No. C 297
March 2018

Assessing the Environmental Implications of a Regional Industrial Symbiosis Network for Innovative Products

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Med stöd från:
In cooperation with Econova AB and Linköping University

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Funded by: Re:Source Strategic Innovation Program through FORMAS, Vinnova and Energimyndigheten
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Report number C 297
ISBN 978-91-88787-31-6
Edition Only available as PDF for individual printing

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This report has been reviewed and approved in accordance with IVL's audited and approved management system.

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Summary

Industrial symbiosis (IS), where different entities collaborate over energy, utilities, materials or services to create value and lower cost and environmental impact, has been identified as an approach to improve resource efficiency. North of Norrköping, Sweden, an industrial symbiosis network of firms exists, which currently exchange by-products, wastes and energy. These include Econova, the paper and sawmill of Holmen, municipal waste actors and energy providers (i.e. Tekniska Verken). Through these synergies, several innovative products based on forest, paper, sawmill and energy by-products have been created.

The focus of the project will highlight the environmental performance of the industrial symbiosis network and pay particular attention to the value of facilitation services by Econova to produce hard surfaces and soil products for the consumer and bulk market.

The results suggest that there are significant benefits due to the exchanges of material and energy between the firms in the IS network. Large reductions in greenhouse gas emissions and local impacts, namely eutrophication and acidification impacts are possible. Furthermore, large reductions in abiotic resource depletion are also possible. Overall, compared to a reference scenario, with no synergies, the IS network can annually reduce:

- GHG emissions with roughly 170 million kg (170 000 tonnes) CO_2-eq
- Eutrophication impacts by roughly 750 tonnes PO_4-eq
- Acidification impacts by roughly 190 tonnes SO_2-eq
- Abiotic resource depletion with nearly 340 000 GJ-eq

It was shown that all firms in the network benefit from the synergies involved. Replacing peat with fiber mulch led to significant environmental impact reductions for Econova, leading to reduced impacts for the main products, i.e. consumer and bulk soils. Furthermore, by providing fiber sludge to Econova, there are also benefits provided to Holmen Paper by reduced landfilling and being provided a share of the credits for replaced peat; and larger benefits in potential future scenarios where larger shares of fiber sludge are shared. Holmen Sawmill and Paper plants were also illustrated to receive large benefits from using heat supplied by Holmen Paper. Finally, all firms which install ECA surfaces showed significant improvements in comparison to surfaces produced with concrete and asphalt.

Finally, the results point to the importance of the facilitation of by-products and wastes by Econova, and the significant value this creates in the region, with large potential to improve environmental performance of firms and their products.

Acknowledgements

The author and research team members are grateful for the support provided from Re:Source Strategic Innovation Program through Swedish Energy Agency, Vinnova and Formas. We would also like to thank Holmen, Tekniska Verken i Linköping AB and employees at Econova who have provided data and other comments, in addition to the internal reviewers for providing valuable input to improve the report.

1 Introduction

Sustainable development has been identified as a key challenge in most economies, with climate change and resource scarcity imperative on agendas of many. Since the dawn of industrial development, resource consumption has increased at an unprecedented rate to fuel growth worldwide. Nations worldwide have thus set forth ambitious targets and actions, putting climate change and resource efficiency on the agenda, to reduce their environmental impacts and move away from traditional linear production systems more toward resource efficient and "circular" production systems. Industrial symbiosis (IS), where different entities collaborate over energy, utilities, materials or services to create value and lower cost and environmental impact, has been identified as an approach to improve resource efficiency.

North of Norrköping, in the Åby-Bråviken area, there is currently an industrial symbiotic network of firms exchanging by-products. These include exchanges with, and in between, the paper and sawmill of Holmen, Econova, municipal actors and energy providers (i.e. Tekniska Verken). Through these synergies, several innovative products based on forest, paper and sawmill and energy by-products. The focus of the project will highlight the environmental performance from the facilitation of industrial residues by Econova and exchanges between the firms in the symbiosis network. These include the handling and upcycling of by-products and wastes to produce soil products for the consumer market and for soil used for professional actors (hereafter labelled as bulk soil) for construction projects. Econova handles compost and several by-products from Holmen, namely bark and fiber sludge. Econova facilitates the collection and transformation of these products into bark mulch (*barkmull*) and fiber mulch (*fibermull*) which are used as a soil improvement material in garden soil products; ultimately replacing peat. Each year Econova produces large quantities of soil for the consumer market and for bulk applications (e.g. professional construction projects). Thereafter, Tekniska Verken, and to a lesser extent Holmen, produce large volumes of fly- and bottom ash from their incinerators. Econova has created a market to add value to the ash, avoiding landfilling, in a process to create cement stabilized ash which is used for industrial surface applications and for timber storage facilities; named ECA (Econovas cementstabiliserande aska). The product creates a durable surface for many applications and provides an alternative to the use of concrete and asphalt. Finally, within the Holmen "cluster," heat is exchanged between the paper and sawmill, reducing the need for heat at the saw mill for drying.

This report is part of a larger assessment of the business and environmental developments of the symbiotic developments from Econova in the Re:Source project *Industrial symbiosis: enabling innovative thinking and new business development.* In this report, and as part of this project, Dr. Michael Martin at IVL Swedish Environmental Research Institute has led a work package to assess the potential environmental benefits of the synergies within the larger industrial symbiosis network of firms in the region. The results presented in this report review the environmental assessment, led and conducted by Dr. Martin, with input from Econova, Holmen and Tekniska Verken.

2 Methodology

To review the environmental benefits created through the synergies, life cycle assessment was used to review the system. This was done using methods for applying LCA to industrial symbiosis to compare the current system with a reference and future scenarios, including improvements.

2.1 Applying Life Cycle Assessment to Industrial Symbiosis

In the literature, an underlying consensus is that industrial symbiosis will lead to mutual benefits for companies involved in the exchanges; i.e. both environmental and economic benefits. Those studies which provide quantifications of IS networks typically review a selected few exchanges or quantify the entire IS network (Wolf and Karlsson, 2008; Mattila et al., 2010; Sokka et al., 2011). In order to review the environmental implications of the IS network, life cycle assessment (LCA) was used and applied to the network. LCA is typically used to review and assess the environmental sustainability of products and services as it allows for reviewing and understanding the possible environmental impact tradeoffs of decisions made between production stages and on other systems. Hitherto, only a limited number of examples of the use of LCA to review the environmental implications of industrial symbiosis networks are available in the literature (Martin, 2013; Martin et al., 2015; Mattila et al., 2012; Chertow and Lombardi, 2005; Sokka et al., 2011). However, Mattila et al. (2012) and Martin et al. (2015) have extended the framework and provided guidance on the use of LCA for reviewing IS networks.

The assessment of the environmental impacts (and benefits) of the industrial symbiosis network follows the methodology outlined in Martin et al. (2015) for LCA to IS networks. Using this method allows for the review of both the impacts from the network (as a whole) and the benefit for individual firms in the network. Furthermore, the method allows for an “equal distribution” of benefits created by replacing conventional products, through the shared use of resources, i.e. in the outlined 50/50 method. This method is advantageous when, and if, no other LCA is mandatory in policy and to review the symbiotic system as an arrangement of actors benefiting from one another. Otherwise, it is difficult to partition the benefits, and impacts, between producers and actors in the IS network; see Figure 1 below.

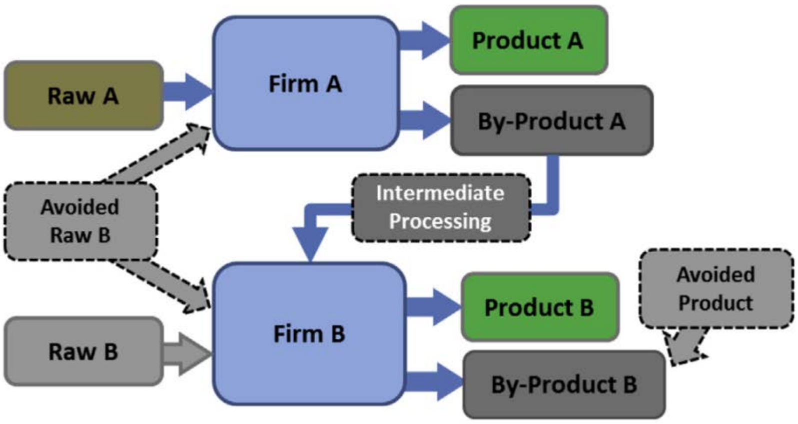

Figure 1: Illustration of methodology using the 50/50 method. Illustration from Martin et al. (2015)

Figure 1 above, illustrates the approach for a simple exchange between Firms A and B. The "fair" distribution of credits from the avoidance of Raw B is produced by providing Firm A and B a share (50%) of the credit for the equivalent amount of Raw B avoided. As to not double-count the benefits and to model changes to the system by removal of Raw B, Firm B is provided a burden/impact for the production of Raw B; thus Firm B would only receive 50% of the impact of Raw B in total. Furthermore, by-products leaving the system are still avoided, according to the use of system expansion methodology. Intermediate processing is also possible, and the impacts of such a step are to be distributed between the firms involved in the exchange following the same 50/50 logic; this can include distributing impacts from upgrading and transport between the different companies involved in an exchange.

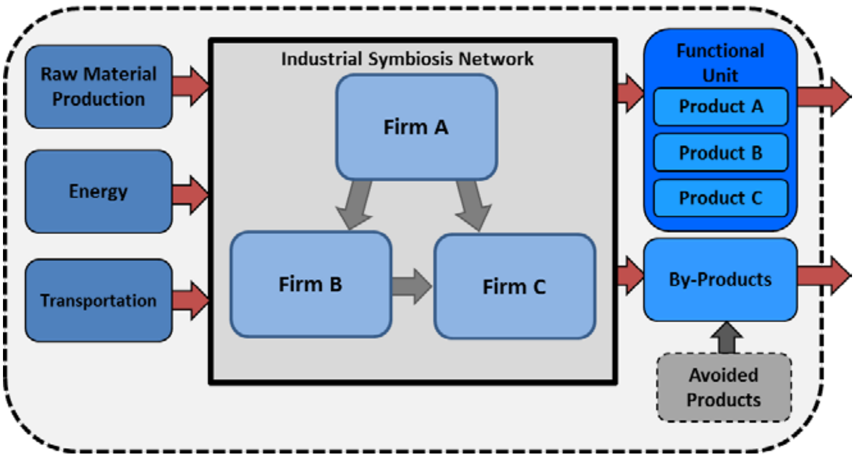

Figure 2: Illustration of methodological choices and data for reviewing an IS network, as outlined in Martin et al. (2015)

Furthermore, the approach of Martin et al. (2015) also outlines the selection, and potential impacts, of methodological considerations used for the quantifications including e.g. the choice of reference systems, allocation methods, system boundaries and functional unit(s); see Figure 2. More information on applying a "system expansion" approach to avoid allocation can be found in Weidema (2001).

