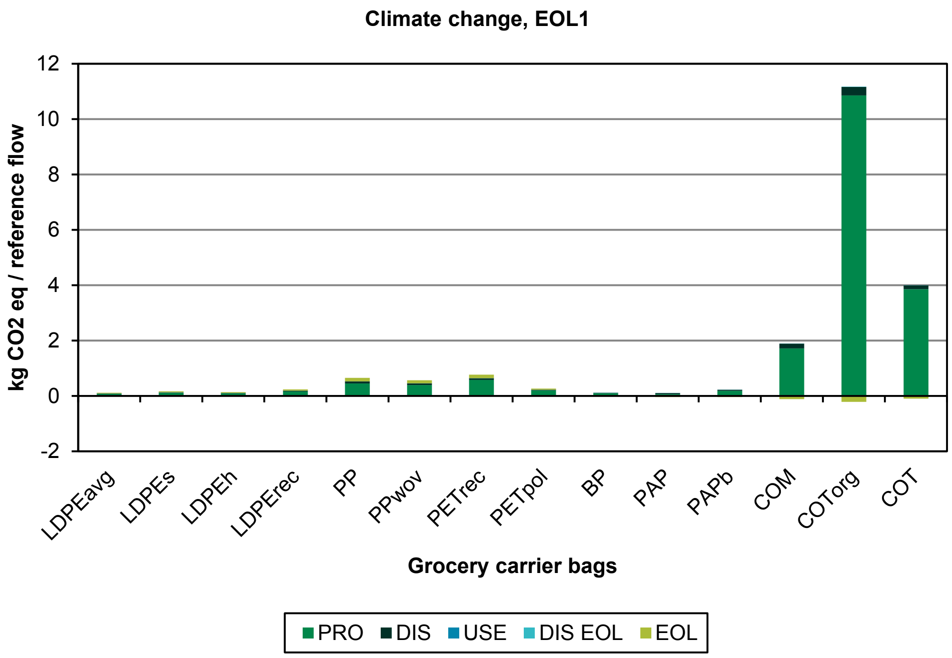


Figure 17. Characterized results for the climate change impact category, incineration end-of-life option (EOL1) expressed as kg CO_2 equivalents per reference flow, for the carrier bags LDPEavg, LDPEs, LDPEh, LDPErec, PP, PPwov, PETrec, PETpol, BP, PAP, PAPb, COM, COTorg, COT. PRO: production, DIS: distribution, USE: use; DIS EOL: end-of-life, packaging; EOL: end-of-life, carrier bag; NET: net result

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6. Discussion

6.1 Identification of the best disposal option for each carrier bag

Table 22 indicates, for each of the carrier bags in the rows, the disposal option providing the lowest environmental impacts, for each of the impact categories in the columns. In order to facilitate reading, incineration (EOL1) was associated with red colour, recycling (EOL2) was associated with light blue and secondary reuse as waste bin bag (EOL3) was assigned light green colour.

Overall, EOL3 is the disposal option that provided the lowest environmental impacts for most of the impact categories and carrier bag options. As observed in the contribution analysis for each of the carrier bags, this is due to the fact that reuse as waste bin bag before incineration allowed avoiding production and disposal of an LDPE carrier bag. The difference between EOL1 results and EOL3 results was larger (and EOL3 comparatively more beneficial) when the weight of the carrier bag was comparable to the weight of the LDPE waste bin bag, as in the case of LDPE carrier bags (LDPEs, LDPEh, LDPErec), biopolymer bags (BP) and paper bags (PAP, PAPb). For heavier carrier bags, and especially for the cotton (COTorg, COT) and the composite (COM) bags, the difference between EOL1 and EOL3 result was smaller. EOL3 thus resulted being the overall best disposal option, provided that the reused carrier bag can fulfil the waste bin bag function.

The results shown in the table also highlight that for heavier plastic carrier bags (PP, PPwov, PETrec) recycling (EOL2) resulted in being the most favourable disposal option in some impact categories, especially resource depletion and climate change. Therefore, collecting the waste bin bags within the recyclables waste stream might be a viable option for this type of carrier bags. The results for the ozone depletion, human toxicity, non-cancer effects and freshwater eutrophication impact categories showed a consistent preference for the EOL1 disposal scenario, due to the avoided environmental impacts connected to electricity and heat production that are avoided recovering energy within the incineration process.

Table 22. Disposal options providing the lowest environmental impacts for each of the carrier bags in the rows and each of the impact categories in the columns. The colour scale refers to the disposal option: red was assigned to incineration (EOL1), blue to recycling (EOL2), and green to secondary reuse as a waste bin bag (EOL3). Please refer to the abbreviations for the acronyms for carrier bags scenarios and impact categories.

Scenario name	CC	OD	HTC	HT NC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD	Water
LDPE avg	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
LDPE s	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1
LDPE h	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
LDPE rec	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
PP	EOL 2	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 2	EOL 3	EOL 3
PPwov	EOL 2	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 2	EOL 3	EOL 3
PETrec	EOL 2	EOL 1	EOL 2	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 2	EOL 3	EOL 3	EOL 3	EOL 2	EOL 2
PET-pol	EOL 3	EOL 1	EOL 2	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 2	EOL 3	EOL 3	EOL 3	EOL 2	EOL 2
BP	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
PAP	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
PAPb	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
CO-Torg	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
COT	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
COM	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3

6.2 Which carrier bag provides the lowest environmental impact to fulfil the function?

Table 23 provides the hierarchy of the characterized results between all carrier bags and disposal options. Each column provides the carrier bag and disposal option results, ordered from lowest impact to highest impact, for each of the impact categories indicated in the columns. The colour pattern was assigned in order to distinguish carrier bag types and to aid readability. Dark blue was assigned to LDPE, lighter blue to PP bags and so on.

For climate change, the carrier bags scoring the lowest climate change impacts were unbleached paper, biopolymer and LDPE carrier bags. Paper and biopolymer bags provided the lowest scores when reused as a waste bin bag. Whether it was reused or incinerated, paper provided a slightly better climate change performance than LDPE carrier bags. LDPE carrier bags provided a preferable performance than other carrier bags for climate change when they were reused, secondarily when they were recycled and thirdly incinerated. Heavier carrier bags provided the highest climate change impacts, with polyester, PP, recycled PET, composite and cotton providing increasingly higher climate change impacts. As observed in the contribution analysis, a similar pattern could be identified for the impact categories of human toxicity, cancer effects, and resource depletion, fossil. The lowest impacts for the remaining impact categories were provided by LDPE carrier bags. LDPEavg results represent an average LDPE carrier bag; between LDPE carrier bags LDPEh obtained the lowest impacts in most impact categories. The highest impacts in all impact categories were provided by organic cotton.

Overall, light carrier bags such as LDPE, paper and biopolymer were the carrier bag alternatives that provided the lowest environmental impacts in order to provide for the function expressed in the functional unit of this LCA. Heavier multiple-use carrier bags such as composite and cotton bags obtain the highest environmental impacts across all impact categories. For this reason, it is useful to determine the number of necessary reuse times to lower the environmental impacts related to their production to values comparable to lighter carrier bags.

Table 23. Hierarchy of the results obtained by each carrier bag alternative for each of the disposal options, subdivided by impact categories. The cells in the table represent the result scores, sorted from lowest (lowest environmental impacts per impact category, top) to highest (highest environmental impacts per impact category, bottom). The colour scale was assigned to facilitate distinguishing between carrier bag types.

CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD	Water
PAP EOL3	LDPE avg EOL1	PAP EOL3	COM EOL1	LDPE avg EOL3	LDPE avg EOL3	LDPEs EOL3	LDPE avg EOL2	LDPE avg EOL2	LDPE rec EOL1	PPwov EOL3	LDPE avg EOL3	PAP EOL3	PPwov EOL3	LDPEh EOL3
BP EOL3	LDPEh EOL1	LDPE avg EOL3	PP EOL1	LDPEh EOL3	LDPEh EOL3	LDPE rec EOL3	LDPEh EOL2	LDPEh EOL2	LDPEs EOL1	LDPE avg EOL3	LDPEh EOL3	LDPE avg EOL3	LDPE avg EOL3	BP EOL3
PAP EOL1	LDPE avg EOL3	PAPb EOL3	PPwov EOL1	LDPEs EOL3	LDPEs EOL3	LDPEh EOL3	LDPEs EOL2	LDPEs EOL2	LDPEh EOL1	LDPEh EOL3	LDPE avg EOL1	PAP EOL1	LDPE avg EOL1	LDPEs EOL3
LDPE avg EOL3	LDPEh EOL3	LDPE avg EOL2	LDPE rec EOL1	LDPE avg EOL1	LDPE avg EOL1	LDPE avg EOL3	LDPE rec EOL2	LDPE avg EOL1	LDPEs EOL3	PP EOL3	LDPEs EOL3	LDPE avg EOL2	LDPEh EOL3	LDPE avg EOL3
LDPE avg EOL2	LDPEs EOL1	LDPE avg EOL1	LDPEs EOL1	LDPEh EOL1	LDPEh EOL1	PAPb EOL3	PAPb EOL2	LDPEh EOL1	LDPE avg EOL1	LDPEs EOL3	LDPEh EOL1	LDPEh EOL3	PP EOL3	BP EOL1
BP EOL1	LDPEs EOL3	LDPEh EOL3	PETrec EOL1	LDPEs EOL1	LDPEs EOL1	PPwov EOL3	PPwov EOL2	LDPE rec EOL2	LDPE rec EOL3	LDPE rec EOL3	LDPE avg EOL2	LDPEs EOL3	PPwov EOL1	LDPE rec EOL3
LDPEh EOL3	LDPE rec EOL1	PAP EOL1	LDPEh EOL1	LDPE rec EOL3	LDPE rec EOL3	PP EOL3	LDPE avg EOL3	LDPEs EOL1	LDPEh EOL3	BP EOL3	PAPb EOL3	LDPEh EOL2	LDPE avg EOL2	LDPE avg EOL1
LDPEs EOL3	LDPE-rec EOL3	LDPEh EOL2	LDPE avg EOL1	LDPE avg EOL2	LDPE rec EOL1	PETpol EOL3	PETpol EOL2	PAP EOL2	LDPE avg EOL3	PAPb EOL3	BP EOL3	LDPE avg EOL1	LDPEh EOL1	LDPEh EOL1
LDPEh EOL2	LDPE avg EOL2	PAPb EOL1	PETpol EOL1	LDPE rec EOL1	LDPE avg EOL2	BP EOL3	PAP EOL2	PETpol EOL2	LDPE avg EOL2	PETpol EOL3	LDPEs EOL1	BP EOL3	LDPEs EOL3	LDPE rec EOL1
PAP EOL2	LDPEh EOL2	LDPEh EOL1	PAPb EOL1	LDPEh EOL2	LDPEh EOL2	PAP EOL3	PP EOL2	PAPb EOL2	LDPEh EOL2	PETrec EOL3	LDPEh EOL2	LDPEs EOL2	PP EOL1	LDPEs EOL1
LDPE avg EOL1	LDPEs EOL2	LDPEs EOL3	BP EOL1	LDPEs EOL2	LDPEs EOL2	PETrec EOL3	LDPEh EOL3	LDPE rec EOL1	LDPEs EOL2	LDPE avg EOL1	LDPE rec EOL3	LDPEh EOL1	LDPEh EOL2	LDPE avg EOL2
PAPb EOL3	LDPE rec EOL2	PAP EOL2	PAP EOL1	LDPE rec EOL2	PAPb EOL3	LDPE avg EOL1	LDPEs EOL3	PPwov EOL2	LDPE rec EOL2	LDPEh EOL1	PAPb EOL1	PAP EOL2	LDPEs EOL1	LDPE rec EOL2
LDPEs EOL2	PAP EOL1	PAPb EOL2	COT EOL1	PPwov EOL3	BP EOL3	LDPEh EOL1	LDPE rec EOL3	PP EOL2	PAPb EOL1	COM EOL3	BP EOL1	LDPE rec EOL3	LDPEs EOL2	LDPEh EOL2
LDPEh EOL1	PAP EOL3	LDPEs EOL2	COT org EOL1	PETpol EOL3	LDPE rec EOL2	COM EOL3	PETrec EOL2	PETrec EOL2	PAPb EOL3	LDPEs EOL1	LDPEs EOL2	LDPEs EOL1	LDPE rec EOL3	LDPEs EOL2
LDPE rec EOL3	BP EOL1	PPwov EOL3	LDPE avg EOL3	PPwov EOL1	PAPb EOL1	LDPEs EOL1	PETpol EOL3	PETpol EOL1	PAPb EOL2	PAP EOL3	PETpol EOL3	PAPb EOL3	PPwov EOL2	PAPb EOL3
LDPEs EOL1	BP EOL3	BP EOL3	LDPEh EOL3	PETpol EOL1	BP EOL1	PETpol EOL1	LDPE avg EOL1	PPwov EOL1	PPwov EOL1	LDPE rec EOL1	LDPE rec EOL1	LDPE rec EOL2	LDPE rec EOL1	PAPb EOL1
LDPE rec EOL2	PAP EOL2	LDPEs EOL1	LDPEs EOL3	PP EOL3	PETpol EOL3	BP EOL1	PAP EOL3	PP EOL1	PPwov EOL3	PETpol EOL1	PAP EOL3	BP EOL1	PP EOL2	PAP EOL3
PAPb EOL1	PETpol EOL1	PETpol EOL2	BP EOL3	BP EOL3	PETpol EOL1	PAP EOL1	LDPEh EOL1	PAP EOL1	PETpol EOL2	PAP EOL1	PETpol EOL1	PETpol EOL3	LDPE rec EOL2	PAP EOL1
PETpol EOL3	PETpol EOL3	PETpol EOL3	PAP EOL3	PP EOL1	PETpol EOL2	LDPE rec EOL1	PPwov EOL3	BP EOL1	PP EOL1	PPwov EOL1	PAPb EOL2	LDPE rec EOL1	BP EOL3	PETpol EOL2

Table 23. (continued) Hierarchy of the results obtained by each carrier bag alternative for each of the disposal options, subdivided by impact categories. The cells in the table represent the result scores, sorted from lowest (lowest environmental impacts per impact category, top) to highest (highest environmental impacts per impact category, bottom). The colour scale was assigned to facilitate distinguishing between carrier bag types.

CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD	Water
PETpol EOL2	PAPb EOL1	PPwov EOL1	PETpol EOL3	PETpol EOL2	PAPb EOL2	PAPb EOL1	PAPb EOL3	PAPb EOL1	PP EOL3	COT EOL3	LDPE rec EOL2	PETpol EOL2	PAPb EOL3	PETpol EOL3
PAPb EOL2	PAPb EOL3	BP EOL1	LDPE rec EOL3	BP EOL1	PAP EOL3	COT EOL3	LDPEs EOL1	PETrec EOL1	PETpol EOL1	PAPb EOL1	PPwov EOL3	PAPb EOL1	PAPb EOL2	PETpol EOL1
LDPE rec EOL1	PETpol EOL2	PP EOL3	PAPb EOL3	PAP EOL3	PAP EOL1	LDPE avg EOL2	PP EOL3	COM EOL1	PETpol EOL3	PP EOL1	PAP EOL1	PETpol EOL1	PAPb EOL1	PPwov EOL3
PETpol EOL1	PAPb EOL2	LDPE rec EOL3	LDPE avg EOL2	PAP EOL1	PPwov EOL3	LDPEh EOL2	PETrec EOL3	COT EOL1	PPwov EOL2	PETrec EOL1	PPwov EOL1	PAPb EOL2	BP EOL1	PPwov EOL1
PPwov EOL2	PPwov EOL1	PETpol EOL1	LDPEh EOL2	PPwov EOL2	PPwov EOL1	LDPEs EOL2	BP EOL3	LDPE avg EOL3	BP EOL1	BP EOL1	PP EOL3	PPwov EOL2	PETpol EOL2	PP EOL3
PPwov EOL3	PPwov EOL3	PP EOL1	PPwov EOL3	PP EOL2	PAP EOL2	PPwov EOL1	LDPE rec EOL1	LDPEh EOL3	BP EOL3	COT org EOL3	PAP EOL2	PPwov EOL3	PETpol EOL3	PP EOL1
PP EOL2	PP EOL1	LDPE rec EOL2	LDPEs EOL2	PAP EOL2	PP EOL3	PP EOL1	PETpol EOL1	LDPEs EOL3	PAP EOL1	COM EOL1	PP EOL1	PP EOL2	PETpol EOL1	PPwov EOL2
PPwov EOL1	PP EOL3	LDPE rec EOL1	PETrec EOL3	PETrec EOL3	PP EOL1	PETrec EOL1	PAP EOL1	PAPb EOL3	PAP EOL3	COT EOL1	PETpol EOL2	PPwov EOL1	PETrec EOL2	PP EOL2
PP EOL3	PETrec EOL1	PPwov EOL2	PP EOL3	PETrec EOL1	PPwov EOL2	LDPE rec EOL2	PPwov EOL1	BP EOL3	PAP EOL2	COT org EOL1	PPwov EOL2	PP EOL3	PETrec EOL3	PETrec EOL2
PP EOL1	PETrec EOL3	PP EOL2	LDPE rec EOL2	PAPb EOL3	PETrec EOL3	PAP EOL2	PP EOL1	LDPE rec EOL3	PP EOL2	PAP EOL2	PP EOL2	PP EOL1	PETrec EOL1	PETrec EOL3
PETrec EOL2	PPwov EOL2	PETrec EOL2	PAPb EOL2	PAPb EOL1	PETrec EOL1	COT org EOL3	PAPb EOL1	COT org EOL1	PETrec EOL2	LDPE avg EOL2	PETrec EOL3	PETrec EOL3	COM EOL3	PETrec EOL1
PETrec EOL3	PP EOL2	PETrec EOL3	PETpol EOL2	PETrec EOL2	PP EOL2	PETpol EOL2	BP EOL1	PETpol EOL3	PETrec EOL1	LDPEh EOL2	PETrec EOL1	PETrec EOL2	COM EOL1	PAPb EOL2
PETrec EOL1	PETrec EOL2	PETrec EOL1	COM EOL3	PAPb EOL2	PETrec EOL2	PAPb EOL2	PETrec EOL1	PAP EOL3	PETrec EOL3	LDPEs EOL2	PETrec EOL2	PETrec EOL1	PAP EOL3	PAP EOL2
COM EOL3	COM EOL1	COM EOL3	PAP EOL2	COM EOL3	COM EOL3	PPwov EOL2	COM EOL3	PPwov EOL3	COM EOL1	PAPb EOL2	COM EOL3	COM EOL3	PAP EOL2	COM EOL3
COM EOL1	COM EOL3	COM EOL1	PPwov EOL2	COM EOL1	COM EOL1	PP EOL2	COT EOL3	PP EOL3	COM EOL3	LDPE rec EOL2	COM EOL1	COM EOL1	PAP EOL1	COM EOL1
COT EOL3	COT EOL1	COT EOL3	PP EOL2	COT EOL3	COT EOL3	PETrec EOL2	COT org EOL3	PETrec EOL3	COT EOL1	PETpol EOL2	COT EOL3	COT EOL3	COT EOL3	COT EOL3
COT EOL1	COT EOL3	COT EOL1	COT EOL3	COT EOL1	COT EOL1	COM EOL1	COM EOL1	COM EOL3	COT EOL3	PPwov EOL2	COT EOL1	COT EOL1	COT EOL1	COT EOL1
COT org EOL3	COT org EOL1	COT org EOL3	PETrec EOL2	COTorg EOL3	COTorg EOL3	COT EOL1	COT EOL1	COT EOL3	COT org EOL1	PP EOL2	COT org EOL3	COT org EOL3	COT org EOL3	COT org EOL3
COT org EOL1	COT org EOL3	COT org EOL1	COT org EOL3	COT org EOL1	COT org EOL1	COT org EOL1	COT org EOL1	COT org EOL3	COT org EOL3	PETrec EOL2	COT org EOL1	COT org EOL1	COT org EOL1	COT org EOL1

6.3 How many times should a carrier bag be reused?

This Section provides the calculated number of primary reuse times for each carrier bag type, as indicated in Section 3. The number of reuse times provided in Table 24 indicates how many times the carrier bag alternatives in the rows should be reused in order to provide the same environmental performance of the reference LDPE carrier bag (LDPEavg), associated with EOL3 as a disposal option. The number of reuse times for each carrier bag alternative was calculated for each disposal option: EOL1, EOL2, and EOL3

The results are provided for the climate change impact category, as well as across impact categories. The result score across all impact categories was obtained by calculating the number of primary reuse times necessary for each impact category, and identifying the maximum score across all impact categories. This maximum score represents the maximum number of reuse times that would be required to obtain the same environmental performance of the reference LDPE carrier bag considering all impact categories. Results for each impact category, minimum-maximum ranges between number of reuse times and average number of reuse times are provided in Appendix C.

Zero values are shown where LDPEavg, EOL3 is compared to itself. Values lower than zero corresponds to carrier bag options that already provide a better environmental performance than the carrier bag option to which they are compared. Values higher than zero indicate how many times the corresponding carrier bags in the rows should be reused before being disposed of (with its corresponding end-of-life scenario) in order to provide the environmental performance of LDPEavg, EOL3.

Table 24. Calculated number of primary reuse times for the carrier bags in the rows, associated with the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3). Results are provided for the climate change impact category and across impact categories. Yellow cells highlight the most preferable disposal option. Results for COTorg, COT and COM have been rounded.

	LDPEavg, EOL3					
	Climate change			**All impact categories**		
	EOL1	EOL2	EOL3	EOL1	EOL2	EOL3
LDPEavg	0.5	0.1	0.0	1.2	5.0	0.0
LDPEs	1.3	0.7	0.3	2.3	7.8	0.5
LDPEh	0.9	0.4	0.3	1.7	6.1	0.3
LDPErec	2.2	1.4	1.2	3.4	11.7	1.6
PP	8.0	6.0	7.3	38	52	37
PPwov	6.8	5.0	5.9	33	45	32
PETrec	9.6	8.2	8.6	95	84	96
PETpol	2.6	1.9	1.9	35	28	35
BP	0.2	-	-0.8	41	-	42
PAP	-0.2	0.5	-1.3	42	77	43
PAPB	1.5	2.2	0.6	30	72	43
COTorg	150	-	149	20000	-	20000
COT	53	-	52	7100	-	7100
COM	23	-	23	870	-	870

For climate change, the LDPE carrier bag alternatives LDPEs, LDPEh, LDPErec provided a comparable performance to the average LDPE carrier bag, with lower number of reuse times obtained for the EOL3 disposal options. The results indicate that LDPEh is the carrier bag providing the best climate change performance, since this carrier bag type is associated to the lowest number of reuse times for all end-of-life options. In general, LDPE carrier bags should be reused at least one time before being used as a waste bin bag.

Heavier fossil-carbon based bags provided the lowest number of reuse times for the EOL2 disposal options. The results indicate that these types of carrier bags should be reused 5 – 10 times before being disposed, with exception for the polyester bag, whose preferable disposal option was EOL3 and which scored a needed reuse of 2 times.

Unbleached paper and biopolymer bags scored negative values, indicating that the climate change impact associated with these bags is already lower than the climate change impact associated with the average LDPE carrier bag. The negative value indicates that for these types of carrier bags, reuse before disposal would not even be necessary to provide a better climate change result. Moreover, the results indicate that paper and biopolymer are a better option than LDPE with respect to climate change impacts. Bleached paper should be reused for 2 times, due to the higher environmental costs related to its production.

The absolute highest number of reuse times for the climate change impact category was obtained for composite and cotton carrier bags. In particular, conventional cotton carrier bags should be reused at least 50 times before being disposed of; organic cotton carrier bags should be reused 150 times based on their environmental production cost. This calculated number of primary reuse times for cotton bags complies with results of previous studies. For example, Edwards and Fry (2011) calculated a number of around 130 reuse times required for cotton carrier bags to provide similar climate change impacts in comparison to HDPE carrier bags, which were chosen as reference in that study.

When all impact categories were taken into consideration, Table 24 provides the highest number of reuse times across all the considered environmental indicators. The results for each impact category are available in Appendix C. LDPE carrier bags provided the absolute best environmental performance. With reuse as waste bin bag as the considered as disposal option, it suffices to reuse LDPE carrier bags one time before reusing them as waste bin bag. Heavier PP carrier bags and polyester bags would need to be reused 30 – 40 times. Paper and biopolymer carrier bags should be reused up to 40 times in order to provide for a similar environmental performance, mostly due to the impacts in the freshwater eutrophication impact category. In a number of categories bleached paper was found to have a lower impact than unbleached paper. The reason for this difference was found to be due to a lower data quality for bleached paper that did not include as detailed a dataset. Since the difference in production of bleached versus unbleached kraft paper is only the bleaching step, we did not find it realistic that unbleached paper could have higher impacts. For these categories we therefore assume that the bleached number must be the same or higher than the unbleached number. In order to provide a comparable performance to LDPE in all impact categories, the number of reuse times for cotton and composite bags increased to thousands of times.

For LDPE carrier bags, the number of reuse times was rather uniform across impact categories. For PP and PET bags, some impact categories presented higher reuse times than others, especially ozone depletion, terrestrial eutrophication, freshwater eutrophication and water use. For these indicators, the results of PP and PET carrier bags were considerably higher (such as one order of magnitude) than the results obtained by the LDPE carrier bag. This occurred because for PP and PET carrier bags the higher environmental cost of production is not compensated by the energy or material recovered – while for the lighter LDPE carrier bag the environmental production costs are lower. The same observations can be made for BP and

PAP carrier bags, which obtained considerably higher numbers of reuse times for terrestrial and freshwater eutrophication impact categories. Lastly, the high number of reuse times scored by cotton and composite bags is due only to the ozone depletion impact category, where cotton production provides considerably large impacts.

It is important to remark that, even if LDPE scored a low (to zero) number of reuse times, this is due to the fact that it was compared to a reference LDPE carrier bag. Reuse of each type of carrier bags, even LDPE, should be carried out as many times as possible before disposal. In the case of heavier carrier bags, customers of Danish supermarkets should be informed on the optimal number of reuse times of multiple-use carrier bags offered as alternatives for the LDPE carrier.

Finally, it is important to consider that the avoided reference bag can in practice also be reused, and if this is the case then the reuse number calculated above would proportionally be as many times higher as it was reused. The resulting reuse numbers calculated in this study should therefore be seen as a minimum reuse number that could be higher.

All results presented above are linked to specific types of bags used on the market today. If the bags were designed differently with larger volume to carrying weight ratio, from recycled material instead of primary material where only one type material is presented, or some other type of improvement the results would come out better than the standard version of the same bag.

This study focused on identifying the number of reuse times based on the environmental performance of the carrier bags, rather than considering the actual realistic lifetime for different bag types considering their material type, production, and functionality. The results obtained on the minimum number of reuse times are intended to raise the discussion among the stakeholders on the effective expected lifetime of each carrier bag. While the calculated number of reuse times might be compliant with the functional lifetime of PP, PET and polyester carrier bags, it might surpass the lifetime of bleached paper, composite and cotton carriers, especially considering all environmental indicators.

6.4 Influence on data and assumptions on the results

Data availability was found to be rather low. The number of reviewed LCA reports and data available in the literature was limited. In particular, data on the manufacturing part for the carrier bags (energy and ancillary materials requirements) was rather scarce in the majority of the LCA reports consulted for this project. As far as the production of the main material of the carrier bags is concerned, more datasets were available for LDPE, and fewer datasets were available for other plastic types, such as PP, polyester, biopolymers and textiles. This did not allow as much preliminary testing on the datasets employed as it was possible for virgin LDPE. Higher data quality and availability would allow LCA practitioners to explore better alternative materials for the production of carrier bags, especially data on recycled polymers and their performance during manufacture and recycling.

The physico-chemical material composition used for modelling input-specific emissions in the EASETECH LCA model allowed retrieving generic impacts for material groups, such as plastic, paper, textile. The emissions mostly contributed to impacts to atmosphere via the incineration process, especially for plastic carrier bags.

Regarding the carrier bag manufacturing process, we observed that most of the production impacts were ascribable to the production of the carrier bag material (Tables 13 – 21). The material production process contributed less only in the LDPE and PP carrier bags manufacturing, but described most of the impacts from the manufacturing phase for most of the remaining carrier bags, as observed in previous LCA studies. Carrying out a streamlined LCA

considering only the production of the carrier bags' main material would have underestimated the impacts for LDPE and PP. However, even if for LDPE carrier bags most of the production emissions arise from manufacturing phase (energy and ancillary material requirements), these carrier bags are still providing the overall best environmental performance. In general, manufacturing data quality was mostly sensitive when bags were composed of light material or material with low associated impacts.
For the modelling of the virgin LDPE waste bin bag we employed a dataset representing lower quality LDPE than the one used for modelling LDPE carrier bags. The use of this dataset resulted in lower savings from avoiding production and disposal of a waste bin bag. If we had modelled the waste bin bag as the LDPE carrier bags, savings from replacing a waste bin bag would have been even higher. Still, even using a conservative assumption for the production data of the waste bin bag, reuse as waste bin bag was one of the most preferable end-of-life options, especially for low weight and non-fossil carbon carrier bags (LDPE, paper, biopolymer). If the waste bin bag was made of recycled polymer material, we expect that the impacts connected to its production would have been slightly lower. In this case, the carrier bag scenarios that would be mostly affected would be the ones associated with the lightest carrier bag weight: LDPE, paper, biopolymer. These carrier bags would present slightly lower benefits from EOL3, but still result among the carrier bags with the overall lowest associated impacts for EOL1.

The large transportation distances were considered conservative. Although distribution did not largely contribute to the impacts, knowing the exact location of the facilities, especially the recycling facilities assumed to be in Europe, would probably lower the impacts connected to transportation. Lower transportation distances are especially expected to slightly reduce the impacts of the EOL2 scenarios.

We did not find any available specific end-of-life data for recycled polymers, therefore we could not apply specific higher losses during material production and recovery. If higher losses would occur during manufacturing and recovery, there would be higher impacts related to the production of the carrier bag with recycled material, as well as lower revenues from the recycling process. This would affect the result for EOL2 as preferable waste management option for PETrec.

Regarding the critical assumptions highlighted in Section 3, rounding to two bags when the functionality expressed in the functional unit was not provided resulted in larger impacts for bags that did not comply with the functional unit. In particular, the organic cotton bag provided considerably high impacts.

Moreover, using virgin LDPE to model recycled LDPE resulted in higher impacts from the production phase of the LDPErec carrier bag, but also to higher revenues from recycling. Indeed, the recycled material is going to substitute production of virgin material instead of recycled polymer.

The assumption of lower yield used to model the production of organic cotton increased the impacts connected to its production, as can be seen from the contribution analyses in Table 19 and 20. However, the use of two bags in order to comply for the functional unit for organic cotton bags influenced the results to a larger extent. For example, comparing the climate change score for one organic cotton bag (5.4 kg CO2-eq/bag, Table 19) and for one conventional cotton bag (3.9 kg CO2-eq/bag, Table 20), we obtain the following:

$$\frac{(5.4-3.9)}{3.9}\cdot 100 = 38\%$$

$$\frac{((5.4 \cdot 2) - 3.9)}{3.9} \cdot 100 = 177\%$$

Where 38 % represents the increase in climate change impact with respect to conventional cotton by using a lower yield for organic cotton, and 177 % represents the Increase in climate change impact with respect to conventional cotton by using 2 bags for organic cotton. 38 % is higher than the assumed yield (-30 %) because organic cotton bags presented a slightly larger weight with respect to conventional cotton bags.

If we had included the additional data on the conventional cotton bag pointed out by the project partners after the first iteration of the report (please see Section 2), the average weight associated to the conventional cotton bag would have lowered to 194.6 grams from the initial 232 grams (see Table 2), and the volume would have been 28.3 litres. The number of bags required to fulfil the functional unit would have still been 1, but the lower weight would have lowered the impacts (for example, we calculated 16 % lower impacts for climate change) and lowered the number of reuse times by roughly 10 times. These considerations about volume of the organic cotton bag and the weight of the conventional cotton bag will be expanded further in a dedicated part about design considerations (please see Section 7).

As far as the choice for the marginal energy technologies is concerned, using a non-future marginal energy would have entailed having coal in the energy mix, and would have provided higher savings from energy recovery in the incineration process, especially for climate change.

Considering recycling feasible for biopolymer and textile carrier bags would mean allowing for the recovery of these materials through separate collection and re-processing, therefore ultimately lowering the impacts connected to the production of the carrier bags. However, specific attention should be required to the substituted materials from such recovery processes, especially for cotton, which is unlikely to substitute production of primary cotton.

Lastly, in case the carrier bags cannot fulfil the functionality of waste bin bags, EOL3 should not be considered as a viable option.

The choice of reference flow, the use of virgin LDPE data for LDPErec and reuse as waste bin bag only for LDPE carrier bags were tested in a sensitivity analysis, which is provided in Section 7.

7. Sensitivity analysis: critical assumptions

This Section evaluates whether and in what measure a selection of the modelling choices and critical assumptions identified in the LCA methodology Section (Section 3) influence the results. The results for the most preferable disposal option and carrier bag, as well as number of primary reuse times, were re-calculated according to alternative modelling choices.

7.1 Choice of reference flow: rounding

The choice of calculating the reference flow by rounding to two carrier bags when one was not sufficient to comply with the functional unit was tested by calculating the required number of bags with fractions. This sensitivity analysis is based on the fact that the rounding to two bags might provide a large overcapacity with respect to the functional unit. We also wanted to test the effect on the results on “optimizing” the carrying capacity of the bags instead of just assuming that another bag of the same type would be bought by the customers.