The following sections provide more details on the methods, scenarios, boundaries and function of the system.

3 Scenarios Assessed

The industrial symbiosis network was assessed using several scenarios to review the environmental performance of the network. These included a scenario to review the performance of the current network of exchanges, comparing this to a reference system where no IS network was in place and reviewing potential improvements in the future.

In order to review how the IS network improves the products, and the environmental benefits provided by Econova's management and valorization of waste products, a reference system is used for comparison to the current system. The selection of this reference system is important, as several authors suggest; see e.g., Martin et al., 2015; Sokka et al., 2012; Mattilla et al., 2012. This is due to the fact that the reference system is normally chosen as the counterfactual system producing the same function as the studied symbiosis system (Martin et al., 2015). As such, the assumptions made for the reference system will determine the overall benefit compared to other scenarios.

Furthermore, in order to allow for a comparison of the reference versus the current IS network, and additionally a future scenario, the functional equivalence is important. Thus, the functional unit is important in the analysis to understand this evolution and comparisons are done based on main product outputs from the IS network in Åby-Bråviken; see Figure 3. The functional unit of the system is thus set as the annual production of consumer soil, bulk soil, paper, sawn boards, compost, surfaces and electricity production based on production figures for 2016. All scenarios have a functional unit which is functionally equivalent[1].

For the life cycle assessment of the system, the life cycle impact assessment (LCIA) method, CML 2014 was employed. The impact categories, GWP (100)-Global warming potential (measured in kg CO_2-eq), AP-Acidification Potential (measured in kg SO_2-eq), EP-Eutrophication Potential (measured in kg PO_4-eq) and ABD- Depletion of abiotic resources - fossil fuels (measured in MJ) were included. This was done in order to provide a review of the global, regional and resource implications of the IS network, and potential changes; and due in part to the use of renewable resources and substitution of fossil inputs in the scenarios assessed.

[1] In the reference and future scenarios, the total output (e.g. in tonnes) may be different. While the values are dissimilar, the function is till equivalent. An example of this is the output of soil. In the reference system the total weight of soil output is higher than the current scenario. This is due to the fact that more peat and lime are used compared to fiber mulch.

3.1 Current IS Network

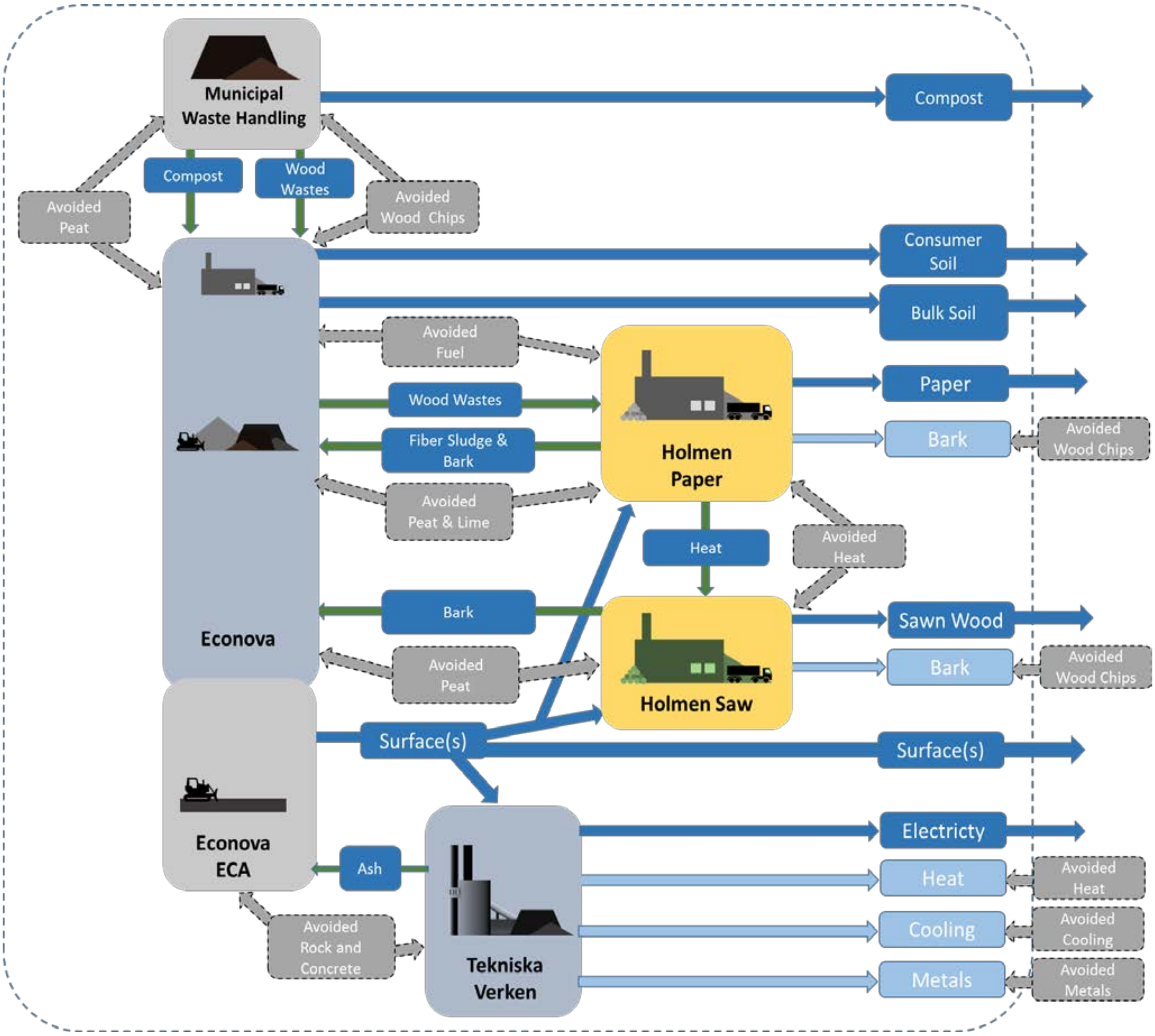

Figure 3: System description reviewing input and outputs of the different of firms for the synergies reviewed. The dashed boundary represents the system boundary of the study. Other boxes and arrows denote main outputs (dark blue arrows out of the boundary), avoided products and processes (gray dashed boxes and arrows), by-products (light blue boxes), applied impacts (dark gray boxes and arrows) and exchanges (thin blue arrows). Material and energy inputs, besides synergies are not reviewed in the Figure; see subsequent tables for more information.

3.1.1 Econova (Soil Products)

Figure 4: Several large piles of different by products used to develop soil at Econova

Data for the inputs and transportation distances of materials used in soil products from Econova were provided by Econova (2017) based on figures for 2016 for both consumer and construction soil; see Table 1 and Table 2. It was assumed that transportation of peat had an average distance of 200 km, and all other products from the market a distance of 100 km. For transportation of products between Econova and Holmen, the transport distance was shared between the firms (i.e. half the assumed total 5 km). For the mixing, loading and shipping of soils at Econova's soil mixing grounds in Åby, it was assumed that roughly 1500 hours of diesel machine use (e.g. tractors, loaders, dump trucks, etc.) were used for mixing, delivering, etc. each of the different soil types; see a depiction of the Econova soil site in Figure 4. LCI data for the soil components, diesel vehicle operation and energy requirements were obtained from Ecoinvent v 3.3. See the Appendix for further information.

Table 1: Inputs and Outputs for the Consumer Soil Production from Econova

Econova-Consumer Soil							
		Flow	Origin/ Class.	Amount	Unit	Use/ Destination	Transp. (km)
Inputs	Material	Peat		52 000	Tonne	-	200
		Bark	IS-Holmen Paper	7 700	Tonne	-	2.5
		Fiber Mulch	IS-Holmen Paper	17 500	Tonne		2.5
		Compost	IS-MSW	4 800	Tonne		10
		Plastic		2	Tonne		100
		Sand		16 500	Tonne		100
		Lime		1 000	Tonne	-	100
		Fertilizers		300	Tonne	-	100
	Energy	Electricity		0.45	GWh		-
		Machine Operation		1 500	Hours		
Outputs	Material	**Consumer Soil (Bags)**	**Main Product**	**94 810**	**Tonne**	**Market**	**200**

Table 2: Inputs and Outputs for the Bulk Soil Production from Econova

Econova-Bulk Soil							
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Peat	-	15 600	Tonne	-	200
		Bark Mulch	IS-Holmen	5 470	Tonne	-	2.5
		Fiber Mulch	IS-Holmen	11 200	Tonne	-	2.5
		Compost	IS-MSW	6 600	Tonne	-	10
		Rec. Soil	-	15 000	Tonne	-	50
		Sand and Clay	-	6 000	Tonne	-	100
		Lime	-	960	Tonne	-	100
		Fertilizers	-	240	Tonne	-	100
	Energy	Machine Operation	-	1 500	Hours	-	-
Outputs	Material	**Bulk Soil**	**Main Product**	54 960	**Tonne**	**Market**	100

3.1.2 Holmen Paper and Sawmill

Information on material and energy inputs and outputs for Holmen's paper plant and sawmill were obtained from Holmen (2017 a,b). Actual figures for the fiber sludge exchange with Econova were provided by Econova (2017). Thereafter, assumptions were made based on the data available for the different flows of by-products (e.g. bark, saw dust, etc.) used for heat and external markets. The logs used for the sawmill and paper production were assumed to be transported no further than 150 km, as Holmen owns forest operations in the region. Paper and sawn timber were assumed to be transported 200 and 150 km respectively. By-products are assumed to be used 100 km from Bråviken. For transportation of products between Econova and Holmen, the transport distance was shared between the firms (i.e. half the assumed total 5 km).

LCI data for the inputs and emissions for the incineration and energy production, the material inputs, paper, board production, and electricity were obtained from Ecoinvent v 3.3. See the Appendix for further information.

Table 3: Inputs and Outputs for Holmen Paper

Holmen Paper							
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Wood/Timber	-	1 160 000	Tonne	-	100
		Paper Pulp	-	800	Tonne	-	100
		Water	-	13 900 000	Tonne	-	-
		Surface	IS-Econova ECA	25 000	m^2	-	-
	Energy	Heat-Recycled Wood	IS-Econova	22	GWh	-	-

		Electricity	-	1 500	GWh	-	-
		Heat-Fossil	-	42	GWh	-	-
		Heat-Bark	-	134	GWh	-	-
		Heat- Fiber Sludge	-	67	GWh	-	-
Outputs	Material	**Paper**	**Main Product**	**520 000**	**Tonne**	**Market**	200
		Fiber Sludge (Mulch)	By-Product	28 700	Tonne	IS-Econova	2.5
		Other	By-Product	12 720	Tonne		2.5
		Bark	By-Product	6 580	Tonne	IS-Econova	2.5
		Energy By-Products	By-Product	135 000	Tonne	-	100
	Energy	Electricity	-	-	GWh	-	-
		Heat	By-Product	110	GWh	IS-Holmen Sawmill	-

Table 4: Inputs and Outputs for Holmen Sawmill

Holmen Sawmill							
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Logs	-	800 000	Tonne	-	150
	Energy	Electricity	-	26	GWh	-	-
		Heat- Fossil	-	25	GWh	-	-
		Heat	IS-Holmen Paper	110	GWh	-	-
Outputs	Material	**Sawn Timber**	**Main Product**	**440 000**	**m^3**	**Market**	150
		Bark	By-Product	6 580	Tonne	IS-Econova	3
		Wood/Bark	By-Product	190 420	Tonne	Market	100

3.1.3 Econova ECA (Surface)

ECA surfaces, and the area produced annually, i.e. for 2016, were modeled based on input from Econova (2017) and expert estimates. The ECA surfaces were assumed to be 30-40 cm thick, with varying layers of cement, crushed rock, fly and bottom ash[2]. Table 5 and Table 6 review the material inputs-outputs for the ECA surfaces installed in Norrköping and Linköping respectively. Further details on the assumptions and different modeling of the surfaces are found in the Appendix. Materials used for the production of the ECA surfaces were assumed to be transported no further than 100 km. The transportation of fly ash and bottom ash from Linköping to Norrköping was assumed to be roughly 40 km, split between the two firms facilitating this synergy. For production of ECA in Linköping, fly ash and bottom ash are assumed to be transported a maximum distance of 2 km. Operation of diesel machinery was assumed to take 5 min/m^2 (0.08 hours/m^2) for producing the ECA surfaces.

[2] See more information about Econova's ECA surfaces at: http://www.econova.se/atervinning/konstruktion/hardgjorda-ytor/3464519.3478358.3547025a

Table 5: Inputs and Outputs for the ECA Surface production in Norrköping

Econova ECA-Norrköping							
		Flow	Origin/ Class.	Amount	Unit	Use/ Destination	Transp. (km)
Inputs	Material	Cement	-	10 800	Tonne	-	100
		Crushed Rock	-	5 520	Tonne	-	50
		Fly Ash	IS-Tekniska Verken	1 125	Tonne	-	20
		Bottom Ash	IS-Tekniska Verken	5 250	Tonne	-	20
	Energy	Machine Operation	-	4 200	hours	-	-
Outputs	Material	Surface	-	50 000	m^2	IS-Surface Holmen	-
		Surface	**Main Product**	**5 000**	**m^2**	**Market (Surface)**	-

Table 6: Inputs and Outputs for the ECA Surface production in Linköping

Econova ECA-Linköping							
		Flow	Origin/ Class.	Amount	Unit	Use/ Destination	Transp. (km)
Inputs	Material	Cement	-	2 160	Tonne	-	100
		Crushed Rock	-	1 100	Tonne	-	100
		Fly Ash	IS-Tekniska Verken	225	Tonne	-	2
		Bottom Ash	IS-Tekniska Verken	1 800	Tonne	-	2
	Energy	Machine Operation	-	830	Hours	-	-
Outputs	Material	Surface	-	10 000	m^2	IS-Surface Tekniska Verken	-

LCI data for the ECA surface inputs, diesel vehicle operation and energy requirements were obtained from Ecoinvent v 3.3. See the Appendix for further information.

3.1.4 Tekniska Verken

For the CHP plant, and subsequent use of the by-products such as ash for ECA production, details were provided based on information provided by Tekniska Verken (2017) and Econova (2017). It was assumed that by-products from the CHP plant replace conventional products such as metals, heat, electricity for cooling, gravel, etc. Ash fractions were split in order to allocate a share of ash for transportation from Linköping for ECA surfaces in Norrköping, while other shares are used for ECA surfaces in Linköping. However, the largest share of ash is assumed to be used for landfill covering, etc. (Tekniska Verken, 2017). Transportation of household wastes, both domestic and imported, were assumed to have a maximum distance of 100 km. The transportation distance for ash fractions used in Norrköping for ECA surfaces was shared between Tekniska Verken and

Econova (i.e. half of the total assumed 40 km distance). Thereafter, all other by-products were assumed to include a transportation distance of 100 km to their potential markets.

Electricity is the main product of the system, with district heating and cooling as the main energy by-products, which replace conventional heating and cooling (electricity). By-products from incineration, e.g., metals, were assumed to have a market and replace other waste metals.

Table 7: Inputs and Outputs for the CHP Plant in Linköping (Tekniska Verken)

<table>
<tr><th colspan="8">Tekniska Verken</th></tr>
<tr><th></th><th></th><th>Flow</th><th>Origin/ Class.</th><th>Amount</th><th>Unit</th><th>Use/ Destination</th><th>Transp. (km)</th></tr>
<tr><td rowspan="3">Inputs</td><td rowspan="3">Material</td><td>Domestic Household Waste</td><td>-</td><td>390 790</td><td>Tonne</td><td>-</td><td>150</td></tr>
<tr><td>Imported Household Waste</td><td>-</td><td>347 700</td><td>Tonne</td><td>-</td><td>500</td></tr>
<tr><td>Surface</td><td>IS-Econova ECA</td><td>10 000</td><td>m^2</td><td>-</td><td>-</td></tr>
<tr><td rowspan="11">Outputs</td><td rowspan="8">Material</td><td>Bottom Ash –Norr.</td><td>By-Product</td><td>5 250</td><td>Tonne</td><td>IS-ECA-Norr.</td><td>20</td></tr>
<tr><td>Fly Ash-Norr.</td><td>By-Product</td><td>1 125</td><td>Tonne</td><td>IS-ECA-Norr.</td><td>20</td></tr>
<tr><td>Bottom Ash-Link.</td><td>By-Product</td><td>1 800</td><td>Tonne</td><td>IS-ECA-Link.</td><td>1</td></tr>
<tr><td>Fly Ash-Link.</td><td>By-Product</td><td>225</td><td>Tonne</td><td>IS-ECA-Link.</td><td>1</td></tr>
<tr><td>Metals Magnetic</td><td>By-Product</td><td>4 640</td><td>Tonne</td><td></td><td>100</td></tr>
<tr><td>Slag</td><td>By-Product</td><td>67 680</td><td>Tonne</td><td>-</td><td>100</td></tr>
<tr><td>Metals Non-Magnetic</td><td>By-Product</td><td>2 120</td><td>Tonne</td><td>-</td><td>100</td></tr>
<tr><td>Ash Other</td><td>By-Product</td><td>129 600</td><td>Tonne</td><td>-</td><td>100</td></tr>
<tr><td rowspan="3">Energy</td><td>Electricity</td><td>Main Product</td><td>263</td><td>GWh</td><td>Market</td><td>-</td></tr>
<tr><td>Heat</td><td>By-Product</td><td>1 300</td><td>GWh</td><td>Market</td><td>-</td></tr>
<tr><td>Distr. Cooling</td><td>By-Product</td><td>52</td><td>GWh</td><td>Market</td><td>-</td></tr>
</table>

Link.-Linköping, Norr.-Norrköping

LCI data for energy production from municipal waste incineration and all data for replaced conventional products were obtained from Ecoinvent v 3.3. See the Appendix for further information on the datasets used.

3.1.5 Municipal Waste Management

Compost is also used by Econova in their consumer and bulk soils. In this report, it was assumed that all compost was obtained from municipal waste management regionally; and only a share of this is used by Econova. It was assumed that roughly 600 hours of diesel vehicle operation were used annually to mix and load compost. Gardening waste was assumed to be collected within 30 km of the composting operations. The market for the compost was assumed to be within 50 km. Transportation for the synergy with Econova was shared between the two firms (i.e. half the assumed 20 km distance).

Table 8: Inputs and Outputs for the Municipal waste handling (reviewing only composting)

	Municipal Waste Handling						
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Gardening/ Yard Waste	-	28 800	Tonne	-	30
	Energy	Machine Operation	-	600	Hours	-	-
Outputs	Material	**Compost**	**Main Product**	**19 200**	**Tonne**	**Market**	50
		Compost (Econova)	By-Product	4 800	Tonne	IS-Econova	10

LCI data compost production and diesel vehicle operation from municipal waste handling were obtained from Ecoinvent v 3.3. See the Appendix for further information.

3.2 Reference System(s)

In order to assess the potential benefits from Econova's handling of different waste streams to produce soil and surfaces, a reference system, labelled *Reference*, was also reviewed. In this reference system, many of the by-products from Holmen used at Econova, in addition to compost, were assumed to be replaced by a larger share of peat. As peat has a lower pH value, it requires the use of lime, and thus in the reference system for soil production requires more lime. The substitution of fiber mulch for peat in the reference scenario was assumed to be 1.4:1 according to figures from Econova (2017). Furthermore, the substitution of bark mulch for peat and compost was assumed to be 1:1. See the Appendix for further details on the total inputs for the commercial and bulk soil in the reference systems.

In the case of surfaces, it was assumed that if ECA surfaces were not produced and used, a similar area of concrete would be used for the surfaces in both Linköping and Norrköping. As ash would not be used in the surfaces, the different fractions were assumed to be used in conventional approaches, i.e. landfilling and sent to closed mines in e.g. Norway. The concrete would have an overall thickness of 50 cm. In order to review the sensitivity to the choice of replaced surface, an additional reference scenario was developed to review the replacement of asphalt surfaces, i.e. instead of concrete as aforementioned. It was assumed, in this case, that the asphalt surface would be thicker (i.e. 70 cm thick). The implications for the overall performance are available in the analysis, labelled as *Reference-Asphalt*. Again, see the Appendix for further information on the flows for the references system.

In the reference scenario, there it is assumed that there are no exchanges between Holmen Sawmill and Holmen Paper, fiber sludge was assumed to be landfilled and thus the production heat is altered (i.e. reduced heat production from fiber mulch).

3.3 Potential Future Integrated System

As the importance of fiber mulch and other by-products were outlined, a further scenario to review a possible increase in fiber mulch used in soils in the future was included. This scenario was similar to the *Current* scenario, but all fiber sludge from Holmen was used at Econova to replace peat. This reduced the need for lime, and decreased the overall weight of the soils output. However, this increased the transportation (tonne-km) of fiber sludge between Holmen and Econova. In place of fiber sludge used as a fuel for heat production at Holmen, it was assumed that more of the by-products (e.g. bark) were used for heat production, thus reducing the amount of bark available to the market as a by-product. See the Appendix for further information on the flows for the future scenario, labelled *Future-Fiber* in the subsequent figures.