The reference flow of this sensitivity analysis step was re-calculated for the bags that did not comply with the functional unit and that required two bags (as shown in Table 3): LDPEs, LDPErec, BP, PAP, PAPb and COTorg. The number of substituted waste bin bags was re-calculated as well (Table 25). The effect of using fractions instead of rounding to another bag has also lowered the number of substituted waste bin bags for the corresponding carrier bags. For the bags that could provide more volume and weight holding capacity than the average LDPE carrier bag (for example woven PP and conventional cotton) one bag was considered instead of the fraction, and the number of substituted waste bin bags was left unchanged.

The reference flow change did not influence the preferred disposal option for each carrier bag. The hierarchy of the most preferable carrier bag option for each impact category changed only slightly. Paper obtained comparatively better results in human toxicity, cancer effects, and in resource depletion, fossil, than in the present study, due to the lower environmental costs related to the production of the carrier bag. The emissions related to production were larger when the number of bags per reference flow was rounded to two. In general, LDPE carrier bags still resulted as the carrier alternative providing the overall best performance in the highest number of impact categories, with LDPEs now providing the overall best performance within virgin LDPE carrier bags.

The reference flow change for some of the carrier bags mostly influenced their calculated number of reuse times. Table 26 shows that LDPEs and COTorg were the carrier bags that considerably lowered the number of reuse times. In particular, when the reference flow was not rounded, organic cotton presented less than half of the calculated number of reuse times than what previously calculated, both for climate change and for all impact categories. The results highlight the importance of the design of the bags, which is going to be discussed further in a dedicated paragraph.

LDPEs, BP and PAP provided a negative number of reuse times, which signifies that these carrier bag types provided a better environmental performance for climate change than the average LDPE carrier bag. Across all impact categories, LDPE carrier bags provided a similar performance, while heavier fossil carbon-based carrier bags, paper and biopolymer, presented a generally higher number of calculated reuse times. Calculated number of reuse times for BP and PAP was halved when considered across all impact categories.

Table 25. Reference flow and number of substituted bin bags used for the scenario analysis.

Scenario name	Volume enough?	Weight holding Capacity enough?	Reference flow calculation	Reference flow (number of bags needed)	Number of sub-stituted bin bags
LDPEavg	Yes	Yes	Not changed	1.0	1.0
LDPEs	No	No	$Max\left(\frac{Volume\ LDPEavg}{Volume\ LDPEs}, \frac{Weight\ hold.LDPEavg}{Weight\ hold.LDPEs}\right)$	1.2	1.0
LDPEh	Yes	Yes	Not changed	1.0	1.1
LDPErec	No	No	$Max\left(\frac{Volume\ LDPEavg}{Volume\ LDPErec}, \frac{Weight\ hold.LDPEavg}{Weight\ hold.LDPErec}\right)$	1.1	1.1
PP	Yes	Yes	Not changed	1.0	1.3
PPwov	Yes	Yes	Not changed	1.0	1.6
PETrec	Yes	Yes	Not changed	1.0	1.9
PETpol	Yes	Yes	Not changed	1.0	1.4
BP	No	No*	$Max\left(\frac{Volume\ LDPEavg}{Volume\ LDPErec}, \frac{Weight\ hold.LDPEavg}{Weight\ hold.LDPErec}\right)$	1.0	1.0
PAP	Yes	No*	$\frac{Weight\ hold.LDPEavg}{Weight\ hold.PAP}$	1.0	1.0
PAPb	Yes	No*	$\frac{Weight\ hold.LDPEavg}{Weight\ hold.PAPb}$	1.0	1.0
COTorg	No	Yes	$\frac{Volume\ LDPEavg}{Volume\ COTorg}$	1.1	1.0
COT	Yes	Yes	Not changed	1.0	1.2
COM	Yes	Yes	Not changed	1.0	1.4

* In this sensitivity analysis the weight holding capacity of 12.0 kg of paper and biopolymer bags was considered effective.

Table 26. Calculated number of primary reuse times for each carrier bag in the rows in comparison to LDPEavg, EOL3, for the reference flow in Table 25. Results are provided for the climate change impact category and across impact categories. Results for COTorg, COT and COM have been rounded. Results in brackets report the previously calculated results in Table 24 for the carrier bags with a changed reference flow.

	LDPEavg, EOL3					
	Climate change			**All impact categories**		
	EOL1	EOL2	EOL3	EOL1	EOL2	EOL3
LDPEs	0.3 (0.5)	0.0 (0.1)	-0.2 (0.00)	0.9 (1.2)	4.1 (5.0)	0.2 (0.0)
LDPEh	0.9	0.4	0.3	1.7	6.1	0.3
LDPErec	0.8 (2.2)	0.3 (1.4)	0.2 (1.2)	1.7 (1.7)	6.2 (6.1)	0.5 (0.3)
PP	8.0	6.0	7.3	38	52	37
PPwov	6.8	5.0	5.9	33	45	32
PETrec	9.6	8.2	8.6	95	84	96
PETpol	2.6	1.9	1.9	35	28	35
BP	-0.4 (0.2)	-	-0.9 (-0.8)	21 (41)	-	22 (42)
PAP	-0.6 (-0.2)	-0.3 (0.5)	-1.1 (-1.3)	22 (42)	38	22 (43)
PAPb[8]	0.3	0.6	-0.2	22 (42)	38	22 (43)
COTorg	84 (150)	-	83 (149)	10000 (20000)	-	10000 (20000)
COT	53	-	52	7100	-	7100

[8] The highest value for bleached paper was increased to be equal to the value for unbleached paper

COM	23	-	23	870	-	870

7.2 Secondary reuse as a waste bin bag allowed only for LDPE carriers

In this Section, results are presented considering that secondary reuse as a waste bin bag (EOL3) could be possible only for LDPE carrier bags. This modelling choice would represent the choice of allowing secondary reuse as a waste bin bag only for the carrier bags that can fully provide for the same functionality. The results for the best disposal option for each carrier bag are provided in Table 26. As previously discussed, reuse as waste bin bag before being incinerated is the best disposal option for LDPE carrier bags. For heavier plastic bags recycling resulted often one of the best options, provided that the carrier bags can be effectively recycled. For the remaining bags, incineration was the disposal option that provided the lowest environmental impacts.

As far as the hierarchy of results is concerned, the carrier bags providing the lowest impacts have only slightly changed. Incineration of paper and biopolymer carrier bags and secondary reuse of the LDPE carrier bags still provided the lowest climate change environmental impacts. For the other impact categories, LDPE carrier bags represented the alternative with the overall lowest environmental impacts, as already observed. The results indicate that allowing secondary reuse as waste bin bag only for LDPE carrier bag provides little influence on the hierarchy of the most favourable carrier bag alternative for each impact category. For the number of reuse times, if EOL3 is not allowed for all carrier bag alternatives other than LDPE carrier bags, non-LDPE carrier bags have to be reused in average at least one additional time before being incinerated. The results correspond to Table 24 presented previously, without considering the EOL3 column for the non-LDPE carrier bags.

Table 26. Disposal options providing the lowest environmental impacts for each of the carrier bags in the rows and each of the impact categories in the columns. The colour scale refers to the disposal option: red was assigned to incineration (EOL1), blue to recycling (EOL2), and green to secondary reuse as a waste bin bag (EOL3). EOL3 was considered possible only for LDPE carrier bags.

Scenario name	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD	Water
LDPEavg	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
LDPEs	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1
LDPEh	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
LDPErec	EOL 3	EOL 1	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3	EOL 1	EOL 3	EOL 3	EOL 3	EOL 3	EOL 3
PP	EOL 2	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 2	EOL 1	EOL 1
PPwov	EOL 2	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 2	EOL 1	EOL 1
PETrec	EOL 2	EOL 1	EOL 2	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 2	EOL 1	EOL 1	EOL 2	EOL 2	EOL 2
PETpol	EOL 2	EOL 1	EOL 2	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 2	EOL 1	EOL 1	EOL 2	EOL 2	EOL 2
BP	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1
PAP	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 2	EOL 1
PAPb	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 2	EOL 1
COM	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1
COTorg	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1
COT	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1	EOL 1

7.3 Recycled LDPE

Since the dataset for recycled LDPE was missing in the Ecoinvent database, the recycled LDPE carrier bag was modelled modifying the virgin LDPE production dataset. As shown in Appendix B, for PET the recycled inventory dataset presents lower emissions than the virgin inventory dataset for all impact categories. In this sensitivity analysis, the virgin LDPE production inventory of emissions used for the recycled LDPE carrier bag was lowered by 25 %. This signified that the environmental costs for the production of LDPE were lowered by the same extent for all environmental indicators, as well as the benefits from the recycling of recycled LDPE.

The results obtained by the recycled LDPE carrier bags lowered for all impact categories, as shown in Table 27 below. Table 27 provides the percent variation of the newly tested LDPErec scenario with the results presented in Tables (10 – 12). Climate change results lowered by 12 % for EOL1, by 18 % for EOL2, and by 8 % for EOL3. For human toxicity, cancer effects (HTNC), and freshwater eutrophication (FE), the Table shows positive percent variation because the original result scores were already negative numbers. The highest variations occurred for human toxicity, cancer effects, particulate matter (PM), photochemical ozone formation (POF), terrestrial acidification (TA), terrestrial eutrophication (TE) and marine eutrophication (ME).

The preferred management option for LDPErec, which was mostly EOL3 for the different impact categories, did not change. The hierarchy of the carrier bags providing the lowest performance for each environmental indicator changed for the impact categories of particulate matter, photochemical ozone formation, terrestrial and freshwater eutrophication, where LDPErec provided the best performance. The results for the remaining impact categories did not change: virgin LDPE provided the overall best performance, along with paper and biopolymer for the climate change impact category.

The number of reuse times was recalculated as well and it is presented in Table 28. Considering the end-of-life scenario where LDPErec provides the best performance, which is EOL3, The number of reuse times lowered only slightly: by 0.4 for the climate change impact category, and by 0.5 across all impact categories. The results are more comparable to those obtained for virgin LDPE carrier bags in Table 24, but are still larger because of the two bags required in order to provide for the functionality expressed in the functional unit.

Table 27. Percent variation from the LDPErec scenario results presented in Tables 10 – 12 obtained by lowering the virgin LDPE material production impacts by 25 %.

	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RDfos	RD	Water
EOL1	-12%	-7%	-10%	2%	-42%	-4%	-31%	-53%	-116%	8%	-43%	-12%	-26%	-1%	-1%
EOL2	-8%	-1%	-5%	45%	-11%	-2%	-17%	-18%	-20%	-3%	-16%	-5%	-16%	-1%	-1%
EOL3	-18%	-6%	-12%	2%	-64%	-6%	-47%	-76%	-194%	12%	-61%	-17%	-39%	-1%	-2%

Table 28. Calculated number of primary reuse times for LDPErec carrier bag in the rows in comparison to LDPEavg, EOL3, for the reference flow in Table 3. Results are provided for the climate change impact category and across impact categories. The inventory dataset for the production of virgin LDPE was lowered by 25 %. Numbers in brackets are the previous results for LDPErec reported in Table 24.

<table>
<tr><th></th><th colspan="6">LDPEavg, EOL3</th></tr>
<tr><th></th><th colspan="3">Climate change</th><th colspan="3">All impact categories</th></tr>
<tr><th></th><th>EOL1</th><th>EOL2</th><th>EOL3</th><th>EOL1</th><th>EOL2</th><th>EOL3</th></tr>
<tr><td>LDPErec</td><td>1.8 (2.2)</td><td>1.2 (1.4)</td><td>0.8 (1.2)</td><td>2.0 (3.4)</td><td>9.1 (11.7)</td><td>1.1 (1.6)</td></tr>
</table>

7.4 Final remarks on sensitivity analysis

The tested methodological assumptions allowed for understanding of the robustness of the results obtained with respect to critical assumptions taken for this LCA study. Table 29 summarizes the results of the sensitivity analysis on the assumptions.

The assumptions tested modified the best end-of-life option for each of the carrier bags assessed only when reuse as waste bin bag was not allowed for non-LDPE carriers. In general, after reusing as many times as possible the carrier bag, it could be reused as waste bin bag before being incinerated when possible. For paper and biopolymer bags, this can occur with limited waste weight and by avoiding wet waste and sharp edges. For heavier carriers, such as PP, PET and polyester, recycling may be an option, but providing benefits only in a limited number of impact categories.

The hierarchy of the carrier bags providing the best disposal for each of the impact categories considered, varied for some impact categories when lower impacts were associated to recycled LDPE production. Overall, the hierarchy did not change with respect to the general conclusions observed in the discussion section: light carrier bags, such as LDPE, paper and biopolymer, are the carrier bags providing the lowest impacts across the impact categories assessed.

Lastly, the number of reuse times considerably changed when the reference flow was changed, but mostly for the organic cotton bag. For this carrier bag type, rounding to two carrier bags when the volume of one bag was not enough considerably influenced the results. Considering a fraction of the reference flow (1.1) instead of rounding, required 45 % less cotton to be produced; this considerably lowered the impacts connected to cotton production. As already observed in the discussion of the results, it is important to notice that the difference connected to the reference flow choice is larger than the assumption on the organic cotton yield presented in the assumptions section. The calculated number of reuse times for the organic cotton bag is however still very high.

Table 29. Overview of the changes in the results induced by changes in the assumptions for the reference flow, allowed secondary reuse and different calculation method for the reuse times.

Tested assumption	Induced change		
	Best end-of-life option for each carrier bag	Hierarchy of carrier bags for each impact category	Calculate number of primary reuse times
Reference flow	Not changed	Not changed	Yes, especially for organic cotton: number of reuse times reduced by half
EOL3 not allowed for non-LDPE carriers	Yes, EOL1 instead of EOL3	Not changed	+1 (average)
LDPErec modelled by lowering LDPE production impacts by 25%	Not changed	LDPErec best option for PM, POF, TE, FE	-1 for LDPErec

7.4.1 Carrier bag design

The results of the sensitivity analysis suggest that for the carrier bags with the highest weight and with the highest impacts connected to production, the ability to provide for the functionality expressed in the functional unit is essential. In particular, if Danish retailers want to provide a multiple-use carrier bag alternative to LDPE carrier bags that is made of cotton or textile-based composite materials, their attention should be placed on the weight of the bag and on its volume. The textile bag should preferably be of light weight and with enough volume to provide for the same capacity of LDPE carrier bags. The example provided in the discussion of the results showed that using a conventional cotton bag of a lower weight had lowered the number of reuse times by 10 units.

All the multiple use bags (PP, PET, Cotton etc.) could carry significantly more weight than the reference flow, but varied highly in volume. This indicates that it is possible to design bags that can be high in both volume and weight. For some consumers the weight could be the limiting factor, but for other consumers it could for some bags mean that weight holding capacity would be the limiting factor. No matter the consumer preference, there is not a rational for not optimizing the volume per material weight.

As far as the carrier bag material is concerned, organic cotton provides environmentally preferable production conditions by avoiding the use of fertilizers and pesticides, but with a lower yield. The lower production yield translates in overall higher environmental impacts connected to its production, and to a higher required number of reuse times in order to “amortize” its environmental production costs.

Regarding the material of the carrier bags, one more observation could be raised for the use of recycled polymers for the manufacturing of the carrier bags. If all the LDPE carrier bags had the same volume capacity, weight holding capacity and thickness (and weight of the carrier bag), the dataset for the production of recycled LDPE was available, the recycled LDPE would result as the best option. This would be especially true for EOL3, since the recycled LDPE would be substituting a virgin LDPE waste bin bag.

However, the virgin and recycled LDPE carrier bags examined for this LCA study had different volume and weight holding capacities. In order for the recycled LDPE carrier bag to carry the same volume as the virgin LDPE carrier bags, more than one bag would be required. This increased the environmental impacts associated with the recycled LDPE carrier bag, and this was the reason why it does not result as the best option between the carrier bags examined.

Indeed, the results for LDPErec were more influenced by the sensitivity analysis on the reference flow than the sensitivity analysis on the production data.
Lastly, it would be useful for customers to be reminded of the indicative number of reuse times obtained by this report by adding this information on the multiple-use carrier bag, for example “reuse me at least 10 times”, and together with a suggested end-of-life option “reuse me as waste bin bag”, for example.

8. Conclusions

This study identified the best disposal option for each of the carrier bags available in Danish supermarkets in 2017. In general, reusing the carrier bag as a waste bin bag is better than simply throwing away the bag in the residual waste and it is better than recycling. Recycling can potentially offer more benefits in the case of heavy plastic bags, such as PP, and PET. Reuse as a waste bin bag is most beneficial for light carrier bags, such as LDPE, paper and biopolymer. When reuse as a waste bin bag is not feasible, for example when the bag can easily be punctured, torn, or wetted, incineration is the most preferable solution from an environmental point of view.