4 Results

The results suggest that there is significant potential for emissions reductions due to the synergies between Holmen firms and for developing soil and surfaces. However, as shown in Figure 5-Figure 9, the impacts, for the symbiotic network are dominated by the operations at Holmen and Tekniska Verken. This is due largely in part to the magnitude of bio-based products and energy from the production at the aforementioned companies in comparison to the other producers, i.e. Econova, Municipal Waste handling, etc. However, there is a clear reduction in impacts from Econova soil when comparing the *Reference* scenario with the *Current* and *Future-Fiber* scenarios. Further details on the implications for the different products and firms are provided in the analysis section below.

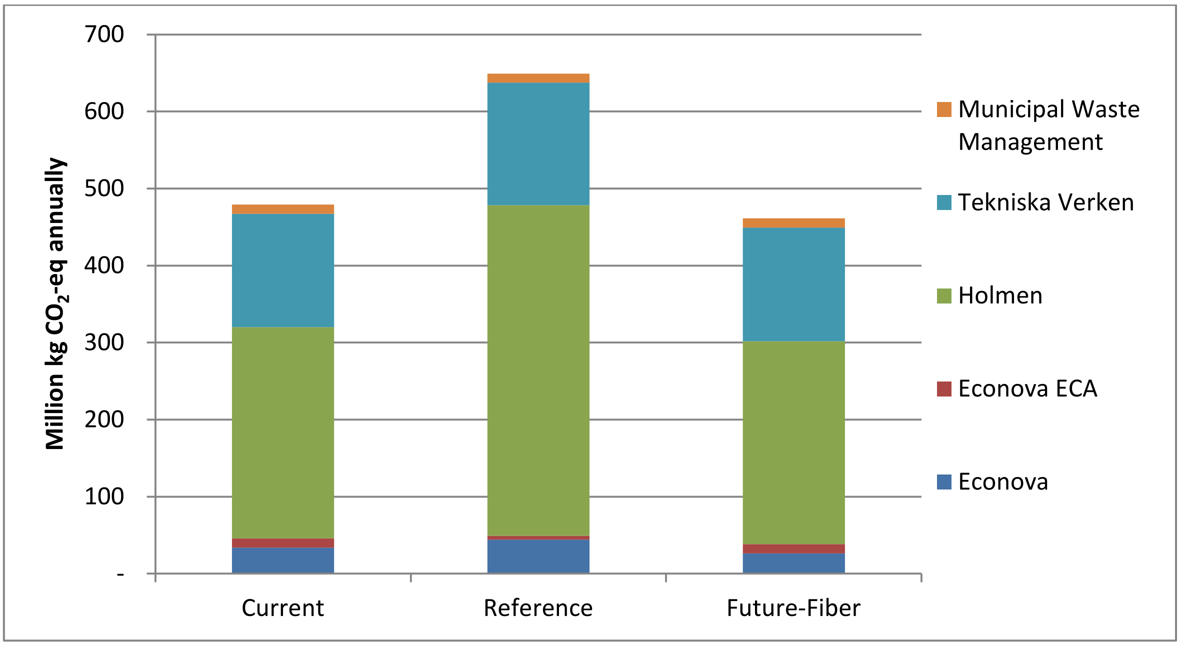

Figure 5: Comparing the Climate impacts of the Current, Future-Fiber and Reference Scenarios (shown in Million kg CO_2-eq annually)

Figure 5 illustrates that the primary reduction in climate impacts when comparing the reference to current scenario can be attributed to large impact reductions from Holmen and Econova's soil and surface production (i.e. concrete vs. ECA surfaces). There is also a reduction in potential eutrophication impacts when comparing the reference and Current and Future-Fiber scenarios, primarily from Holmen and Econova, as seen in Figure 6. However, only slight reductions in acidification impacts and abiotic resource depletion are illustrated in Figure 7 and Figure 8 (again primarily due to reductions from Holmen and Econova).

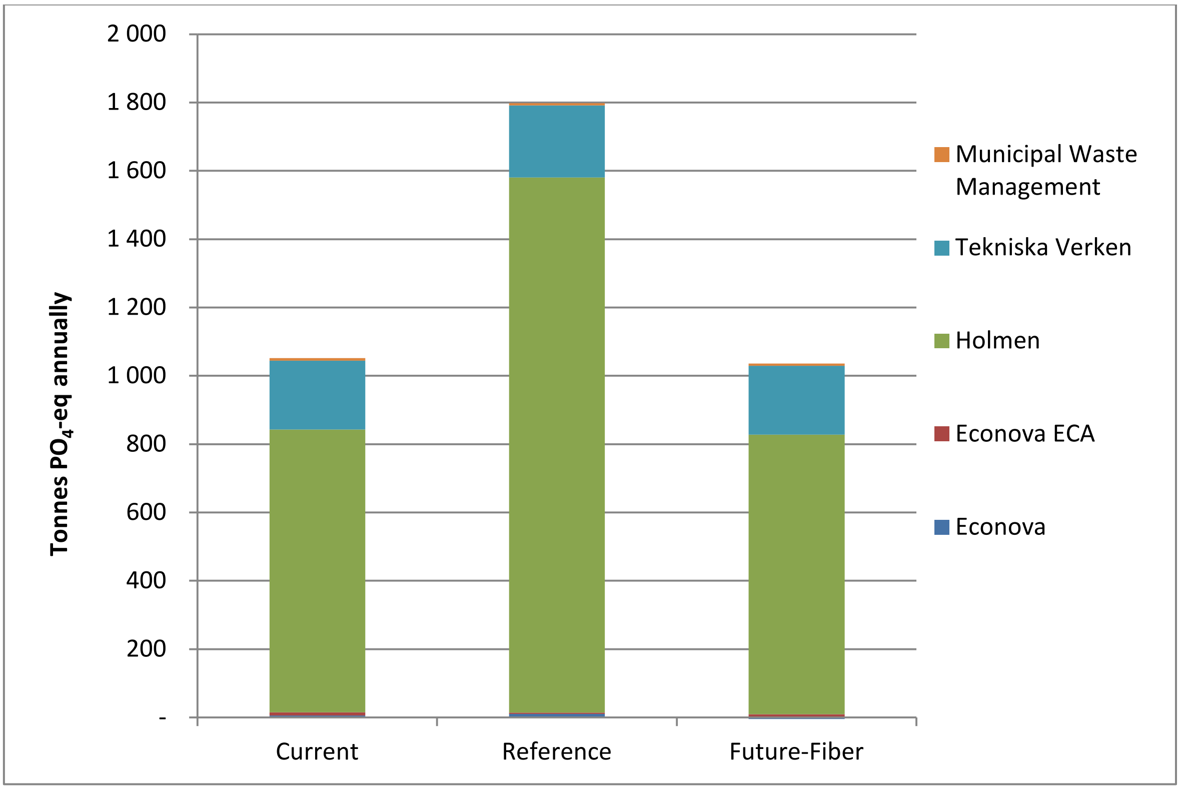

Figure 6: Comparing the Eutrophication impacts of the Current, Future-Fiber and Reference Scenarios (shown in Tonnes PO_4-eq annually)

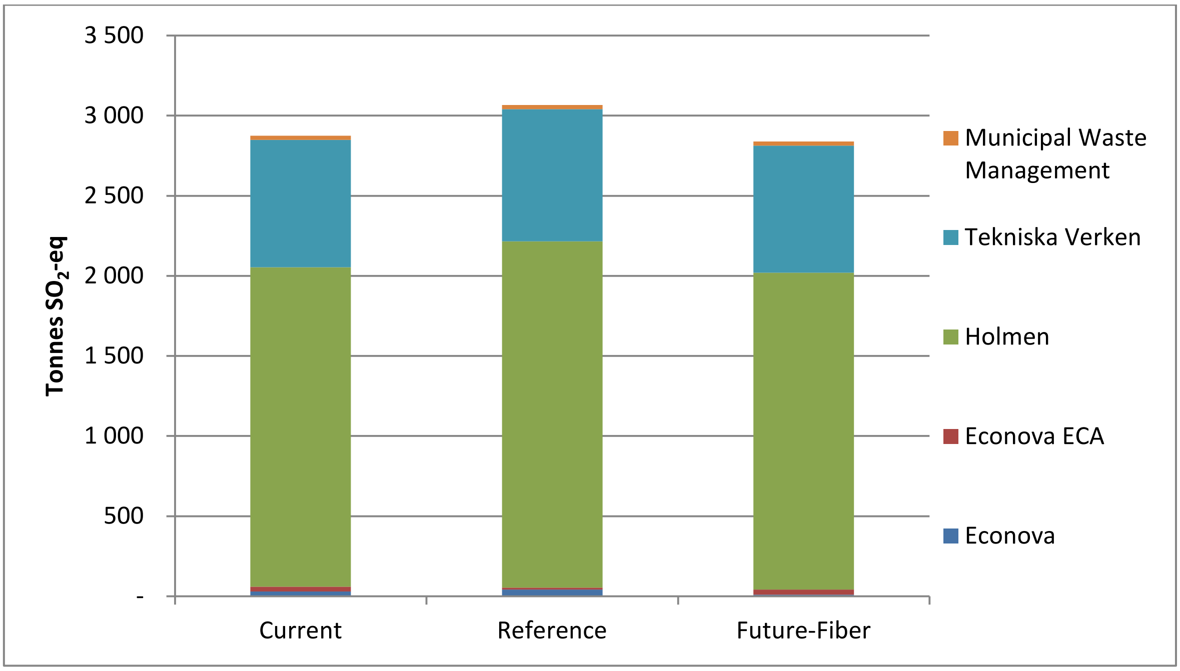

Figure 7: Comparing the Acidification impacts of the Current, Future-Fiber and Reference Scenarios (shown in Tonnes SO_2-eq annually)

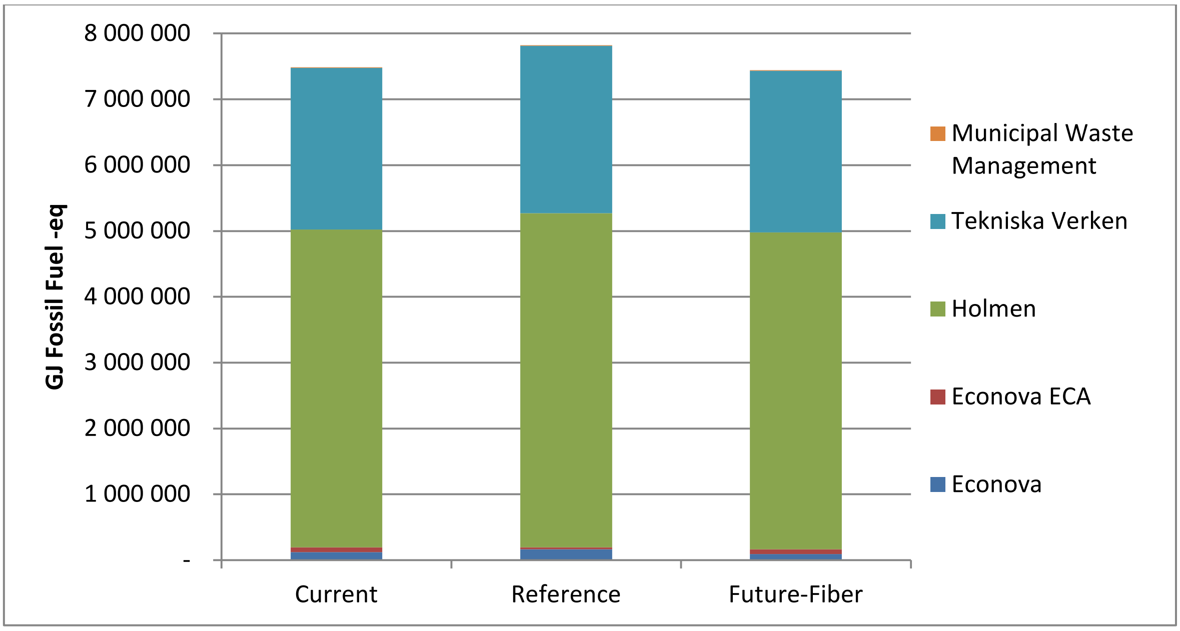

Figure 8: Comparing the depletion of abiotic resources (measured in GJ fossil fuel-eq) for Current, Future-Fiber and Reference Scenarios

Figure 9 thereafter compares the transportation of materials in tonne-km. The transportation is dominated by Holmen, Tekniska Verken and Econova; for which decreases can also be illustrated between the Reference, Current and Future-Fiber scenarios. Decreases are mainly due to reductions in transportation of peat; see also Appendix.

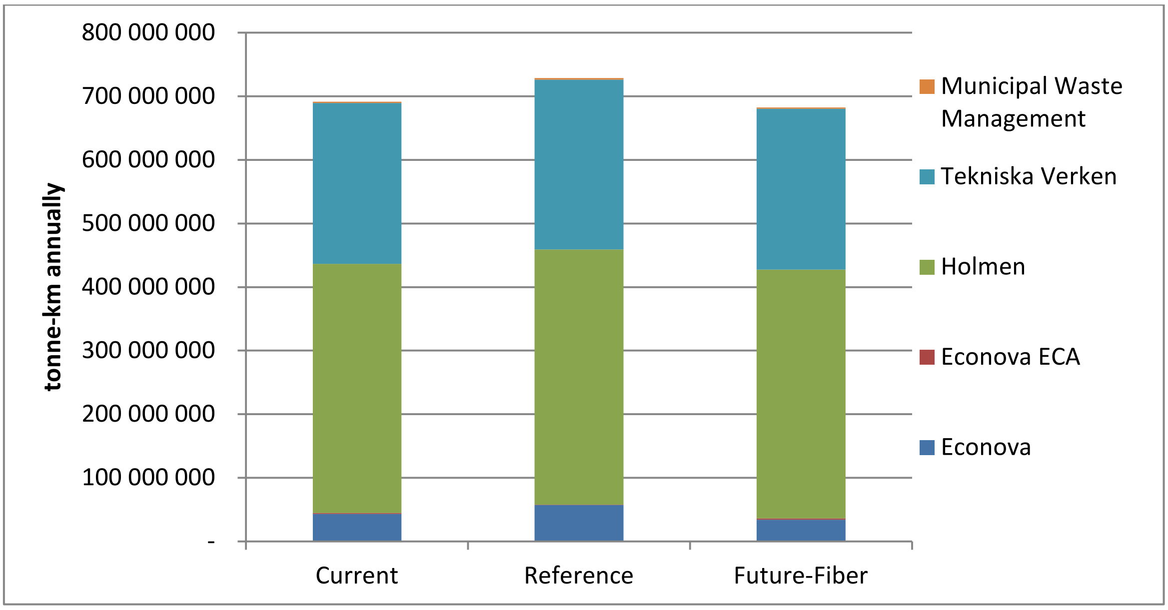

Figure 9: Comparing the transportation amounts for the Current, Future-Fiber and Reference scenarios (shown in Tonnes-km annually)

4.1 Sensitivity to Reference System Choice

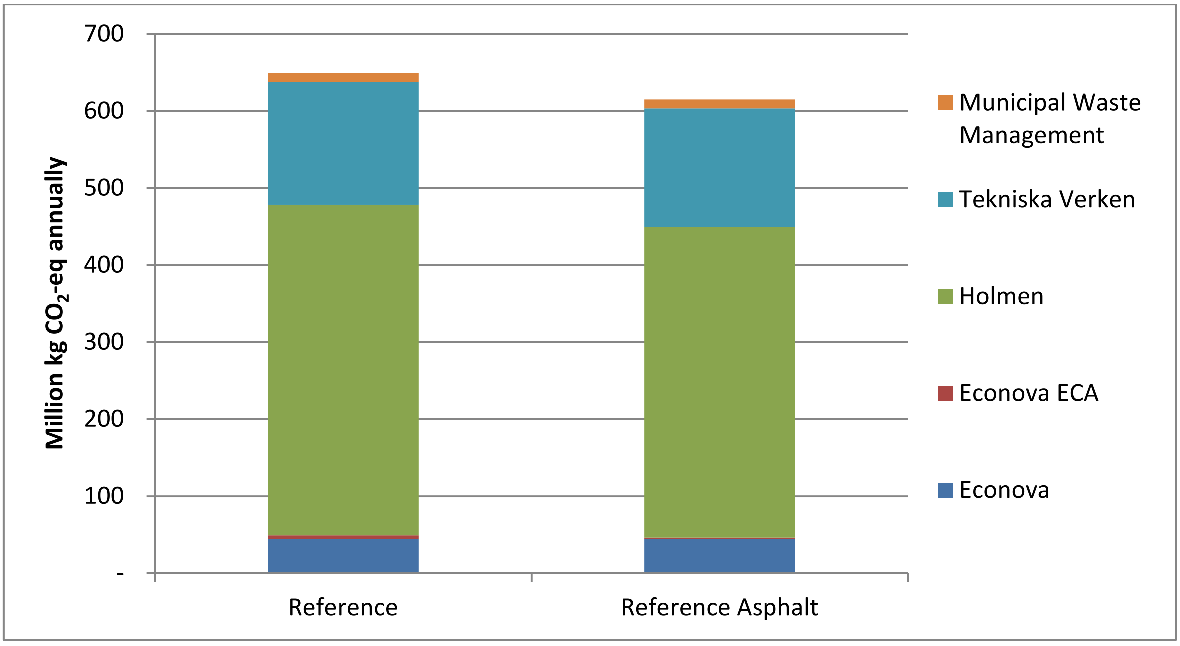

Figure 10: Reviewing the sensitivity of reference system choice on GHG emissions

As shown in Figure 10, and apparent for GHG emissions and eutrophication potential, there is a significant change in emissions if the reference surfaces, in place of ECA, are assumed to be concrete or asphalt. The asphalt surface has reduced GHG emissions compared to the concrete surface, even with an increased thickness of the surface. However, if asphalt was chosen as the reference surface, this could increase potential acidification impacts and abiotic resource depletion. Table 9 shows the changes possible when comparing ECA surfaces with reference scenarios for the different impact categories.

Table 9: Change in potential impacts if asphalt was chosen for the reference surface

	GHG emissions	Eutrophication Impacts	Acidification Impacts	Abiotic Resource Depletion
Reference	-	-	-	-
Reference-Asphalt	-5%	-1%	0%	5%

5 Analysis: Implications for Firms and Products

The following figures and tables provide an analysis of the impacts (and benefits) for the individual firms of the IS network. This is followed by a review of particular implications for Econova and Holmen.

5.1 Environmental impacts

As shown in Table 10, the GHG emissions of the IS network are dominated by the plants with the largest magnitude of production inputs and outputs (i.e. Holmen Paper and Tekniska Verken). However, as shown, these plants also benefit from the symbiotic network when comparing the *Reference* and *Current* (and *Future-Fiber*) scenarios. However, Econova soil production and surface production are also shown to benefit greatly from the synergies involved. Similar findings for the other impact categories were also found; further details on the implications for other impact categories can be illustrated in the Appendix (Figure A 1-Figure A 4).

Table 10: GHG emissions from firms in the symbiotic network (measured in million kg CO_2-eq annually)

	Current	Reference	Reference Asphalt	Future-Fiber
Econova Consumer Soil	24	31	31	20
Econova Bulk Soil	11	13	13	10
ECA Surfaces Linköping	2	0	0	2
ECA Surfaces Norrköping	10	5	2	10
Holmen Sawmill	36	82	69	36
Holmen Paper	238	347	335	230
Tekniska Verken	147	159	154	147
Municipal Waste	12	12	12	12

5.2 Implications for Econova Products

The assessment is centered on reviewing the environmental benefits from by-product and material synergies facilitated by Econova, thus it is important to review the implications of the synergistic exchanges for these products. Furthermore, as shown in the preceding table (and reference to the Appendix), the overall impacts are dominated by Holmen and Tekniska Verken, thus making the potential benefits for Econova less apparent from the figures. The following sections provide a review of the implications for soil products and surfaces from Econova.

5.2.1 Soil

As Figure 11 reviews, there are significant benefits when comparing the *Current* scenario to the *Reference* scenario for the soil products. The consumer soil has a reduction in GHG emissions of over 20%, while eutrophication, acidification and abiotic resource depletion are reduced by roughly 20%. Bulk soil also illustrates large reductions in all impact categories, with savings of over 20% apparent for all impact categories reviewed. In comparison to the *Reference* scenario, *the Future-Fiber* scenario, illustrates even larger impact reductions than the current scenario, due in large part to the benefits provided by using fiber mulch replacing peat; see also Figure 12. The consumer and bulk soils illustrate GHG emissions, eutrophication and acidification impacts and abiotic resource depletion reductions of over 30%. In the *Future-Fiber* scenario, for the bulk soil, reductions of roughly 40% or more are also apparent for acidification and abiotic resource depletion.