In general, LDPE carrier bags, which are the bags that are always available for purchase in Danish supermarkets, are the carriers providing the overall lowest environmental impacts when not considering reuse. In particular, between the types of available carrier bags, LDPE carrier bags with rigid handle are the most preferable. Effects of littering for this type of bag were considered negligible for Denmark. Carrier bags alternatives that can provide a similar performance are unbleached paper and biopolymer bags, but for a lower number of environmental indicators. Heavier carrier bags, such as PP, PET, polyester, bleached paper and textile bags need to be reused multiple times in order to lower their environmental production cost. Between the same bag types, woven PP carrier bags provided lower impacts than non-woven PP bags, unbleached paper resulted more preferable than bleached paper, and conventional cotton over organic cotton.

For all carrier bags, reuse as many times as possible before disposal is strongly encouraged. This study also calculated how many times each bag would need to be reused in order to lower its associated environmental impacts to the levels of the LDPE carrier bag. The number of calculated reuse times varies if only one environmental indicator is observed, or if all environmental indicators are taken into account.

The results are the following[9]:

- **Simple LDPE bags**: Can be directly reused as waste bin bags for climate change, should be reused at least 1 time for grocery shopping considering all other indicators; finally reuse as waste bin bag.
- **LDPE bags with rigid handle**: Can be directly reused as waste bin bags considering all indicators; finally reuse as waste bin bag.
- **Recycled LDPE bags**: Reuse for grocery shopping at least 1 time for climate change, at least 2 times considering all indicators; finally reuse as waste bin bag.
- **PP bags, non-woven**: Reuse for grocery shopping at least 6 times for climate change, and up to 52 times considering all indicators; finally dispose with recyclables, otherwise reuse as waste bin bag if possible, lastly incinerate.

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[9] The number of times for “all indicators” refers to the highest number of reuse times among those calculated for each impact category. For light carrier bags (LDPE, PP, PET...) the high numbers of reuse times are given by a group of impact categories with similar high values. Conversely, for composite and cotton the very high number of reuse times is given by the ozone depletion impact alone. Without considering ozone depletion, the number of reuse times ranges from 50 to1400 for conventional cotton, from 150 to 3800 for organic cotton, and from 0 to 740 for the composite material bag. The highest number is due to the use of water resource, but also to freshwater and terrestrial eutrophication. Results for the number of reuse times for each impact category, minimum-maximum ranges and average number of reuse times are provided in Appendix C.

- **PP bags, woven**: Reuse for grocery shopping at least 5 times for climate change, at least 45 times considering all indicators; finally dispose with recyclables, otherwise reuse as waste bin bag if possible, lastly incinerate.
- **PET bags**: Reuse for grocery shopping at least 8 times for climate change, and up to 84 times considering all indicators; finally dispose with recyclables, otherwise reuse as waste bin bag if possible, lastly incinerate.
- **Polyester bags**: Reuse for grocery shopping at least 2 times for climate change, and up to 35 times considering all indicators; finally dispose with recyclables, otherwise reuse as waste bin bag if possible, lastly incinerate.
- **Biopolymer bags**: Can be directly reused as waste bin bags for climate change, should be reused and up to 42 times for grocery shopping considering all other indicators. Finally, reuse as waste bin bag if possible, otherwise incinerate.
- **Unbleached paper bags**: Can be directly reused as waste bin bags for climate change, should be reused and up to 43 times considering all other indicators. Finally, reuse as waste bin bag if possible, otherwise incinerate.
- **Bleached paper bags**: Reuse for grocery shopping at least 1 time for climate change, and up to 43 times considering all indicators; reuse as waste bin bag if possible, otherwise incinerate.
- **Organic cotton bags**: Reuse for grocery shopping at least 149 times for climate change, and up to 20000 times considering all indicators; reuse as waste bin bag if possible, otherwise incinerate.
- **Conventional cotton bags**: Reuse for grocery shopping at least 52 times for climate change, and up to 7100 times considering all indicators; reuse as waste bin bag if possible, otherwise incinerate.
- **Composite bags**: Reuse for grocery shopping at least 23 times for climate change, and up to 870 times considering all indicators; reuse as waste bin bag if possible, otherwise incinerate.

This study focused on identifying the number of reuse times based on the environmental performance of the carrier bags. The results obtained on the minimum number of reuse times are intended to raise the discussion among the stakeholders on the effective expected lifetime of each carrier bag. While the calculated number of reuse times might be compliant with the functional lifetime of PP, PET and polyester carrier bags, but might surpass the lifetime of bleached paper, composite and cotton carriers, especially considering all environmental indicators. In addition it should be kept in mind that the reuse times calculated are held up against a use of a reference bag a single time. If the reference bag is reused, it would mean that the reuse time of the other bags would increase proportionally.

In particular, the results of the present assessment have highlighted the importance of the design of the carrier bag and its functionality, especially for cotton carriers. In order to lower the number of reuse times, designs with light fabric and large volumes should be preferred. These design differences can largely lower the impacts. However, the required number of reuse times for all impact categories may still be unfeasible and more than the lifetime of the bag.

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Appendix A. **Life Cycle Inventories (LCIs)**

This Section provides the data and corresponding references utilized for the present LCA study.

Table A1. Material composition used for each carrier bag,

Scenario	Material	Material composition used
LDPEAVG	LDPE	Soft plastic (Riber et al., 2009)
LDPEs	*LDPE simple*	Soft plastic (Riber et al., 2009)
LDPEh	*LDPE rigid handle*	Soft plastic (Riber et al., 2009)
LDPErec	LDPE recycled	Soft plastic (Riber et al., 2009)
P2a	PP non-woven	Soft plastic (Riber et al., 2009)
PPwov	PP woven	Soft plastic (Riber et al., 2009)
PETREC	PET recycled	Soft plastic (Riber et al., 2009)
PETPOL	Polyester	Soft plastic (Riber et al., 2009)
BP	Biopolymer	Soft plastic (Riber et al., 2009); modified according to Razza (2014)
PAP	Paper	Paper and carton containers (Riber et al., 2009)
PAPB	Paper	Paper and carton containers (Riber et al., 2009)
COTORG	Cotton organic	Textiles (Riber et al., 2009)
COT	Cotton conventional	Textiles (Riber et al., 2009)
COM	Jute, PP, cotton	Textiles (Riber et al., 2009)
W1	LDPE	Soft plastic (Riber et al., 2009)
All	Packaging: cardboard	Other clean cardboard (Riber et al., 2009)

Table A2. Amount of material needed for production of the carrier bags and the waste bin bag, percent lost during production and final weight of the bag.

Scenario	Amount material produced (kg/bag)	Percent lost during manufacturing (%/bag)	Weight carrier bag (kg/bag)
LDPEavg	0.025	5.15	0.024
LDPEs	0.019	5.15	0.018
LDPEh	0.031	5.15	0.029
LDPErec	0.026	5.15	0.025
PP	0.144	5.05	0.137
PPwov	0.125	5.05	0.119
PETrec	0.159	5.15	0.151
PETpol	0.048	5.05	0.046
BP	0.018	1.03	0.018
PAP	0.045	5.15	0.042
PAPb	0.045	5.15	0.042
COTorg	0.254	0.98	0.252
COT	0.234	0.98	0.232
COM	0.282	0.98	0.279
W1	0.010	5.15	0.009

Table A3. Ecoinvent processes utilized to model the production of the material of the carrier bags. All datasets were retrieved from Ecoinvent version 3.4 (2017), consequential.

Scenario	Ecoinvent process name
LDPEavg	Market for polyethylene, low density, granulate; GLO (kg)
LDPEs	Market for polyethylene, low density, granulate; GLO (kg)
LDPEh	Market for polyethylene, low density, granulate; GLO (kg)
LDPErec	Market for polyethylene, low density, granulate; GLO (kg)
PP	Market for polypropylene, granulate; GLO (kg)
PPwov	Market for polypropylene, granulate; GLO (kg)
PETrec	Market for polyethylene terephthalate, granulate, amorphous, recycled; RoW (kg)
PETpol	Market for polyethylene terephthalate, granulate, amorphous; GLO (kg)
BP	Market for polyester-complexed starch biopolymer; GLO (kg)
PAP	Kraft paper production, unbleached; RER (kg)
PAPb	Kraft paper production, bleached; RER (kg)
COTorg	Market for textile, woven cotton; GLO (kg)
COT	Market for textile, woven cotton; GLO (kg)
COM	Market for textile, jute; GLO (kg) Market for polypropylene, granulate; GLO (kg) Market for textile, woven cotton; GLO (kg)
W1	Packaging film production, low density polyethylene; RER (kg)

Table A4. Ecoinvent processes utilized to model the treatment of residues from production, for each carrier bag. All datasets were retrieved from Ecoinvent version 3.4 (2017), consequential.

Scenario	Ecoinvent process name
LDPEAVG, LDPEs, LDPEh, LDPErec, W1	Treatment of waste polyethylene, municipal incineration; Europe without Switzerland (kg)
P2a, PPwov	Treatment of waste polypropylene, municipal incineration; CH (kg)
PETREC, PETPOL	Treatment of waste polyethylene terephthalate, municipal incineration; Europe without Switzerland (kg)
BP, PAP, PAPB	Treatment of waste paperboard, municipal incineration; Europe without Switzerland (kg)
COTORG, COT, COM	Treatment of waste textile, soiled, municipal incineration; RoW (kg)

Table A5. Carrier bag production: material and energy requirements. The literature references are provided as superscript. The references were used to obtain average consumption values.

Scenario	Electricity	Heat	Water	Titanium dioxide	Ink	Cotton thread	PP thread	Glue	Packaging amount
	kWh/kg	MJ/kg	L/kg	kg/kg	kg/kg	kg/kg	kg/kg	kg/kg	kg/kg
LDPEAVG, LDPEs, LDPEh, LDPErec (LDPE)	0.741	1.522[a]	-	0.034	0.011[a]	-	-	-	0.048
	0.998[a]			0.032[a]					0.078[a]
	0.987[a]			0.070[b]					0.042[b]
	0.490[b]			0.001[c]					0.024[c]
	0.609[c]								
	0.950[c]								
	0.410[d]								
PP, PPwov (PP)	1.854	1.308	0.807[a]	-	0.054	0.007	0.004[a]	-	0.069
	0.612[b]	2.616[a]			0.067[d]	0.004[a]			0.087[a]
	1.500[c]	Negligible[e]			0.042[d]	0.010[b]			0.069[b]
	2.204[d]					0.009[d]			0.050[c]
	3.100[d]					0.006[d]			
PETREC (PET)	1.854	1.308	0.807[a]	-	0.054	0.007	0.004[a]	-	0.069
PETPOL (Polyester)	1.854	1.308	0.807[a]	-	0.054	0.007	0.004[a]	-	0.069
BP (Biopolymer)	1.112	-	1.343[a]	0.021[a]	0.005[a]	-	-	-	0.043
	1.066[a]	Negligible[e]							0.054[a]
	0.858[c]								0.033[c]
	1.413[c]								
PAP, PAPB (Paper)	0.216	-	-	-	0.014[a]	-	-	0.027	0.049
	0.042[b]							0.027[a]	0.058[a]
	0.390[d]							0.027[b]	0.040[b]
COTORG, COT (Cotton)	0.006[a]	0.092[a]	-	-	-	0.007[a]	-	-	0.108[a]
COM (Composite)	0.006[a]	0.092[a]	-	-	-	0.007[a]	-	-	0.108[a]

a (Edwards and Fry, 2011)
b (Kimmel and Cooksey, 2014)
c (Mori et al., 2013)
d (Muthu and Li, 2014)
e (Khoo and Tan, 2010)

Table A6. **With reference to the energy and material requirements listed in Table A4, this table provides the Ecoinvent datasets utilized for the corresponding energy and material requirements. For completeness, the table reports in which scenarios the datasets were used.**

Ancillary material		Scenario							
Type	Ecoinvent process (v 3.4, consequential)	LDPEAVG LDPEs LDPEh LDPErec	PP PPwov	PETREC	PETPOL	BP	PAP PAPB	COTORG COT	COM
Electricity	Market group for electricity, high voltage; RER (kWh)	X	X	X	X	X	X	X	X
Heat	Market group for heat, district or industrial, natural gas; RER (MJ)	X	X	X	X			X	X
Water	Market for tap water; Europe without Switzerland (kg)		X	X	X	X			
Titanium dioxide	Market for titanium dioxide; RoW (kg)	X				X			
Ink	Market for printing ink, rotogravure, without solvent, in 55% toluene solution state; GLO (kg)	X	X	X	X	X	X		
Cotton thread	Market for textile, woven cotton; GLO (kg)		X	X	X			X	X
PP thread	Market for polypropylene, granulate; GLO (kg)		X	X	X				
Glue	Bitumen adhesive compound production, hot; RER						X		
Packaging	Corrugated board box production; RER (kg)	X	X	X	X	X	X	X	X

Table A7. Transportation distances utilized in this LCA study.

Transportation process	Distance	EOL1	EOL2	EOL3
Transport of packaging material to carrier bag production facility (EU)	2000 km	X	X	X
Transport of carrier bag to supermarket (EU-DK)	2000 km	X	X	X
Collection of packaging from supermarkets (DK)	15 km	X	X	X
Transport to packaging recycling (DK-EU)	2000 km	X	X	X
Collection of residual waste (DK)	10 km	X		X
Transport fly ash (DK-EU)	500 km	X		X
Transport bottom ash (DK-EU)	100 km	X		X
Collection of recyclables (DK)	15 km		X	
Transportation to sorting (DK)	500 km		X	
Transportation to recycling (DK-EU)	2000 km		X	

Table A8. Ecoinvent process used in order to model transportation.

Transportation process	Ecoinvent process (v 3.4, consequential)
Transport of packaging material to carrier bag production facility (EU)	Transport, freight, lorry 16-32 metric ton, EURO6; RER (metric ton*km)
Transport of carrier bag to supermarket (EU-DK)	
Transport to packaging recycling (DK-EU)	
Transportation to sorting (DK)	
Transport fly ash (DK-EU)	
Transport bottom ash (DK-EU)	
Transportation to recycling (DK-EU)	
Collection of packaging from supermarkets (DK)	
Collection of recyclables (DK)	
Collection of residual waste (DK)	

Table A9. Material losses during recycling of single-wall corrugated cardboard packaging.

Material fraction	Recycled (%)	Residues (%)
Other clean cardboard (Riber et al., 2009)	91	9

Table A10. Material and energy requirements and corresponding Ecoinvent processes used for the modelling of the recycling of single-wall corrugated cardboard packaging. Material and energy requirements were obtained from Skjern Papirfabrik (2005).

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
Market group for tap water; RER	17	kg/kg Total Wet Weight
Market group for electricity, high voltage; RER	1.5	kWh/kg Total Wet Weight
Natural gas, from high pressure network (1-5 bar), at service station; CH	0.069	kg/kg Total Wet Weight
Linerboard production, kraftliner; RER	-0.9	kg/kg Total Wet Weight

Table A11. Emissions during recycling of single-wall corrugated cardboard packaging.

Elementary exchange	Compartment	Sub compartment	Amount	Unit	Per
Nitrogen oxides	air	unspecified	8.80E-05	kg	kg Total Wet Weight
Carbon dioxide, fossil	air	unspecified	0.18	kg	kg Total Wet Weight
Sulfur dioxide	air	unspecified	0.0001	kg	kg Total Wet Weight
COD, Chemical Oxygen Demand	water	surface water	0.0011	kg	kg Total Wet Weight
Nitrogen	water	surface water	6.00E-05	kg	kg Total Wet Weight
Phosphate	water	surface water	2.50E-06	kg	kg Total Wet Weight
Suspended solids, unspecified	water	surface water	0.00016	kg	kg Total Wet Weight
Particulates, > 2.5 um, and < 10um	air	unspecified	2.80E-05	kg	kg Total Wet Weight

Table A12. Ecoinvent process used for modelling the treatment of residues from packaging recycling.

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
Treatment of waste paperboard, municipal incineration; Europe without Switzerland	1	kg/kg Total Wet Weight

Table A13. Material and energy requirements and corresponding Ecoinvent processes used for the modelling of the incinerator technology. Material and energy requirements were obtained from Vestforbrænding (2013). Electricity recovery was considered 22 %, heat recovery 73 %. Please refer to Appendix B for the marginal electricity and heat utilized.

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
quicklime production, milled, packed; CH	0.00034	kg/kg Total Wet Weight
market for ammonia, liquid; RER	0.00153	kg/kg Total Wet Weight
activated carbon production, granular from hard coal; RER	0.00104	kg/kg Total Wet Weight
market for tap water; Europe without Switzerland	0.397	kg/kg Total Wet Weight
hydrochloric acid production, from the reaction of hydrogen with chlorine; RER	5.60E-06	kg/kg Total Wet Weight
market for sodium hydroxide, without water, in 50% solution state; GLO	2.40E-05	kg/kg Total Wet Weight
market for calcium carbonate, precipitated; GLO	0.00567	kg/kg Total Wet Weight
Marginal electricity, see Appendix B	-0.22/3.6	kWh/MJ
Marginal heat, see Appendix B	-0.73	MJ/MJ

Table A14. Emissions to the air, unspecified, Vestforbrænding (2013).