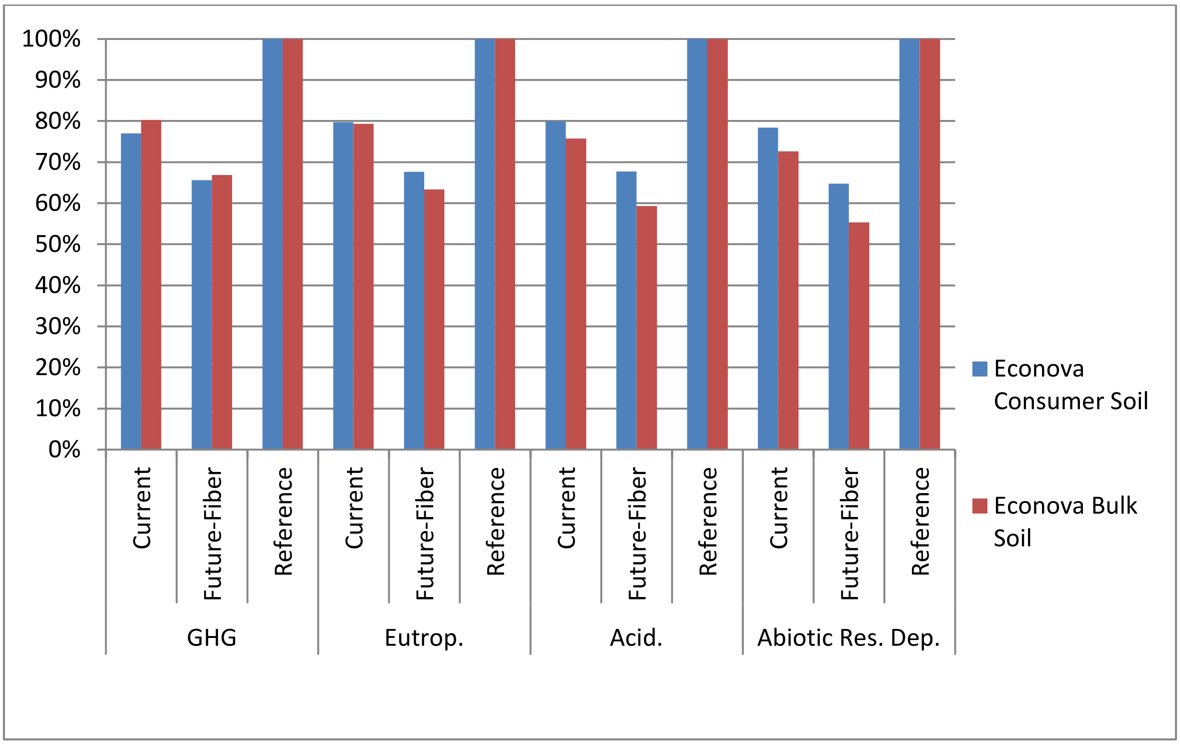

Figure 11: Comparison of the potential impact reductions when comparing the Reference, Future-Fiber and Current Scenarios for Econova products (GHG-Greenhouse gas emissions, Eurtop.-Eutrophication Impacts, Acid.-Acidification, Abiotic Res. Dep.-Abiotic Resource Depletion)

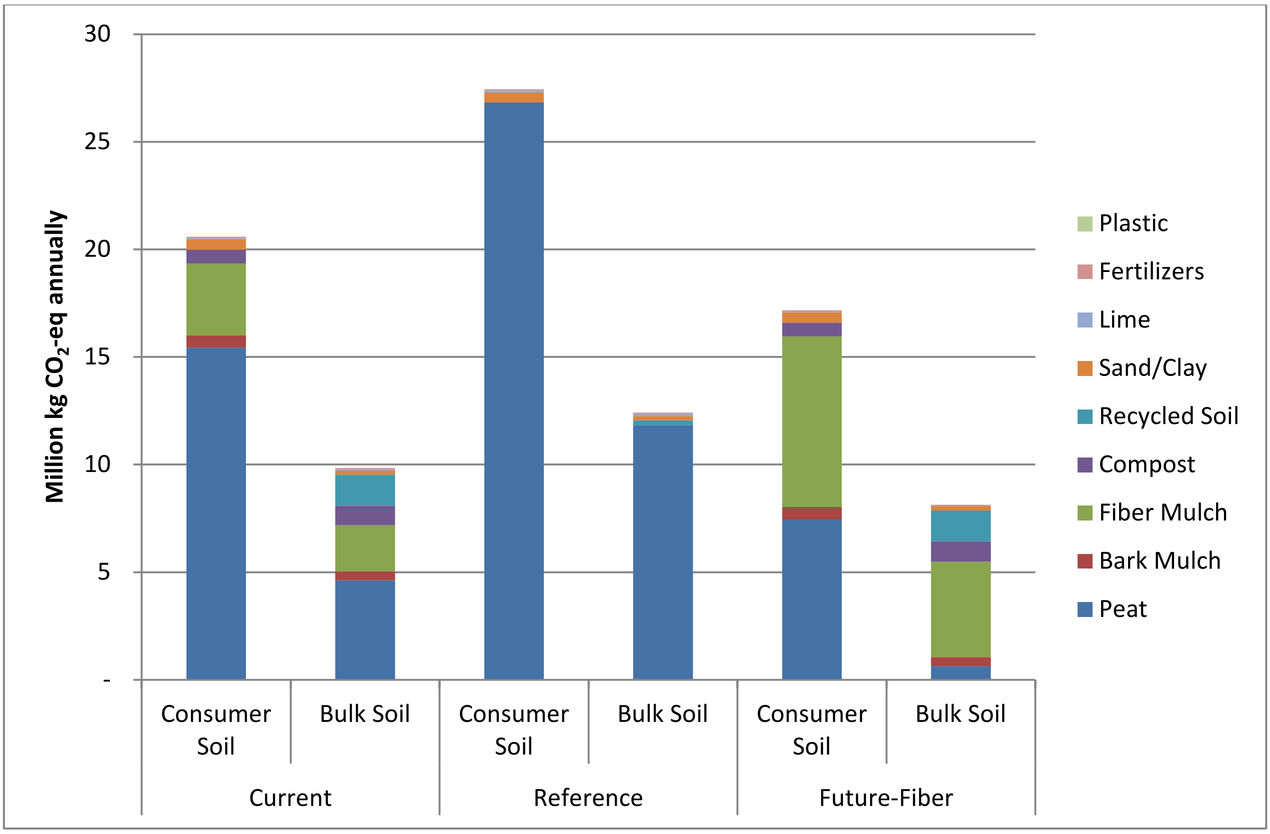

Figure 12: Annual emissions from soil inputs for the Consumer Soil and Bulk Soil in the Current Scenario (measured in million kg CO_2-eq annually)

As shown in Figure 12, the largest contribution of GHG emissions comes from the peat used in the consumer and bulk soils in the *Current* scenario. Comparing the consumer and bulk soil with the reference scenario shows a significant increase in GHG emissions due to the substitution of by-products for peat. As illustrated in the *Future-Fiber* scenario, the GHG emissions arising from peat are nearly halved as more fiber mulch is used and leading to lower overall emissions for material inputs; although this subsequently increased the impacts from fiber mulch.

The use of fiber mulch, which replaces peat, was shown to lead to significant impact reductions for Econova soils. As depicted in Figure 12, in the *Future-Fiber,* despite reducing peat, there is an increase in emissions from fiber mulch. This is due to the "burden" associated with the incoming fiber mulch based on the methodology used, i.e. Martin et al. (2015). Due to fact that Econova receives a by-product from Holmen, they are burdened with half the impact of the replaced product (in this case peat) while Holmen is given a credit for half the replaced product; again see Figure 1 or Martin et al. (2015) for more information. Despite the burden, the benefits of removing peat are still significant for reducing Econova's overall GHG emissions annually.

When reviewing the impact on the output consumer soil, as Figure 13 illustrates, there is roughly a 23% reduction in emissions per bag produced, due to the use of different by-products for soil production in the *Current* scenario compared to the *Reference* scenario. The primary reason for this is due to the reduction of peat in the soil, through the use of fiber mulch; which also reduces the use of lime. In the *Future-Fiber* scenario, where more fiber mulch is provided by Holmen, and less peat is used by Econova, the GHG emissions per bag can be reduced more than 34%.

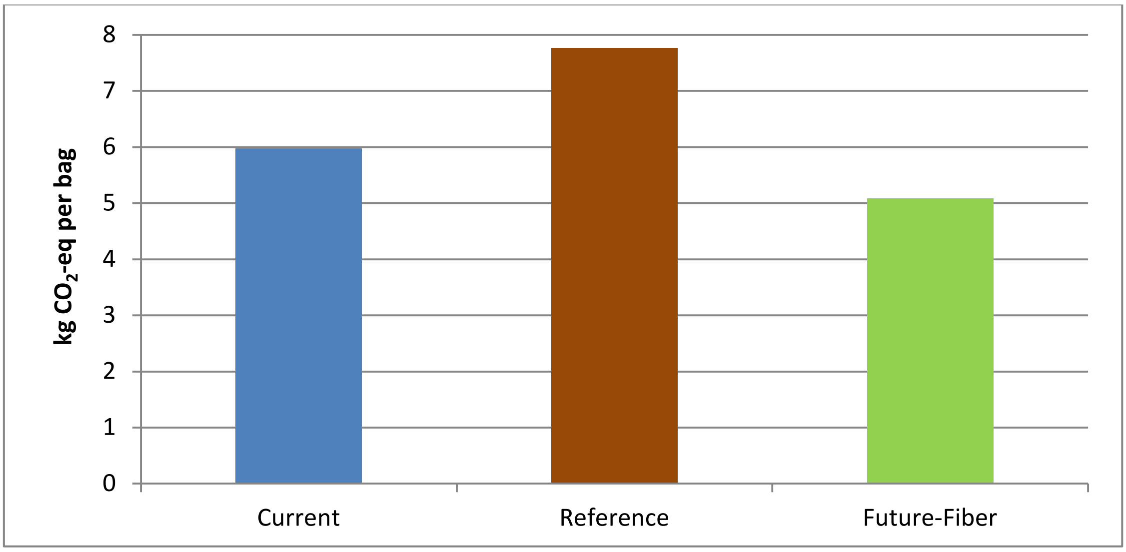

Figure 13: GHG emissions for bags of consumer soil from Econova (measured in kg CO_2-eq per bag) in the different scenarios

When comparing the output of the different soil products, per kg of produced soil, there are also large emissions reductions possible. For both the bulk and consumer soils, the current scenario can reduce GHG emissions by roughly 17%. The largest reductions can be illustrated for bulk soils. The reductions are further increased in the *Future-Fiber Mulch scenario,* where GHG emissions reductions are increased to over 25% for both the bulk and consumer soil; see Figure 14.

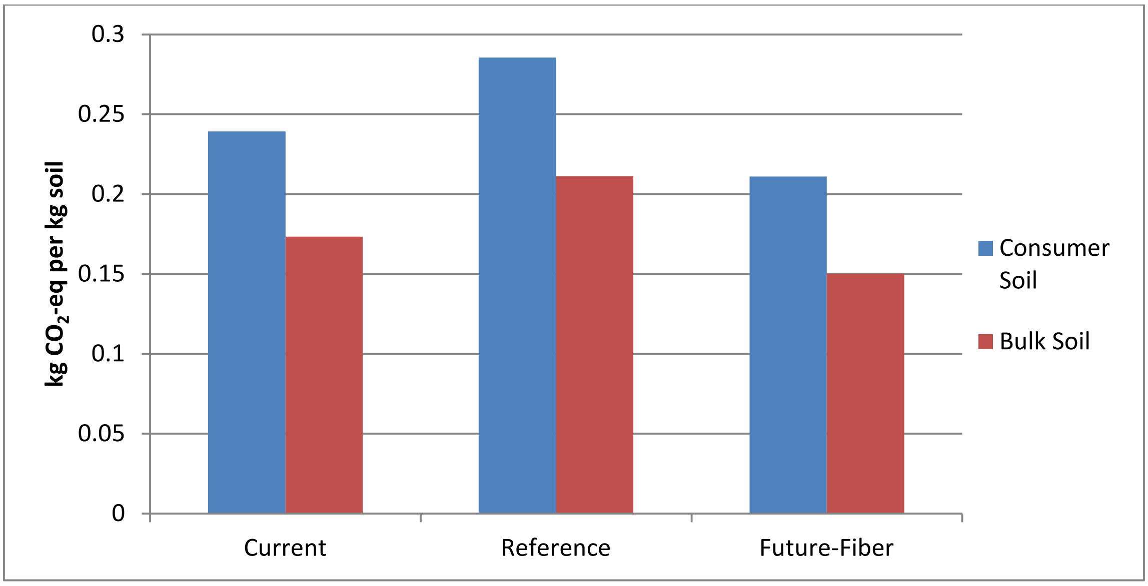

Figure 14: Comparing the emissions of consumer soil and bulk soil per kg (measured in kg CO_2-eq)

5.2.2 Surfaces

In the case of Econova ECA, a reference system would not exist, i.e. the scale of the operations would not be in place if there were no exchanges to develop the new surfaces. Thus, with only a small share of the surfaces accounted for as a main product of the *Current* scenario (roughly 5 000 m^2 for surfaces produced outside of the synergies reviewed), there would exist little to no impacts in the *Reference* scenario. The *Current* scenario, with much larger impacts due to the production of the ECA surfaces and internal synergies, in this case, should not be compared with the *Reference* scenario where no synergies and fewer surfaces are produced. Instead, each firm which has ECA surfaces in the *Current* scenario is "burdened" in the *Reference* scenario with the default surfaces (i.e. asphalt or concrete). However, by facilitating the production of surfaces made from by-products, the ECA surfaces lead to large reductions for other firms in the IS network. For example, by providing a surface made from by-products, the ECA surface can provide a savings of up to 30 million kg CO_2-eq for Holmen and nearly 6 million kg CO_2-eq for Tekniska Verken, if it is assumed that concrete is replaced; see Table 11.

Table 11: Review of GHG emissions from surfaces in the Reference scenarios vs. Current Scenario (measured in Million kg CO_2-eq)

Scenario	Holmen	Tekniska Verken
Current	9.9	2.1
Reference	39.5	7.9
Reference-Asphalt	14.2	2.8

5.3 Holmen

As shown in the impacts for the *Reference* vs. *Current* scenarios, the Holmen "cluster" benefits significantly from the symbiotic links between Holmen Sawmill and Holmen Paper, and by providing Econova with by-products which are used to produce soil. In the *Future-Fiber* scenario, where the only change is using all fiber sludge for soil instead of as a fuel in boilers, it is apparent from the preceding analysis of Econova, that large benefits may occur for Econova's products. However, benefits from sharing of by-products, such as fiber sludge, are also apparent for Holmen. As illustrated in Table 12, there are many impact reductions in all impact categories reviewed when comparing the *Reference* and *Current* scenarios. The increased transfer of fiber sludge illustrates benefits for Holmen Paper, though these are less significant. This is due primarily to the magnitude of synergies reviewed (compared with the large share of synergies assessed in the *Current* scenario, and with the only change an increase in fiber sludge for the *Future-Fiber* scenario); see also Appendix.

Table 12: Comparing the impacts for the Reference, Current and Future-Fiber Scenarios for Holmen firms in the IS network

Impact Category	Scenario	Holmen Sawmill	Holmen Paper
GHG (Million kg CO2-eq)	***Reference***	82	347
	Current	36	238
	Future-Fiber	36	230
Eutrophication (Tonnes PO4-eq)	***Reference***	106	1 460
	Current	78	749
	Future-Fiber	78	749
Acidification (Tonnes SO2-eq)	***Reference***	344	1 818
	Current	281	1 714
	Future-Fiber	281	1 710
Abiotic Resource Depletion (GJ-eq Fossil Resource Depletion)	***Reference***	1 023 161	4 056 169
	Current	913 533	3 912 700
	Future-Fiber	913 533	3 902 234

However, as suggested in previous research (cf. Martin et al., 2015), while firms may be interested in the overall benefit they receive for different individual synergies, these individual benefits from the synergies may have much broader system benefits. As illustrated in Table 13, when reviewing the implications of increasing fiber sludge synergies, there are large reductions in GHG emissions for Econova operations, while only minor reductions at Holmen. However, a reduction of 11 million kg CO_2-eq emissions are illustrated for Holmen Paper; though again this is small in comparison to overall emissions of the Holmen Paper operations in the *Current* Scenario, roughly 240 million kg CO_2-eq emissions annually. In comparison, Econova's entire soil production has an annual emission of roughly 35 million CO_2-eq emissions annually.

Table 13: Reviewing the benefit of increased fiber sludge handling by Econova (measured in Million kg CO_2-eq)

	GHG Emissions Reductions Future-Fiber	Reduction from Current
Econova Consumer Soil	4	-15%
Econova Bulk Soil	1	-15%
Holmen Saw	0.0	0.0%
Holmen Paper	11	-4%

In order to further analyze the system and individual firm benefits of the use of 1 tonne of fiber sludge, Table 14 provides a review of the emissions replaced for different uses of the fiber sludge. Assuming that 1 tonne of fiber sludge can produce roughly 1780 kWh heat if used in a boiler at Holmen. If woodchips or bark were used instead there would be reductions in all impact categories. In comparison, the same 1 tonne fiber sludge could replace roughly 1.4 tonnes of peat and 0.1 tonnes of lime if sent to Econova. As illustrated in Table 14, large impact reductions for peat replacement are possible for GHG emissions. For other impact categories, there is a larger potential for the fiber sludge to reduce impacts.

Table 14: Comparison of potential impact reductions for the use of fiber sludge in soil applications (replacing peat and lime) or for heat production (replacing an equivalent amount of woodchips)

Impact Category	Unit	Peat and Lime	Woodchips
GHG Emissions	kg CO_2 eq.	381	47
Eutrophication Impacts	kg PO_4 eq.	0.04	0.66
Acidification Impacts	kg SO_2 eq.	0.13	0.99
Abiotic Resource Depletion	MJ	263	542

See also Appendix for further information on the impacts and benefits from the clusters and individual firms; which outline the relative extent of the benefits from the synergies and avoided products.

5.4 Tekniska Verken

Similar to the results for Holmen, impacts from Tekniska Verken dominate the overall impacts of the IS network. Thus, impact reductions are not as significant from being a part of the symbiotic, but should not be disregarded. As shown in Table 11, by reducing the amount of ash sent to be landfilled, and using it instead to replace concrete through ECA surfaces, Tekniska Verken was shown to benefit by reduced emissions by nearly 6 million kg CO_2-eq for the surfaces applied in the year 2016. Further benefits from the use of by-products from Tekniska Verken outputs are illustrated in the Appendix.

6 Discussion

6.1 Overall Benefits of the System

As Martin et al. (2015) suggest, the benefits from the IS network may not be equally shared between firms in the network. By-products and waste form different industries can be used by an "upcycling-tenant" in the IS network to valorize the materials and energy; in this case, Econova can be identified as such an upcycling-tenant.

All firms in the symbiotic network were shown to benefit from the symbiotic exchanges of material and energy except for the ECA surface operations by ECA, when comparing to a reference scenario. This was due to the fact that only a small share of the surfaces were considered a *main product* used outside of the symbiosis network in both the current and reference scenarios. However, the burdens from the conventional surfaces were allocated to the firms installing the surfaces. In this respect, the facilitation of different waste products to produce the ECA surfaces provides large benefits to the users of the surfaces compared to traditional concrete or asphalt.

Overall, the benefits, from a systems perspective are substantial when comparing the *Reference* scenario to the *Current* and *Future-Fiber* scenarios. This is primarily a result of removing a large share of the use of peat, through e.g. an increased use of fiber sludge in soils. This can significantly reduce GHG impacts and abiotic resource depletion. Furthermore, the use of ash and other by-products to replace conventional use of concrete was shown to have significant environmental benefits for the system by reducing transportation and creating innovate products replacing conventional fossil dependent products.

Furthermore, as addressed in Baumgarten and Nilsson (2014), there are many further synergies and exchanges facilitated by Econova, which have not been explored in this study. While their study did not review the environmental performance, the environmental benefits provided by Econova, within and outside the region will need to be further explored to illustrate, beyond the synergies explored in this study, the value of facilitation of material and energy exchanges.

6.2 Benefits for Soil Products

The results from this review show significant potential for improving the environmental performance of soil products. However, it is difficult to compare the impacts of the soils reviewed as there is a limited research available on the environmental impacts of gardening soil. Econova, is one of few producers using a large share of industry by-products in their soil products. However, there are a number of producers, using bark and other material. Several previous studies have reviewed the potential benefits of using compost in soils in comparison to peat to illustrate the potential for reducing GHG emissions; see e.g. Boldrin and Hojlund (2008). Previous assessments have been done, but there is little transparency in the assumptions made for soil; see e.g., Fisher and Karunanithi (2014). There are some studies which correspond with findings from this study however, showing reduced GHG emissions from soils with less peat, see e.g., Sonesson et al. (2010). This study therefore provides a novel input for the community by reviewing the impacts of different soil products and can be important in reviews of e.g. urban gardening.