Elementary exchange	Amount	Unit
Carbon monoxide	3.30E-02	kg/kg Total Wet Weight
Dust	4.06E-03	kg/kg Total Wet Weight
HCl	6.58E-03	kg/kg Total Wet Weight
HF	2.70E-04	kg/kg Total Wet Weight
Manganese	1.12E-02	kg/kg Total Wet Weight
NH_3	4.31E-03	kg/kg Total Wet Weight
Nickel	3.47E-06	kg/kg Total Wet Weight
Nitrogen Oxides (NOx)	5.49E-01	kg/kg Total Wet Weight
PAH (B[a]P-eq)	4.31E-06	kg/kg Total Wet Weight
PCDD/F	1.80E-11	kg/kg Total Wet Weight
SO_2/SO_3	1.08E-02	kg/kg Total Wet Weight

Table A15. Transfer coefficients to air emissions from input composition, Vestforbrænding (2013).

Parameter	Unit	Value
Hg	% Hg in	0.7476
Cd	% Cd in	0.0064
Pb	% Pb in	0.0008
Cr	% Cr in	0.0394
Cu	% Cu in	0.003
As	% As in	0.012
Ni	% Ni in	0.033
Sb	%Sb in	0.119

Table A16. Transfer coefficients for degradation and residues for the soft plastic material fraction, Vestforbrænding (2013).

Fraction name	Degradation			Fly ash			Scrap metals			Bottom ash		
	Water (%)	VS (%TS)	Ash (%TS)	Water (%)	VS (%TS)	Ash (%TS)	Water (%)	VS (%TS)	Ash (%TS)	Water (%)	VS (%TS)	Ash (%TS)
Soft plastic	100	99.9	0	0	0	12.6	0	0	0	0	0.1	87.4

Table A17. Emissions to water, Vestforbrænding incinerator.

Elementary exchange	Compartment	Value	Unit
Antimony	water	8.80E-06	kg/kg Total Wet Weight
Arsenic	water	5.60E-07	kg/kg Total Wet Weight
Barium	water	7.20E-06	kg/kg Total Wet Weight
Cadmium	water	9.67E-08	kg/kg Total Wet Weight
Calcium	water	4.16E-02	kg/kg Total Wet Weight
Chloride	water	4.11E+00	kg/kg Total Wet Weight
Chromium	water	4.48E-06	kg/kg Total Wet Weight
Cobalt	water	4.00E-08	kg/kg Total Wet Weight
Copper	water	2.00E-04	kg/kg Total Wet Weight
Fluoride	water	2.08E-03	kg/kg Total Wet Weight
Iron	water	4.00E-05	kg/kg Total Wet Weight
Lead	water	1.20E-06	kg/kg Total Wet Weight
Magnesium	water	2.56E-05	kg/kg Total Wet Weight
Manganese	water	6.40E-07	kg/kg Total Wet Weight
Mercury	water	1.35E-07	kg/kg Total Wet Weight
Molybdenum	water	7.20E-05	kg/kg Total Wet Weight
Nickel	water	1.68E-06	kg/kg Total Wet Weight
Selenium	water	1.12E-06	kg/kg Total Wet Weight
Silicon	water	2.40E-04	kg/kg Total Wet Weight
Zinc	water	2.56E-06	kg/kg Total Wet Weight

Table A18. Material and energy requirements and corresponding Ecoinvent processes used for the modelling of the treatment of fly ashes. Values for material and energy requirements were obtained from Astrup (2008).

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
market for calcium carbonate, precipitated; GLO	-0.035	kg/kg Total Wet Weight
market group for electricity, high voltage; RER	0.013	kWh/kg Total Wet Weight
market group for diesel; RER	0.0006	kg/kg Total Wet Weight

Table A19. Emissions from treatment of fly ashes. (Astrup, 2008).

Elementary exchange	Compartment	Sub compartment	Amount	Unit	Per
Cadmium, ion	water	surface water	3.10E-09	kg	kg Total Wet Weight
Chloride	water	surface water	0.0092	kg	kg Total Wet Weight
Lead	water	surface water	3.10E-10	kg	kg Total Wet Weight
Mercury	water	surface water	6.10E-11	kg	kg Total Wet Weight
Nickel, ion	water	surface water	1.50E-09	kg	kg Total Wet Weight
Sulfate	water	surface water	0.00082	kg	kg Total Wet Weight
Thallium	water	surface water	4.10E-10	kg	kg Total Wet Weight
Zinc, ion	water	surface water	1.40E-08	kg	kg Total Wet Weight

Table A20. Bottom ashes treatment was assumed to occur in a mineral landfill.

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
process-specific burdens, slag landfill; Europe without Switzerland	1	kg/kg Total Wet Weight

Table A21. Sorting efficiency for recyclables. This sorting plant is assumed to operate in Denmark. COWI (2017)

Carrier bag material	Scenarios	Sorted (%)	Residues (%)
LDPE	LDPEAVG, LDPEs, LDPEh, LDPErec	70	30 (to incineration in DK)
PP	PP, PPwov	70	30 (to incineration in DK)
Recycled PET	PETREC	70	30 (to incineration in DK)
Polyester	PETPOL	70	30 (to incineration in DK)
Paper	PAP, PAPB	70	30 (to incineration in DK)

Table A22. Material and energy requirements, sorting plant for recyclables in Denmark. COWI (2017).

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
Marginal electricity, see Appendix B	0.00982	kWh/kg Total Wet Weight
Marginal heat, see Appendix B	0.0189	MJ/kg Total Wet Weight

Table A23. Sorting efficiency of recyclables, at recycling plant. COWI (2017).

Carrier bag material	Scenarios	Sorted (%)	Residues (%)	Reference
LDPE	LDPEAVG, LDPEs, LDPEh, LDPErec	90.3	9.7 (to incineration in EU)	Replast A/S (2000)
PP	PP, PPwov	90.3	9.7 (to incineration in EU)	Replast A/S (2000)
Recycled PET	PETREC	75.5	24.5 (to incineration in EU)	Giugliano et al. (2011)
Polyester	PETPOL	75.5	24.5 (to incineration in EU)	Giugliano et al. (2011)
Paper	PAP, PAPB	91	9 (to incineration in EU)	Skjern Papirfabrik (2005)

Table A24. Material and energy requirements, LDPE recycling (Schmidt and Strömberg, 2006).

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
market group for electricity, high voltage; RER	0.76	kWh/kg Total Wet Weight
market group for tap water; RER	2.6	kg/kg Total Wet Weight
market group for diesel; RER	0.00047	kg/kg Total Wet Weight
steam production, in chemical industry; RER	0.32	kg/kg Total Wet Weight
polyethylene production, low density, granulate; RER	-0.9	kg/kg Total Wet Weight recycled

Table A25. Ecoinvent process used to model end-of-life of LDPE residues from the recycling process.

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
treatment of waste polyethylene, municipal incineration; Europe without Switzerland	1	kg/kg Total Wet Weight

Table A26. Material and energy requirements, PP recycling (Schmidt and Strömberg, 2006).

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
market group for electricity, high voltage; RER	0.76	kWh/kg Total Wet Weight
market group for tap water; RER	2.6	kg/kg Total Wet Weight
market group for diesel; RER	0.00047	kg/kg Total Wet Weight
steam production, in chemical industry; RER	0.89/2.75	kg/kg Total Wet Weight
polypropylene production, granulate; RER	-0.9	kg/kg Total Wet Weight recycled

Table A27. Ecoinvent process used to model end-of-life of PP residues from the recycling process.

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
treatment of waste polypropylene, municipal incineration; CH	1	kg/kg Total Wet Weight

Table A28. Material and energy requirements, PET recycling (Rigamonti et al., 2014). The same process was used for polyester.

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
market group for electricity, high voltage; RER	0.32	kWh/kg Total Wet Weight recycled
market group for tap water; RER	2.96	kg/kg Total Wet Weight recycled
market for sodium hydroxide, without water, in 50% solution state; GLO	0.003	kg/kg Total Wet Weight recycled
steam production, in chemical industry; RER	0.93	kg/kg Total Wet Weight recycled
polyethylene terephthalate production, granulate, amorphous, recycled; Europe without Switzerland	-0.81	kg/kg Total Wet Weight recycled

Table A29. Ecoinvent process used to model end-of-life of PET residues from the recycling process. The same process was used for polyester.

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
treatment of waste polyethylene terephtalate, municipal incineration; Europe without Switzerland	1	kg/kg Total Wet Weight

Table A30. Material and energy requirements, paper recycling to cardboard Skjern Papirfabrik (2005).

External process name	Amount	Unit
market group for electricity, high voltage; RER	1.5	kWh/kg Total Wet Weight
market group for tap water; RER	17	kg/kg Total Wet Weight
natural gas, from high pressure network (1-5 bar), at service station; CH	0.069	kg/kg Total Wet Weight
linerboard production, kraftliner; RER	-0.9	kg/kg Total Wet Weight

Table A31. Emissions to the environment, paper recycling to cardboard Skjern Papirfabrik (2005).

Elementary exchange	Compartment	Sub compartment	Amount	Unit	Per
Nitrogen oxides	air	unspecified	8.80E-05	kg	kg Total Wet Weight
Carbon dioxide, fossil	air	unspecified	0.18	kg	kg Total Wet Weight
Sulfur dioxide	air	unspecified	0.0001	kg	kg Total Wet Weight
COD, Chemical Oxygen Demand	water	surface water	0.0011	kg	kg Total Wet Weight
Nitrogen	water	surface water	6.00E-05	kg	kg Total Wet Weight
Phosphate	water	surface water	2.50E-06	kg	kg Total Wet Weight
Suspended solids, unspecified	water	surface water	0.00016	kg	kg Total Wet Weight
Particulates, > 2.5 um, and < 10um	air	unspecified	2.80E-05	kg	kg Total Wet Weight

Table A32. Ecoinvent process used to model end-of-life of paper residues from the recycling process.

Ecoinvent process name (v 3.4, consequential)	Amount	Unit
treatment of waste paperboard, municipal incineration; Europe without Switzerland (kg)	1	kg/kg Total Wet Weight

Appendix B. Marginal technologies

This Section summarizes the technological processes that have been selected as marginal technologies for the present LCA study. "Marginal technologies" are the technologies that are assumed to be displaced by the additional functionalities provided by the functional unit. A classic example for LCAs of waste management systems is the energy produced during the treatment of waste by incineration. The energy produced represents an additional function, and electricity and heat produced are used in the energy system instead of producing primary energy from other sources.

For the present studies, marginal technologies needed to be identified for the energy recovered during incineration in Denmark and for the secondary material produced from the recycling processes. The following subsections present the processes and datasets chosen. In order to facilitate reading, the selected processes are also provided with their LCIA results according to the same references provided in Table 5 in the report. In addition, in order to provide results in the same figures, we have used the following normalization references.

Table B1. Normalization references for the impact categories in Table 5. The Normalization references are from the Prosuite project which was developed specifically for the recommended ILCD method (Laurent et al., 2013), excluded the long-term compartment. The impact category "Depletion of abiotic resources" respects ILCD recommended characterization factors

Impact Category	Acronyms	Normalization references	Units
Climate change	CC	8.10E+03	PE/year
Ozone depletion	OD	4.14E-02	PE/year
Human toxicity, cancer effects	HTc	5.42E-05	PE/year
Human toxicity, non-cancer effects	HTnc	1.10E-03	PE/year
Particulate matter/Respiratory inorganics	PM	2.76E+00	PE/year
Ionizing radiation, human health	IR	1.33E+03	PE/year
Photochemical ozone formation, human health	POF	5.67E+01	PE/year
Terrestrial acidification	TA	4.96E+01	PE/year
Eutrophication terrestrial	TE	1.15E+02	PE/year
Eutrophication freshwater	FE	6.20E-01	PE/year
Eutrophication marine	ME	9.38E+00	PE/year
Ecotoxicity freshwater	ET	6.65E+02	PE/year
Resources, depletion of abiotic resources, fossil	RDfos	6.24E+04	PE/year
Resources, depletion of abiotic resources (reserve base)	RD	0.0343	PE/year

Appendix B.1 Marginal energy technologies

Electricity

In accordance with the Danish Environmental Protection Agency, the marginal energy technologies used for this project were based on the latest published project from the Danish Environmental Protection Agency, which provided marginal energy technologies for electricity and heat: TemaNord 2016:537 - Gaining benefits from discarded textiles - LCA of different treatment pathways, published by the Nordic Council of Ministers (Schmidt et al., 2016).
In this project, the long-term marginal was defined as capacity growth over a defined period (2020-2030). The marginal was provided as a mix of contributing resources, as shown in Table B2. The electricity marginal mix was then composed of electricity production from single-technology processes from the Ecoinvent v3.4 database, consequential version. The normalized results of the created process for electricity were compared to those of the electricity market, high voltage, for Denmark in Ecoinvent v3.4, consequential and found compliant (Figure B1).

Table B2. Marginal mix, electricity, TemaNord 2016:537

Resource	Percent contribution (%)	Ecoinvent v3.4 process
Biomass	49.8	Electricity production, wood, future; GLO (kWh), consequential
Gas	18.6	Electricity production, natural gas, 10MW; CH, (kWh), consequential
Wind	31.6	Electricity production, wind, <1MW turbine, onshore; DK (kWh), consequential

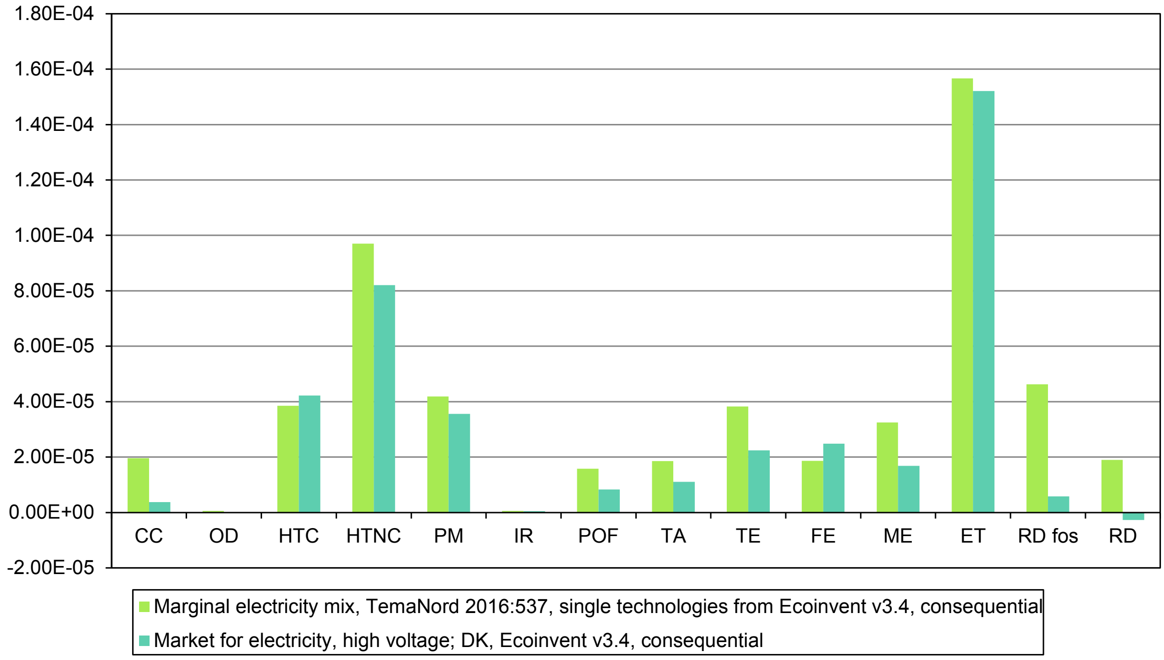

Figure B1. Marginal electricity mix normalized results, obtained from single technology dataset from Ecoinvent v3.4, consequential, according to the percent contribution identified in TemaNord 2016:537, compared to the normalized results of the market for electricity process, retrieved from Ecoinvent v3.4, consequential.

Heat

In the TemaNord 2016:537 project the marginal technology from heat was chosen based on the project Miljøprojekt 1458 (Bang Jensen et al., 2013). The contribution of resources to the marginal heat mix is provided in Table B3. In Miljøprojekt 1458 it was assumed that waste heat could not replace waste heat, therefore heat from incineration is not part of the heat marginal mix. The Ecoinvent 3.4 processes used to compose the dataset are specified in Table B3. For all processes, the selection involved finding heat production datasets from single technologies and comparing the normalized results of many single-technologies for heat production of the same type. Due to high differences between the normalized results and to the unavailability of single technologies datasets for biogas, we selected a process from the allocation at the point of substitution database instead of the consequential one. The differences in the overall normalized result are minor, due to the minor contribution of biogas. Figure B2 provides a contribution analysis of the single technologies composing the dataset.

Table B2. Marginal mix, electricity, Miljøprojekt 1458

Resource	Percent contribution (%)	Ecoinvent v3.4 process
Biomass	39	Heat production, hardwood chips from forest, at furnace 5000kW, state-of-the-art 2014; CH (MJ), consequential
Gas	26	Heat production, natural gas, at boiler modulating >100kW; Europe without Switzerland (MJ), consequential
Coal	20	Heat production, at hard coal industrial furnace 1-10MW; Europe without Switzerland (MJ), consequential
Oil	9	Heat production, heavy fuel oil, at industrial furnace 1MW; CH (MJ), consequential
Biogas	6	Heat and power co-generation, biogas, gas engine; DK (MJ), allocation at the point of substitution

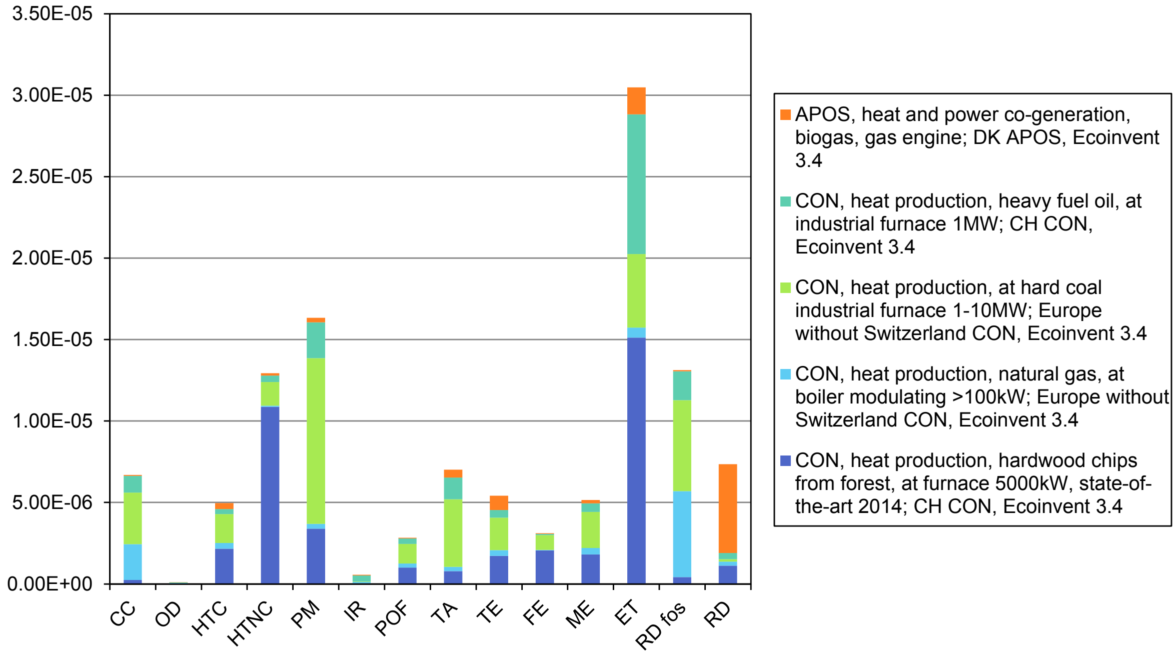

Figure B2. Normalized results and contribution analysis associated with the marginal heat technology (mix) selected for the present LCA study.

Appendix B.2 Marginal materials

The following Table B4 provides a summary of the datasets selected for the production of materials and for the recycling (for the carrier bags for which it was considered possible). All datasets were retrieved from Ecoinvent 3.4, consequential version.

Each dataset was selected after comparison of many datasets for the production of the same material. The criterion for selection of the dataset was general compliance in results with datasets for the same function, and availability of the dataset. For production, market datasets were always selected (if available), since market comprises production shares globally and average transport distances. For substitution, we selected simply the production in a specific geographical area (preferably Europe, since it is where the recycling process is assumed to occur).

For recycled LDPE, there was no available dataset on the production. Therefore, the LCA was carried out considering the same production as virgin LDPE. The results obtained are assumed to be conservative, since the impacts connected to virgin plastics are usually larger than the ones of recycled plastics, as it is shown in Figure B3 for PET, for both datasets are available in Ecoinvent v3.4, consequential.

Table B4. Summary of datasets used as production of materials and for the materials substituted by the secondary material produced from the recycling processes.

Material	Production	Substitution
LDPE	Market for polyethylene, low density, granulate; GLO (kg)	Polyethylene production, low density, granulate; RER (kg)
Recycled LDPE	Market for polyethylene, low density, granulate; GLO (kg)	Polyethylene production, low density, granulate; RER (kg)
PP	Market for polypropylene, granulate; GLO (kg)	Polypropylene production, granulate; RER (kg)
Recycled PET	Market for polyethylene terephthalate, granulate, amorphous, recycled; RoW (kg)	Polyethylene terephthalate production, granulate, amorphous, recycled; Europe without Switzerland (kg)
Polyester	Market for polyethylene terephthalate, granulate, amorphous; GLO (kg)	Polyethylene terephthalate production, granulate, amorphous; RER (kg)
Starch-complexed biopolymer	Market for polyester-complexed starch biopolymer; GLO (kg)	-
Unbleached paper	Kraft paper production, unbleached; RER (kg)	Linerboard production, kraftliner; RER (kg)
Bleached paper	Kraft paper production, bleached; RER (kg)	Linerboard production, kraftliner; RER (kg)
Cotton organic	Market for textile, woven cotton; GLO (kg) Minus “CON, market for nitrogen fertiliser, as N; GLO (kg)”	-
Cotton conventional	Market for textile, woven cotton; GLO (kg)	-
Jute	Market for textile, jute; GLO (kg)	-
LDPE bin bag	Packaging film production, low density polyethylene; RER (kg)	-

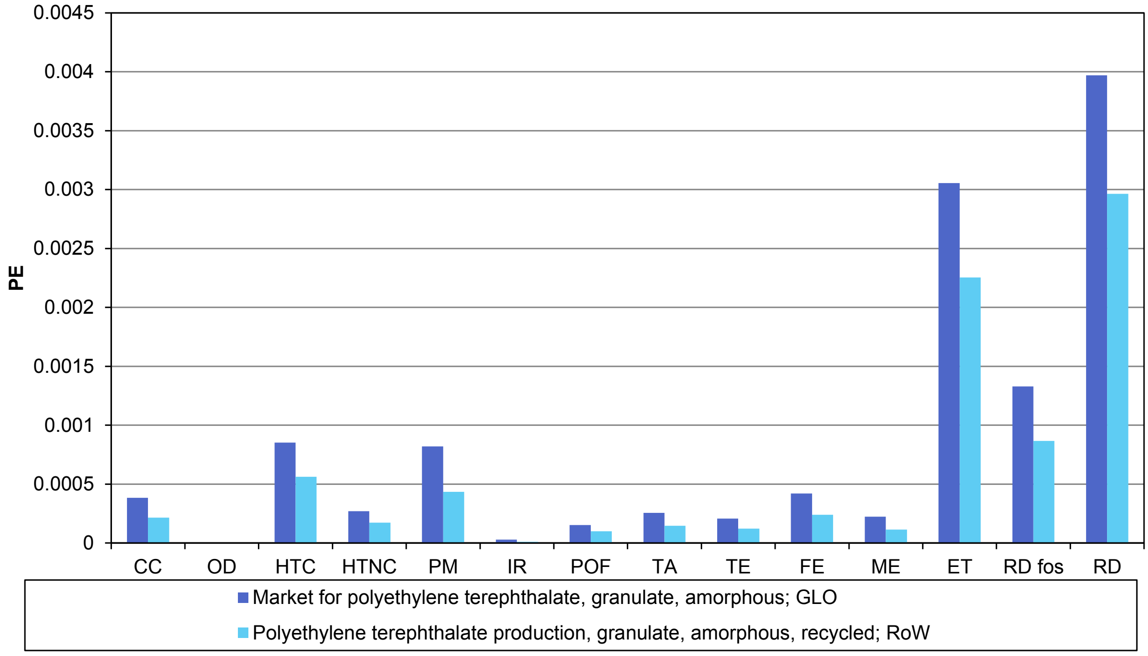

Figure B3. Normalized impact scores for virgin and recycled PET production.

Appendix C. **Additional results**

This Section reports the primary reuse times calculated for all impact categories, which were omitted from the main report for brevity.

Tables C1-C14 provide the calculated number of primary reuse times for each carrier bag in comparison to the reference bag LDPEavg, for each impact category. Table C15 provides a minimum – maximum range obtained with the calculated number of primary reuse times for each impact category. Table C16 provides the minimum-maximum range without the ozone depletion impact category, which provided high result scores affecting the cotton and composite bags. Table C17 provides the average number of reuse times obtained averaging results across all impact categories. Results in Tables C15, C16 and C17 are rounded.

Table C1. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the ozone depletion impact category

	LDPEavg, EOL3		
	Ozone Depletion		
	EOL1	EOL2	EOL3
LDPEavg	-0.2	2.9	0.0
LDPEs	0.2	4.8	0.5
LDPEh	0.0	3.7	0.2
LDPErec	0.9	7.3	1.2
PP	34.5	52.0	34.7
PPwov	29.7	44.9	30.0
PETrec	44.3	60.3	44.7
PETpol	14.3	18.6	14.6
BP	9.4	-	9.7
PAP	7.6	12.0	7.9
PAPb	17.9	22.4	18.2
COTorg	19961.8	-	19962.3
COT	7069.0	-	7069.2
COM	874.1	-	874.3

Table C2. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the human toxicity, cancer effects impact category

	LDPEavg, EOL3		
	Human toxicity, cancer		
	EOL1	EOL2	EOL3
LDPEavg	0.2	0.1	0.0
LDPEs	0.7	0.7	0.4
LDPEh	0.4	0.4	0.2
LDPErec	1.4	1.4	1.1
PP	1.3	1.8	1.0
PPwov	1.0	1.5	0.7
PETrec	5.1	4.6	4.8
PETpol	1.1	0.7	0.9
BP	1.0	-	0.7
PAP	0.3	0.5	-0.1
PAPb	0.4	0.6	0.1
COTorg	424.5	-	424.0
COT	149.6	-	149.4
COM	36.8	-	36.6

Table C3. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the human toxicity, non-cancer effects impact category

	LDPEavg, EOL3		
	Human toxicity, non-cancer		
	EOL1	EOL2	EOL3
LDPEavg	-0.6	0.9	0.0
LDPEs	-1.3	0.9	-0.3
LDPEh	-0.9	0.9	-0.3
LDPErec	-2.2	0.9	-1.1
PP	-6.6	2.6	-5.9
PPwov	-5.6	2.4	-4.7
PETrec	-1.3	5.2	-0.2
PETpol	0.3	2.3	1.1
BP	5.4	-	6.5
PAP	13.5	14.6	14.7
PAPb[10]	13.5	14.6	14.7
COTorg	230.1	-	231.8
COT	80.3	-	81.2
COM	-24.5	-	-23.9

[10] The highest value for bleached paper was increased to be equal to the value for unbleached paper

Table C4. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the particulate matter impact category

	LDPEavg, EOL3		
	Particulate matter		
	EOL1	EOL2	EOL3
LDPEavg	0.6	2.1	0.0
LDPEs	1.4	3.6	0.3
LDPEh	1.0	2.7	0.3
LDPErec	2.7	5.7	1.4
PP	10.2	21.2	9.4
PPwov	8.7	18.2	7.7
PETrec	26.7	32.8	25.5
PETpol	9.1	10.5	8.2
BP	11.1	-	9.9
PAP	16.6	25.3	15.3
PAPb	28.6	37.2	27.4
COTorg	1119.8	-	1118.0
COT	394.6	-	393.7
COM	300.1	-	299.3

Table C5. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the ionizing radiation impact category

	LDPEavg, EOL3		
	Ionising radiation		
	EOL1	EOL2	EOL3
LDPEavg	0.4	3.2	0.0
LDPEs	1.1	5.1	0.4
LDPEh	0.7	4.0	0.2
LDPErec	2.1	7.7	1.3
PP	19.8	35.8	19.3
PPwov	17.0	30.8	16.3
PETrec	32.1	40.6	31.3
PETpol	9.9	12.2	9.3
BP	8.2	-	7.3
PAP	13.8	18.4	12.9
PAPb[11]	13.8	18.4	12.9
COTorg	906.7	-	905.4
COT	321.9	-	321.3
COM	95.5	-	95.0

[11] The highest value for bleached paper was increased to be equal to the value for unbleached paper

Table C6. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the human toxicity, photochemical ozone formation impact category

	LDPEavg, EOL3		
	Photochemical ozone formation		
	EOL1	EOL2	EOL3
LDPEavg	0.5	0.4	0.0
LDPEs	1.3	1.0	0.3
LDPEh	0.9	0.6	0.3
LDPErec	2.2	1.9	1.2
PP	6.4	6.8	5.6
PPwov	5.4	5.7	4.5
PETrec	6.6	8.2	5.5
PETpol	1.6	1.9	0.9
BP	1.7	-	0.6
PAP	1.7	2.5	0.6
PAPb	2.7	3.4	1.7
COTorg	194.7	-	193.2
COT	68.0	-	67.2
COM	36.8	-	36.1

Table C7. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the terrestrial acidification impact category

	LDPEavg, EOL3		
	Terrestrial acidification		
	EOL1	EOL2	EOL3
LDPEavg	0.5	1.3	0.0
LDPEs	1.2	2.4	0.4
LDPEh	0.8	1.7	0.2
LDPErec	2.3	3.9	1.3
PP	6.7	15.0	6.0
PPwov	5.7	12.8	4.8
PETrec	13.6	20.0	12.6
PETpol	4.3	5.8	3.6
BP	8.8	-	7.8
PAP	4.7	7.7	3.6
PAPb	6.8	9.8	5.9
COTorg	756.5	-	755.1
COT	265.5	-	264.8
COM	142.7	-	142.1

Table C8. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the terrestrial eutrophication impact category

	LDPEavg, EOL3		
	Terrestrial eutrophication		
	EOL1	EOL2	EOL3
LDPEavg	0.9	5.0	0.0
LDPEs	1.8	7.8	0.3
LDPEh	1.3	6.1	0.3
LDPErec	3.4	11.7	1.6
PP	19.9	50.7	18.7
PPwov	17.1	43.8	15.6
PETrec	39.9	66.8	38.2
PETpol	14.1	21.3	12.8
BP	28.7	-	26.9
PAP	23.4	34.0	21.6
PAPb	30.0	40.6	28.4
COTorg	3007.7	-	3005.1
COT	1058.5	-	1057.2
COM	740.2	-	739.1

Table C9. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the freshwater eutrophication impact category

	LDPEavg, EOL3		
	Freshwater eutrophication		
	EOL1	EOL2	EOL3
LDPEavg	-0.4	2.9	0.0
LDPEs	-1.0	3.9	-0.4
LDPEh	-0.7	3.3	-0.2
LDPErec	-1.1	5.7	-0.4
PP	29.0	46.6	29.5
PPwov	25.2	40.5	25.9
PETrec	95.3	84.0	96.0
PETpol	34.6	27.7	35.1
BP	41.0	-	41.8
PAP	42.2	44.1	43.0
PAPb[12]	42.2	44.1	43.0
COTorg	3325.3	-	3326.4
COT	1177.8	-	1178.3
COM	592.2	-	592.6

[12] The highest value for bleached paper was increased to be equal to the value for unbleached paper

Table C10. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the marine eutrophication impact category

	LDPEavg, EOL3		
	Marine eutrophication		
	EOL1	EOL2	EOL3
LDPEavg	0.5	1.1	0.0
LDPEs	1.2	2.1	0.4
LDPEh	0.8	1.5	0.2
LDPErec	2.2	3.5	1.3
PP	10.5	15.9	9.9
PPwov	9.0	13.6	8.2
PETrec	13.0	18.6	12.1
PETpol	4.7	5.9	4.0
BP	14.2	-	13.2
PAP	7.8	9.1	6.8
PAPb	10.0	11.4	9.2
COTorg	625.1	-	623.7
COT	220.0	-	219.3
COM	161.3	-	160.8

Table C11. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the freshwater ecotoxicity impact category

	LDPEavg, EOL3		
	Freshwater ecotoxicity		
	EOL1	EOL2	EOL3
LDPEavg	0.4	0.8	0.0
LDPEs	1.0	1.6	0.4
LDPEh	0.7	1.1	0.2
LDPErec	1.9	2.7	1.2
PP	4.2	6.8	3.7
PPwov	3.5	5.8	2.9
PETrec	8.9	15.8	8.2
PETpol	2.3	4.5	1.8
BP	1.6	-	0.8
PAP	2.9	4.0	2.1
PAPb[13]	2.9	4.0	2.1
COTorg	633.5	-	632.4
COT	224.5	-	223.9
COM	84.0	-	83.6

[13] The highest value for bleached paper was increased to be equal to the value for unbleached paper

Table C12. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the resource depletion, fossil impact category

	LDPEavg, EOL3		
	Resource depletion, fossil		
	EOL1	EOL2	EOL3
LDPEavg	0.6	0.2	0.0
LDPEs	1.3	0.8	0.3
LDPEh	0.9	0.5	0.3
LDPErec	2.3	1.6	1.2
PP	8.7	7.3	7.9
PPwov	7.4	6.2	6.5
PETrec	9.9	9.8	8.8
PETpol	2.8	2.3	2.0
BP	1.7	-	0.6
PAP	0.1	1.1	-1.0
PAPb	2.3	3.3	1.4
COTorg	185.9	-	184.3
COT	65.2	-	64.4
COM	26.0	-	25.3

Table C13. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the resource depletion, abiotic impact category

	LDPEavg, EOL3		
	Resource depletion		
	EOL1	EOL2	EOL3
LDPEavg	0.2	0.3	0.0
LDPEs	0.7	1.0	0.4
LDPEh	0.4	0.6	0.2
LDPErec	1.4	1.8	1.1
PP	0.5	1.6	0.2
PPwov	0.3	1.2	0.0
PETrec	12.2	9.6	11.8
PETpol	3.6	2.3	3.3
BP	2.2	-	1.9
PAP	22.7	22.5	22.4
PAPb[14]	22.7	22.5	22.4
COTorg	278.2	-	277.7
COT	98.0	-	97.8
COM	19.2	-	19.0

[14] The highest value for bleached paper was increased to be equal to the value for unbleached paper

Table C14. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3), for the water resource depletion impact category

	LDPEavg, EOL3		
	Water use		
	EOL1	EOL2	EOL3
LDPEavg	1.2	3.3	0.0
LDPEs	2.3	5.4	-0.2
LDPEh	1.7	4.2	-3.9
LDPErec	1.7	3.8	0.5
PP	38.4	51.3	37.2
PPwov	33.1	44.3	31.9
PETrec	69.7	66.2	68.5
PETpol	22.9	19.7	21.6
BP	0.1	-	-2.3
PAP	16.1	77.2	13.6
PAPb[15]	16.1	77.2	13.6
COTorg	3832.8	-	3830.4
COT	1359.3	-	1358.1
COM	276.5	-	275.3

Table C15. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3). The Table shows a (min, max) range obtained considering the minimum and maximum number calculated for each bag for all impact categories. Numbers lower than zero indicate when the carrier bag in the row already provides a better performance than the LDPEavg reference bag.

	LDPEavg, EOL3		
	Min - Max ranges, all impact categories		
	EOL1	EOL2	EOL3
LDPEavg	(-1, 1)	(0, 5)	(0, 0)
LDPEs	(-1, 2)	(1, 8)	(0, 1)
LDPEh	(-1, 2)	(0, 6)	(-4, 0)
LDPErec	(-2, 3)	(1, 12)	(-1, 2)
PP	(-7, 38)	(2, 52)	(-6, 37)
PPwov	(-6, 33)	(1, 45)	(-5, 32)
PETrec	(-1, 95)	(5, 84)	(0, 96)
PETpol	(0, 35)	(1, 28)	(1, 35)
BP	(0, 41)	-	(-2, 42)
PAP	(0, 42)	(0, 77)	(-1, 43)
PAPb[16]	(0, 42)	(1, 77)	(0, 43)

[15] The highest value for bleached paper was increased to be equal to the value for unbleached paper

[16] The highest value for bleached paper was increased to be equal to the value for unbleached paper

COTorg	(150, 20000)	-	(150, 20000)
COT	(50, 7100)	-	(50, 7100)
COM	(-20, 870)	-	(-20, 870)

Table C16. Calculated number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3). The Table shows a (min, max) range obtained considering the minimum and maximum number calculated for each bag for all impact categories, without ozone depletion. Numbers lower than zero indicate when the carrier bag in the row already provides a better performance than the LDPEavg reference bag.

	LDPEavg, EOL3		
	Min - Max ranges, all impact categories w/o ozone depletion		
	EOL1	EOL2	EOL3
LDPEavg	(-1, 1)	(0, 5)	(0, 0)
LDPEs	(-1, 2)	(1, 8)	(0, 0)
LDPEh	(-1, 2)	(0, 6)	(-4, 0)
LDPErec	(-2, 3)	(1, 12)	(-1, 2)
PP	(-7, 38)	(2, 51)	(-6, 37)
PPwov	(-6, 33)	(1, 44)	(-5, 32)
PETrec	(-1, 95)	(5, 84)	(0, 96)
PETpol	(0, 35)	(1, 28)	(1, 35)
BP	(0, 41)	-	(-2, 42)
PAP	(0, 42)	(0, 77)	(-1, 43)
PAPb	(0, 30)	(1, 72)	(0, 28)
COTorg	(150, 3800)	-	(150, 3800)
COT	(50, 1400)	-	(50, 1400)
COM	(-20, 740)	-	(-20, 740)

Table C17. Average number of primary reuse times for the carrier bags in the rows, associated to the disposal options in the columns, necessary to provide the same environmental performance of the average LDPE carrier bag, reused as a waste bin bag before incineration (EOL3). The average number was obtained averaging the results of the carrier bags in the rows for each impact category.

	LDPEavg, EOL3		
	Average number of reuse times		
	EOL1	EOL2	EOL3
LDPEavg	0	2	0
LDPEs	1	3	0
LDPEh	1	2	0
LDPErec	2	4	1
PP	13	21	12
PPwov	11	18	10
PETrec	26	30	25
PETpol	9	9	8
BP	9	-	8
PAP	12	18	11
PAPb	10	16	9

COTorg	2376	-	2375
COT	840	-	840
COM	226	-	225

Appendix D. Critical review

KRITISK REVIEW AF "MILJØMÆSSIGE EFFEKTER AF BRUG AF PLASTBÆREPOSER I FORHOLD TIL ALTERNATIVE BÆREPOSER"
KRISTISK REVIEW AF LCA UDFØRT AF EKSTERN EKSPERT EFTER ISO 14044

Indledning

Dette kritiske review af livscyklusanalysen "LCA of grocery carrier bags" angående miljøeffekterne ved produktion, anvendelse og affaldsbehandling af bæreposer er udført af COWI efter den internationale standard ISO 14044, så vidt muligt.

Processen for det kritiske review var som følger:

- COWI gennemfører første review udført januar 2018.
- DTU forholder sig til reviewet og laver eventuelle rettelser (ny version af rap-port) februar 2018
- COWI forholder sig til rettelserne (nedenstående afsnit og tabel) i det endelige review notat februar 2018
-

Fra COWI blev det kritiske review gennemført af Line Geest Jakobsen og Trine Lund Neidel.

Generelle kommentarer

Generelle aspekter	Kommentarer fra COWI, første runde	Svar på kommentarer fra DTU Miljø	Kommentarer fra COWI, anden runde
Metoderne anvendt er i overensstemmelse med denne internationale standard	Ja, i vid udstrækning. DTU har skrevet, at der er uoverensstemmelse, idet der ikke er foretaget en udveksling med et ekspertpanel undervejs i projektet. Som vi forstår standarden, kan det kritiske review enten foretages af (1) en ekstern ekspert i slutningen af processen, som vi gør her, eller (2) af et interessentpanel, der inddrages i løbet af processen.	According to our understanding of the ISO 14044 standard (document version of 2008, point 6.1), when the results of the LCA are intended to be used to support a comparative assertion intended to be disclosed to the public, the review should be conducted by a panel of interested parties. Therefore, if the present study is going to be disclosed to the public and used for decision support, the critical review according to point 6.3 should apply instead of the critical review by external experts (6.2). The critical review by a panel of interested parties was however not budgeted in the time constraints of the current study.	√
Metoderne er videnskabeligt og teknisk gyldige.	Vi mener ikke, at det giver en fair sammenligning, at runde antallet af poser, der skal anvendes til at opfylde FU, op. Det er forkert at sammenligne f.eks. 2 (kapacitet: 18,8 liter, 10,5 kg) LDPE simple poser med 1 LDPE gns. pose (kapacitet 22,4 liter, 12,0 kg). Det er jo ikke bestemt, at alle altid køber præcis det, der kan være i en standard pose. Der vil jo være en stor overkapacitet i de fleste tilfælde, hvor der er valgt at anvende 2 reference-poser - hvis man f.eks. handlede 44 L/24 kg (dobbelt så meget som FU), vil man jo ikke benytte 4 LDPE virgin simple poser (alternativet), da 3 poser er tilstrækkeligt. Vi mener derfor, at der skal sammenlignes med det antal (ikke afrundet) poser der skal anvendes når begge krav (volumen og vægt kapacitet) er opfyldte. Dette vil betyde, at der f.eks. for	Addressed in the report as critical assumptions (Section 3). New results provided as sensitivity analysis (Section 7). We understand the reviewers' concerns and we have decided to introduce a different way of calculating the reference flow for this LCA study in the sensitivity analysis, instead of using the reference flow used in the study of Edwards and Fry, 2011. We have added a section on critical assumptions where we clearly raise the overcapacity concerns of our reference flow calculation. In the sensitivity analysis, we re-calculated the reference flows as fractions for those bags whose volume and weight holding capacity were inferior to those of an LDPE carrier bag with average characteristics (for example, as you suggest, 1.2 carrier bags for simple virgin LDPE instead of 2). The carrier bags affected by this reference flow change were virgin LDPE simple, LDPE recycled, biopolymer, paper, and organic cotton. For these bags, the change of reference flow resulted in a lower magnitude of	√

	"LDPE virgin simple" vil skulle sammenlignes med 1,2 poser i stedet for 2 (22,4/18,8=1,2).	the results. As far as the overall results are concerned: the most preferable end-of-life option for each carrier bag was not affected the bags providing the lowest impacts for each impact category were still paper, biopolymer and virgin LDPE carrier bags – the best performance among virgin LDPE carrier bags was provided by simple virgin LDPE bags the number of reuse times decreased for the bags affected by the reference flow change. For simple virgin LDPE, recycled LDPE, biopolymer and paper bags, the calculated number of reuse times was similar to the previous results. Biopolymer and paper presented lower number of reuse times across all impact categories. Organic cotton presented a havened number of reuse times: around 80 times for climate change and more than 10000 for all impact categories. The results of this sentivity analysis showed that the choice of reference flow influenced heavily the carrier bag with higher impacts connected to production and with a lower volume than expressed in the functional unit. We have added a dedicated section on carrier bag design where we provided comments on the influence of the design of the carrier bags on the results.	
Anvendte data er hensigtsmæssige og fornuftige	Hvad menes med polyester. Polyester dækker over flere polymerer, bl.a. PET, så hvad menes med denne posetype?	Corrected. We had used a generic polyester production data from Ecoinvent. After your comment, we verified the polymer material of the surveyed polyester bags, which showed to be virgin PET (We have re-modelled the results for this carrier bag type using an Ecoinvent production dataset for virgin PET because a dataset for "polyester PET" was not available. Results have been updated throughout the report and executive summary.	√
	Uddyb beskrivelsen af biopolymer, linje 555 og frem. Er det en komposterbar pose?	Added (now line 645) Yes, the bag is a compostable bag. (+ design considerations on effective compostability)	√
Vurderingsrapporten er gennemskuelig og konsekvent	Det danske resumé har brug for en kritisk gennemlæsning ift. sprog. F.eks. står der organisk i stedet for	We have done a full readthrough of the Danish Summary.	√

	økologisk, og ozonforstyrrelse i stedet for ozonned-brydning.		
Småting	Det er svært at huske hvad scenariebetegnelserne står for. Kunne man overveje forkortelser, der i højere grad er forbundet til materialetype?	Changed. Please see the new list of abbreviations for the carrier bag scenarios..	√
	I resuméerne kan der i linje 120/270 stå de fire LDPE pose typer, der er undersøgt	Added. In the Danish and English summaries, we added a brief description of the four LDPE carrier bags investigated. *"Low-density polyethylene (LDPE), 4 types: an LDPE carrier bag with average characteristics, an LDPE carrier bag with soft handle, an LDPE carrier bag with rigid handle and a recycled LDPE carrier bag."*	√
	Der er forskel i tabellerne IV i de to resumé.	Corrected.	√
	Pilen i figur I (dansk resume) fra Produktion af embal-lage materiale er vendt forkert.	Corrected	√
	Linje 463 under lightweight plastic carrier bags - skriftstørrelsen er forskellig.	Corrected.	√
	Table 2, linje 600, antal LDPE poser simple og rigid handle adderer ikke til 23.	Corrected. The numbers erroneously referred to a previous version of the Table, where there was no distinction between virgin LDPE carrier bags (in total 23) and recycled LDPE carrier bags (in total 3).	√
	Hvorfor står der "no" i table 3, linje 740 for vægt kapa-citet for flg. LDPE recycled, rigid handle, biopolymer og paper - de har en kapacitet på 12 kg?	Corrected. Yes, the recycled LDPE carrier bag with rigid handle has a weight holding capacity of 12 kg. The "No" erroneously reported was a typo. We decided to report the reference flow for simple and rigid handle recy-cled LDPE carrier bag in Table 3 for completeness, but in the end we considered only a scenario with a recycled LDPE carrier bag with average characteristics, due to the low number of recycled LDPE carrier bags encountered in the survey, and due to the lack of data for recycled LDPE carrier bag production.	√
	Table 5, linje 816, i "Human toxicity, non-cancer ef-	Corrected.	√

	fects" står der CTUh/PE/year - skal der ikke bare stå CTUh?	The impact assessment unit was in fact CTUh, CTUh/PE/year refers to the normalized unit, which was not used in the present study and was erroneously reported in Table 5.	
	Anvend samme rækkefølge for poserne i alle tabeller.	Corrected.	√
	Kan der komme et tal efter komma i Figure 16 i y-aksen?	Corrected. Now Figure 16 provides one digit after the comma.	√
	Kan det i Table 15 indikeres, hvilken påvirkningskategori der giver udslag i det største antal genbrug? I har taget "den værste" kategori, men det er væsentligt for tolkningen, at man kan se, om det er generelt højt/lavt, eller skyldes stor spredning imellem impact kategorierne (evt. pga. varierende datakvalitet).	Added in the text. We added in the discussion of the results that for some carrier bags the number of reuse times was rather homogeneous among impact categories, for other carrier bags the number of reuse times was mainly provided by few or just one impact category (as in the case of organic cotton, where the number of reuse times strongly depends on ozone depletion results). This could be related to data (in general, whether it has low quality or not), but also to the structure of the model (for example, the resulting climate change score from the interaction of carrier bag material production data, input specific emissions and energy recovery). For the organic cotton bag, the ozone depletion results were governed by cotton production data.	√
	Det ville være dejligt med billeder af de forskellige posetyper ved beskrivelserne af poserne i afsnit 2, så man i højere grad får et indtryk af hvilke poser, der er tale om.	Provided. Photos have been provided in order to complement the description of the surveyed carried bags in Section 2. (Figures 1-9). We had initially decided not to include the photos in order not to show the brand names on the carrier bags. The Miljøstyrelsen agrees with your request, but suggested to provide examples of the carrier bags instead of photos of the surveyed carrier bags, which would display the names of the retailers.	√

Tjekliste

Følgende skal være dækket af tredjepartsrapporten

Aspekter fra ISO 14044	Kommentarer fra COWI, første runde	Svar på kommentarer fra DTU Miljø	Kommentarer fra COWI, anden runde
Generelle aspekter			
livscyklusvurderingens opdragsgiver, udøveren af livscyklusvurderingen	√		
rapportens dato	√		
erklæring om, at vurderingen er udført i overensstemmelse med kravene i ISO 14044	√		
Vurderingens formål			
grundene til at foretage vurderingen	√		
dens påtænkte anvendelser	√		
målgrupperne	√		
erklæring om, hvorvidt vurderingen påtænkes at understøtte sammenlignende påstande, som er beregnet til offentliggørelse	√		
Vurderingens afgrænsning			
funktion, herunder			
erklæring om ydeevneegenskaber	√		
eventuel udeladelse af yderligere funktioner i sammenligninger	√		
funktionel enhed, herunder			

overensstemmelse med formål og afgrænsning	Nej, se nedenfor		
definition	Der står intet omkring produktion, distribution og affaldsbehandling.	Corrected. The functional unit now specifies more details regarding production, distribution and waste management. Further details have been added in the text following the functional unit definition. *"Carrying one time grocery shopping with an average volume of 22 litres and with an average weight of 12 kilograms from Danish supermarkets to homes in 2017 with a (newly purchased) carrier bag. The carrier bag is produced in Europe and distributed to Danish supermarkets. After use, it is collected by the Danish waste management system."*	√
resultat af ydeevnemåling	√		
systemgrænse, herunder			
udeladelser af livscyklusfaser, processer eller databehov	I EoL scenarierne 1 og 3 er der i boksene der starter i linje 1008 samt 1029 ikke indtegnet indsamling - hvorfor ikke? Det er vel medtaget ikke?	Added collection box in Figures 14-16. Yes, collection was included in the study for cardboard packaging collection and for the collection of the carrier bags for the different end-of-life scenarios. We have added more details in Figures 14-16 by specifying "collection" in the processes. We have provided the same colours as Figure 13.	√
kvantificering af energi-og materialeinput og –output	Mht. anvendelse af produktion af jomfruelig LDPE til at repræsentere den genanvendte LDPE; det ser ud til at der er ret stor forskel for PET, hvilket må formodes for LDPE også. Jeg vil foreslå at lave en følsomhedsanalyse, hvor man f.eks. anvender 25 % mindre udledninger.	Added as sensitivity analysis. The reduced impacts connecetd to LDPE production have lowered the impacts for recycled LDPE carrier bags. LDPE recycled resulted the carrier bag with the lowest associated impacts for particulate matter, photochemical ozone formation, terrestrial and freashwater eutrophication. The calculated number of reuse times decreased by 1 unit. We observed in the discussion of the sensitivity analysis that the sensitivity performed on the reference flow provided larger variations in the results for the calculated number of	√

	reuse times for this type of carrier bag.	
Hvorfor er der anvendt forskellig ekstern process for produktion af LDPE til bæreposen og affaldsposen? (s. 85)	Yes, we have used different external processes for the production of the bags. First of all, for LDPE carrier bags we had some data regarding the production of the carrier bag, for example energy and materials required per kg of produced carrier bag. For the waste bin bag, we did not have such data. For this reason, we decided to use the Ecoinvent dataset for the production of LDPE packaging, which included extrusion of LDPE and ancillary materials consumption. Secondly, the waste bin bags surveyed for this study were thinner and of a visible lower quality compared to the LDPE carrier bags. The Ecoinvent process chosen for waste bin bags production presented slightly lower overall impacts compared to the modelled one for the production of LDPE carrier bag. This was considered in line with the intended use of the bag: the LDPE carrier bags are intended for multiple uses, while the waste bin bag is intended for single use. During the modelling phase, we performed a sensitivity analysis and modelled the waste bin bag exactly as the LDPE carrier bag, but according to the mass of the waste bin bag. The environmental impacts resulted similar to the chosen Ecoinvent process for waste bin bags. Finally, selecting a process with slightly lower impacts for the production of the waste bin bag allows being more conservative regarding the results, since lower benefits will arise from the saving of a waste bin bag.	√
Burde produktion af komposit-posen ikke bestå af de andre dele end jute også, PP og bomuld? I har allerede data for disse processer, så der skal bare en fordeling af de tre materialer til.	Yes, the composite bag was modelled as a combination of the three materials: PP, jute and cotton. Based on the survey, we assumed 80% jute, 10% PP and 10% cotton. This proportion was present in the description of the com-	√

	posite bag scenario in Section 4. We added these details also in the assumptions section.	
Er der i produktion af biopolymer medtaget karbon-lagring?	No, to our understanding the Ecoinvent dataset for the production of starch-complexed biopolymer does not take into account carbon storage. We added this detail in the description of the biopolymer carrier bag scenario, Section 4.	√
Antagelsen om, at der er det samme tab i sortering før genanvendelse for jomfruelig LDPE og genanvendt LDPE i genanvendelsesprocessen kan diskuteres (linje 1065). For genanvendt PET er tabet højere end for ikke genanvendt LDPE (24,5% for genanvendt PET sammenlignet med 9,7% for LDPE). Tabet er måske i højere grad afhængigt af hvorvidt der er tale om genanvendt eller virgint plast og ikke polymer-afhængigt? Vi mener, at tabet for genanvendt LDPE er sat for lavt.	We did not have actual data for recovery efficiencies and residues occurring during recycling for recycled polymers, we only had data for recycling of virgin polymers. Therefore, we assumed that the efficiency was the same based on material type (ex/ same for all LDPE types). Of course the recovery efficiencies could be lower if the quality of the polymer sent to recycling was lower, but we did not have data to substantiate assumptions on lower recovery rates and higher residues production. In any case, even with high recovery rates and low amount of residues produced, EOL2 resulted rarely among the preferable end-of-life options. These assumptions are now specified in Section 3.	√
Antagelse af at rest-produkter fra sortering til genanvendelse af plast- og papirposer foregår i Danmark – det sker ikke i dag. Bør det ikke antages, at det sker i Tyskland eller Sverige – og dermed ikke går til forbrænding i DK? Betyder det ikke det store, så argumenter for det.	Specified in the text. Yes, recycling does not occur in Denmark. The cardboard packaging is assumed to be collcted in Denmark, but then transported abroad (Europe) for sorting and recycling. The same is assumed for the collection for recycling for all the separately collected fractions, which are transported abroad (Europe), sorted and recycled. In both cases, residues are incinerated in an average European incineration process (which was modelled with Ecoinvent processes) and are not assumed to be incinerated in Denmark.	√

		The location of the recycling plat was not disclosed by the project partners, so we assumed a general transportation distance of 2000 km (including also southern Europe) and used Ecoinvent processes based on Europe when possible.	
antagelser vedrørende elektricitetsproduktion	I valgt en fremtidig marginal for elektricitet - Er dette korrekt når nu FU siger 2017?	Specified in the text. Yes, the functional unit is based on carrier bags available for purchase in Danish supermarkets in 2017. However, since the study is assumed to support decisions that will occur in a 10 year period, using a future marginal energy is assumed to well represent the effects in the future waste management system. Moreover, this LCA study is part of a series of assessments conducted by DTU for the Miljøstyrelsen in the end of 2017 regarding decision support for future waste management options. All the assessments are based on the same marginal energy choices.	√
afskæringskriterier for den indledende/første medtagelse af input og output, herunder			
beskrivelse af afskæringskriterier og antagelser	√		
udvælgelsens indvirkning på resultater	Savner en kommentar på hvad udelukkelse af genanvendelse af tekstilerne og biopolymeren betyder.	Specified in the text (line 1029-1038). Excluding recycling for textiles and biopolymers means that carrier bags of these materials will only be tested for EOL1 and EOL3. Considering recycling feasible would mean allowing the recovery of these materials through separate collection and re-processing, therefore lowering the impacts connected to the production of the carrier bags. Recycling of textiles was not taken into account since it mainly occurs outside the Danish waste management system, for example via charity organizations or through return schemes at retailer shops. The extent of recovery of materials can be extremely variable according to the specific collection selected. Regarding biopolymer carrier bags, which are com-	√ Vi kan ikke helt følge argumentationen for ikke at medtage genanvendelse af tekstiler, da indsamlingsmetoden (at den ikke foregår i kommunalt regi) ikke skulle påvirke genanvendelsen. Vi tænker mere, at argumentet skal være, at der kun i ringe grad på nuværende tidspunkt

		postable starch-biopolymer bags, we did not include material recovery through composting, since biopolymer bags are currently sorted out from organic waste management plants.	sker materialegenanvendelse af tekstiler, men primært genbrug, som ikke er så relevant i denne evaluering.
medtagelse af afskæringskriterier for masse, energi og miljø	Ikke specifikt uddybet.	Corrected. We have re-written the system boundaries section, providing a better description of the inputs and outputs.	√
Livscykluskortlægning			
dataindsamlingsprocedurer	√		
kvalitativ og kvantitativ beskrivelse af enhedsprocesser	Der savnes beskrivelse af f.eks. om processerne inkluderer biomassebegrænsning.	Specified in the text (line 1079). Biomass was not considered a limited resource.	√
kilder til udgivet litteratur	Der savnes en kilde på de 30% mindre udbytte fra økologisk bomuldsproduktion (s. 35, linje 862)	Added. The yield of organic cotton farming was assumed 30 % lower than conventional cotton. For the modelling, this implies that 30 % more impacts are considered for the production of organic cotton than conventional cotton. The yield was found to vary in the literature between 20 % and 40 % and according to the geographical location (Forster et al., 2013). Since the Ecoinvent dataset for cotton production is not linked to a specific geographical location, 30 % was considered as average value. The selected value influences the contribution of the production process to the overall impacts related to the organic cotton carrier bag.	√
beregningsprocedurer	√		
validering af data, herunder			
datakvalitetsvurdering	Mangler, f.eks. vurderes det ikke, hvad det betyder, at nogle processer er globale i stedet for europæi-	Added. In Section 3, we have provided a discussion on data re-	√

	ske.	quirements, assumptions used to provide missing data, and critical assumptions. In Section 5, we have provided a discussion of the results in the light of data quality and assumptions. Critical assumptions have been tested as sensitivity analysis and discussed in Section 7. Among other data issues, we have specifically discussed the influence on the results of the choice of European versus global data.	
behandling af manglende data	√		
følsomhedsanalyse til raffinering af systemgrænsen	1. "Choice of reference flow" – lidt svært at forstå hvordan antallet af poser er beregnet. Kan det beskrives bedre, hvordan den nye ydeevne (antal genstande) relateres til de anvendte ydeevner i resten af studiet (bæreevne og volumen).	Specified in the text and in the sensitivity analysis. The reference flow for each bag subtype in Table 3 was calculated taking into consideration both volume and weight holding capacity as conditions that had to be fulfilled at the same time. This means that, for each carrier bag, if the volume or/and the weight holding capacity were lower than the ones specified in the functional unit, we assumed that the customers would need to buy two bags instead of one in order to comply for the same functionality (a grocery shopping of the volume of 22 litres and/or a weight of 12 kilograms). When a bag was required two times, it was modelled by multiplying by two the average weight and volume provided in Table 2. In the cases of biopolymer and paper carrier bags, the weight holding capacity surveyed was in average compliant with the virgin LDPE carrier bag, but provided the highest variance between the samples. For example, the weight that these types of bags were capable of holding varied greatly in the tested samples, especially if the items placed in the bags for the survey had sharp angles, which tore the bags much more easily than for other carrier bag types (Alonso Altonaga, 2017). For these reasons, the weight holding capacity for the reference flow was	√

		considered not respected, and that two bags would be required to carry the same weight. We have decided to replace the sensitivity analysis that used the reference flow of the UK study performed by Edwards and Fry (2011) with a sensitivity analysis that calculated the "fractions" for the carrier bags that required rounding to two bags in order to provide for the functional unit. In the sensitivity analysis, we provided the formula used to re-calculate the reference flow.	
	Table 17: Er værdierne for Biopolymer EOL3 korrekte? De virker lave ift, hvor meget EOL1 værdierne stiger.	The sensitivity analysis results presented in the previous version of the report (old Table 17) is not present anymore. Anyhow, the results for BP, EOL3 were correctly lower than EOL1: this non-fossil carbon and lightweight carrier bag provides larger advantages when used for substituting a virgin LDPE waste bin bag.	√
	3. "Different way to calculate primary reuse" (linje 1553 og frem) giver ingen mer-værdi. Det er jo bare om man regner på antal primær genbrug eller antal gange man bruger posen i alt. Skriv 1-2 linjer om dette i valg af metode i stedet for.	Agree. We have added a sentence in the section "modelling of primary reuse". *Edwards and Fry (2011) performed a similar assessment, but calculating the number of reuse times simply performing a ratio between the carrier bag alternative and the reference carrier bag. Such calculation differs from the method adopted for the present study by providing the number of reuse times, instead of the number of times the bag is used in total (Eq. 2).*	√
	Gentager, at vi anbefaler en følsomhedsanalyse, hvor man f.eks. anvender 25 % mindre udledninger for produktion af jomfruelig LDPE til at repræsentere den genanvendte LDPE.	Added. Please see point 3.3b above.	√
allokeringsprincipper og –procedurer, herunder			

dokumentation og begrundelse for allokeringsprocedurer	Jeg kan ikke læse om der er anvendt biomassebegrænsning eller ej.	Added (please see above comment 4.2).	√
ensartet anvendelse af allokeringsprocedurer	√		
Vurdering af miljøpåvirkninger i livscyklus, hvis anvendt			
LCIA-procedurer, beregninger og resultater af vurderingen	√		
begrænsninger af LCIA-resultater, som vedrører livscyklusvurderingens formål og afgrænsning	√		
sammenhængen mellem LCIA-resultater og formål og afgrænsning	I skriver i linje 677 at "Then, the calculated number of reuse times based on environmental performance was compared to the expected lifetime of the bag and used as a basis for discussion." – Dette synes jeg ikke, at jeg kan se af LCIA/diskussionen. Der er ingen kvantitative levetider på poserne.	Rephrased (now line 792) “Then, the calculated number of reuse times based on environmental performance is intended to raise the discussion among the stakeholders on the effective expected lifetime of each carrier bag.”	√
sammenhæng mellem LCIA-resultaterne og LCI-resultaterne	√		
påvirkningskategorier og kategoriindikatorer under betragtning, herunder den logiske begrundelse for, at de er valgt, herunder antagelser og begrænsninger	√		
beskrivelse af eller henvisning til alle anvendte karakteriseringsmodeller, karakteriseringsfaktorer og metoder, herunder antagelser og begrænsninger	√		
beskrivelse af eller henvisning til alle anvendte værdibaserede valg i forhold til påvirkningskategorier, karakteriseringsmodeller, karakteriseringsfaktorer, normalisering, gruppering, vægtning og, andre steder i LCIA-en, en begrundelse af deres anvendelse og påvirkning på resultaterne	-		
en erklæring om, at LCIA-resultaterne er relative ud-	Mangler	Added both in the LCIA methods description and in the	√

tryk, som ikke forudsiger påvirkninger på kategori-end-point, eller overskridelser af tærskelværdier, sikkerhedsmarginer eller risikoniveauer og, når medtaget som en del af livscyklusvurderingen (LCA), også		section providing the characterized results.	
en beskrivelse af og begrundelse for definitionen og beskrivelsen af eventuelle nye påvirkningskategorier, kategoriindikatorer eller karakteriseringsmodeller anvendt til LCIA'en	√		
en fremstilling af og begrundelse for eventuel gruppering af påvirkningskategorierne	na		
eventuelle yderligere procedurer, som omregner indikatorresultaterne, og en begrundelse for de valgte, referencer, vægtningsfaktorer etc.	na		
en eventuel analyse af indikatorresultaterne, fx følsomheds- og usikkerhedsanalyse eller anvendelse af miljødata, herunder eventuel betydning for resultaterne	√		
data og indikatorresultater fra før en eventuel normalisering, gruppering eller vægtning skal gøres tilgængelige sammen med de normaliserede, grupperede eller vægtede resultater	√		
Livscyklusfortolkning			
resultaterne	Kan det specificeres yderligere, hvad det f.eks. er i materialeproduktion der betyder mest for udledningerne?	Added contribution analysis for the production part for each carrier bag type (Tables 13-21).	√
	Kunne man ud fra konklusionerne om, hvor mange gange poserne skal genanvendes for at matche miljøeffekten for referencen, for hver posetype vurdere, hvorvidt dette er realistisk? Evt. med en farveskala (grøn=realistisk, gul=måske og rød=ikke realistisk)? Som støtte til beslutningstagere. Evt. i resu-	We have decided not to do this, as it will have a part assumptions on average life times. We will leave this to the EPA in their choice on how they wish to use the report. We have commented further on the importance to do such a realism check.	√

	meet.		
antagelser og begrænsninger, som vedrører fortolkningen af resultater, både metodik- og datarelaterede	Kan der siges noget om, hvad betyder, det at nogle af materialeproduktionerne er globale, andre europæiske og nogle andre dele af verden?	Added. We have added a specific paragraph on assumptions and critical assumptions. In particular, with respect to dataset referring to differen geographical locations: *"In general, market and global datasets provided slightly higher emissions than production datasets in specific geographical locations. Therefore, the carrier bags for which only production datasets were available are likely to have slightly lower emissions than using market datasets. Assuming that the carrier bag manufacturers retrieve materials and energy from the market, our preference was always for the market datasets. When not available, we used production datasets, preferably for Europe."*	√
datakvalitetsvurdering	Mangelfuld	Added a discussion of the results with respect to the highlighted data limitations and assumptions.	√
fuld gennemskuelighed, hvad angår værdibaserede valg, logiske begrundelser og ekspertvurderinger	√		
Kritisk review			
navn på og tilhørsforhold for de personer, der udfører review	Navne skal tilføjes		√
redegørelse fra kritisk review	√		
svar på anbefalinger fra det kritisk review	Kommer senere		√

Life Cycle Assessment of grocery carrier bags

Currently, Danish supermarkets provide multiple-use grocery carrier bags of different materials (such as plastic, paper and cotton) that are designed for multiple uses. In order to compensate the environmental impacts connected to the production of the bags, these multiple-use carrier bags need to be reused a number of times.

This Life Cycle Assessment study examined the environmental impacts connected to the production, distribution, use and disposal of multiple-use grocery carrier bags available for purchase in Danish supermarkets for a range of environmental indicators. The study identified which carrier bags provide the lowest impacts for their production and which is the optimal disposal option for specific carrier bag materials. The goal of the study was quantifying the required minimum number of reuse times for each of the multiple-use carrier bags based on their environmental performance.

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