With an increasing awareness of consumers of the environmental impacts of their consumption, it may be interesting to further market these products to capture the value they may encompass. This can be done through different labelling schemes, or even through e.g. Environmental Product Declarations (EPD) or Product Environmental Footprints (PEF). These labels will become increasingly important in the future for procurement of products in the public and private sector. Furthermore, consumers may be willing to pay for more sustainable products, especially when they are related to e.g. food consumption; which is linked to soils or media used for growing (Hempel and Hamm, 2016; Tobler et al., 2011). Nonetheless, it the costs and the overall performance of the product compared to comparable alternatives will need to be reviewed. Currently, soils with fiber mulch are available as a low priced alternative compared to more premium soil brands across Sweden (Econova, 2017). However, it is important that the perception of these products, such as the odor of the soils containing fiber mulch, will need to be explored. Thus, further impact categories for e.g. odor may be interesting to include in future reviews for the products; thus extending the assessments from environmental to social assessments and impacts of the products.

There are also opportunities to improve the environmental performance of the soils produced. For example, there may be a large potential from removing the conventional fertilizers used to provide nutrients to the soil, and increasing the amount of compost or even biofertilizers. Nutrients can be obtained from the many biogas plants in the area, providing a new market for this valuable product (Martin, 2015; Martin and Parsapour, 2012). Furthermore, as reviewed in this study, using more fiber mulch in the soils is also a promising approach to reduce the environmental impact. However, due to current restrictions and permitting, the value of fiber mulch is not fully explored. Soils labelled "organic" must have peat and cannot contain industry by-products[3]. With these restrictions, there is a limitation on the potential for regional circular use of materials. The organic labelling scheme in Sweden, KRAV, states that this is due to the "conditions in Sweden for the availability of peat." Nonetheless, there is an extensive availability of fiber sludge, which is today either incinerated or landfilled. Econova has an extensive market which accepts the use of fiber mulch in soil products, e.g. in bulk soils. As such, the use of instruments such as public procurement may promote the use of these soils and provide an approach to side-step restrictions in regulations for "organic" soils.

6.3 ECA Surfaces

The results suggest that there is a significant potential to improve emissions for surface applications by using the ECA surfaces. This is primarily due to the replacement of conventional concrete surfaces. Many previous studies have also reviewed the use of ash as an additive in concrete to replace other additives and aggregates, illustrating many environmental advantages; see e.g. Flower and Sanjayan (2007) and Kou et al., (2008).

Several previous studies have shown concrete with ash may be a suitable surface material; see e.g. discussions in Ginés et al. (2009). Kou et al (2008) even suggest that the use of fly ash may also improve the properties of concrete made with recycled concrete aggregate, as it can act as a cementitous material. Furthermore, heavy metals stored in the surfaces have been studied extensively in literature due to concerns of heavy metal leaching and other concerns; see e.g. Lederer et al. (2017). However, several scholars have suggested that the leaching may be kept to a minimum (Shi and Kan, 2009) but that the use of ashes may prevent the recycling of the concrete

[3] See e.g. http://www.krav.se/krav-markt-godsel-och-jord

(Lederer et al., 2017). Nonetheless, very few studies review the type of surfaces developed by Econova ECA, and are typically reviewed as surface similar to conventional concrete.

The results reviewed are limited to annual impacts from the surfaces. As such, the surfaces currently installed may offer even larger impact reductions. Holmen and Tekniska Verken currently have a much larger area of ECA surfaces installed, and plan to continue this expansion. It was also suggested from Tekniska Verken and Econova that the ECA surfaces allow for less friction, leading to less diesel consumption for loading, etc. However, this assumption was not tested, and can add to a complementary study of the benefits of ash use in surface applications.

It should also be stressed that the assumptions on the thickness and use of different materials for the ECA surfaces may change for different sites. It was assumed in this study that the surfaces were similar for e.g. Tekniska Verken and the Holmen sawmill and paper plants. Again, however, these different sites may have requirements for load levels (e.g. large trucks carrying lumber) which may be dissimilar. Thus, the results in the study may be over or underestimations of the actual thickness, and subsequent environmental impacts, from the ECA surfaces.

7 Conclusions

The results of this study suggest that the industrial symbiosis network in Norrköping provides substantial environmental impact reductions compared to a situation where no symbiotic exchanges would occur. Holmen Paper and Sawmills show significant environmental benefits from internal synergies, i.e. sharing of heat and by-products, in addition to synergies with Econova. The exchanges facilitated by Econova, include using fiber sludge to replace peat and developing hard surfaces from ash and other aggregates, provide a significant share of the environmental impact reductions. Similar results are found for Tekniska Verken, where ECA surfaces replacing concrete can lead to large environmental impact savings. Together these two residual materials, i.e. fiber sludge and ash, provide strong opportunity for continued growth and environmental recognition once involved industrial partners, and new partners, capture the business and environmental value of the industrial symbiosis. Furthermore, while this study reviews only several exchanges from the network, there are many more symbiotic links facilitated by, above all Econova, in addition to the other firms, which require further research.

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Appendix 1-Scenario Data

Current Scenario

Appendix Table 1: Input-Output Assumptions for the Consumer Soil

Consumer Soil	Amount	Unit	Density (tonnes/m^3)	Total Amount (tonnes)
Peat	104 000	m^3	0.5	52 000
Bark Mulch	22 000	m^3	0.35	7 700
Fiber Mulch	25 000	m^3	0.7	17 500
Compost	6 000	m^3	0.8	4 800
Plastic	2 400	kg	0.001	2.4
Sand	11 000	m^3	1.5	16 500
Lime	1 000	m^3	1	1 000
Fertilizers	300	m^3	1	300

Appendix Table 2: Input-Output Assumptions for the Bulk Soil

Bulk Soil	Amount	Unit	Density (tonnes/m^3)	Total Amount (tonnes)
Peat	31 200	m^3	0.5	15 600
Bark Mulch	15 620	m^3	0.35	5 470
Fiber Mulch	16 000	m^3	0.7	11 200
Compost	11 000	m^3	0.8	6 600
Recycled Soil	10 000	m^3	1.5	15 000
Sand/Clay	4 000	m^3	1.5	6 000
Lime	800	m^3	1	960
Fertilizers	200	m^3	1	240

Reference Scenario

Appendix Table 3: Inputs and Outputs for the Consumer Soil Production from Econova (Reference Scenario)

Econova-Consumer Soil							
		Flow	Origin/ Class.	Amount	Unit	Use/ Destination	Transp. (km)
Inputs	Material	Peat	-	90 402	Tonne	-	200
		Plastic	-	2	Tonne	-	100
		Sand	-	16 500	Tonne	-	100
		Lime	-	1 500	Tonne	-	100
		Fertilizers	-	300	Tonne	-	100
	Energy	Electricity	-	0.45	GWh		-
		Machine Operation	-	1 400	Hours	-	-
Outputs	Material	**Soil (Bags)**	**Main Product**	**108 700**	**Tonne**	**Market**	**200**

Appendix Table 4: Inputs and Outputs for the Bulk Soil Production from Econova (Reference Scenario)

Econova-Bulk Soil							
		Flow	Origin/ Class.	Amount	Unit	Use/ Destination	Transp. (km)
Inputs	Material	Peat	-	39 820	Tonne	-	200
		Soil	-	15 000	Tonne	-	50
		Sand/Clay	-	6 000	Tonne	-	100
		Lime	-	1 440	Tonne	-	100
		Fertilizers	-	240	Tonne	-	100
	Energy	Machine Operation	-	1 400	GWh	-	-
Outputs	Material	**Soil Bulk**	**Main Product**	62 500	**Tonne**	**Market**	100

Appendix Table 5: Inputs and Outputs for the ECA Surfaces from Econova (Reference Scenario)

Econova ECA/Surface (Total)							
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Cement	-	6 000	Tonne	-	100
	Energy	Machine Operation	-	420	Hours	-	-
Outputs	Material	**Surface**	**Main Product**	5 000	**m^2**	**Market**	-

Appendix Table 6: Inputs and Outputs for the Holmen Sawmill (Reference Scenario)

Holmen Saw							
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Logs	-	640 000	Tonne	-	150
	Energy	Electricity	-	26	GWh	-	-
		Heat-Fossil	-	25	GWh	-	-
		Heat	-	110	GWh	-	-
Outputs	Material	**Sawn Timber**	**Main Product**	**440 000**	**m^3**	**Market**	**150**
		Wood/Bark External	By-Product	197 000	Tonne	Market	100

Appendix Table 7: Inputs and Outputs for the Holmen Paper plant (Reference Scenario)

Holmen Paper							
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Wood/Timber	-	928 000	Tonne	-	100
		Pulp	-	800	Tonne	-	100
		Water	-	13 900 000	Tonne	-	-
	Energy	Electricity	-	1 498	GWh	-	-
		Heat Fossil	-	42	GWh	-	-
		Heat Bark	-	223	GWh	-	-
Outputs	Material	**Paper**	**Main Product**	**520 000**	**Tonne**	Market	200
		Fiber Sludge	By-Product	64 700	Tonne	Landfill	50
		Bark	By-Product	154 300	Tonne	Market	100

Appendix Table 8: Inputs and Outputs for Tekniska Verken (Reference Scenario)

Tekniska Verken							
		Flow	Origin/ Class.	Amount	Unit	Use/ Destination	Transp. (km)
Inputs	Material	Domestic Household Waste	-	390 790	Tonne	-	150
		Imported Household Waste	-	347 700	Tonne	-	500
		Surface	-	10 000	m2	-	-
Outputs	Material	Metals Magnetic	By-Product	4 640	Tonne	-	100
		Slag	By-Product	67 680	Tonne	-	100
		Metals Non-Magnetic	By-Product	2 120	Tonne	-	100
		Ash Other	By-Product	138 000	Tonne	-	200
	Energy	**Electricity**	**Main Product**	**260**	**GWh**	Market	**-**
		Heat	By-Product	1 300	GWh	-	-
		Distr. Cooling	By-Product	50	GWh	-	-

Appendix Table 9: Inputs and Outputs for the Municipal Waste Handling, again reviewing only Composting (Reference Scenario)

Municipal Wastes							
		Flow	Origin/ Class.	Amount	Unit	Use/ Destination	Transp. (km)
Inputs	Material	Garden Waste	-	28 800	Tonne	-	30
	Energy	Machine Operation	-	600	Hours	-	-
Outputs	Material	**Compost**	**Main Product**	**24 000**	**Tonne**	**Market**	50

Reference (Asphalt)

Note once again that asphalt replaced concrete in the *Reference –Asphalt Scenario.* In this scenario, the asphalt was assumed to have a thickness of 0.7m (80% of which was asphalt/bitumen, and 20% crushed rock). LCI data for asphalt was obtained from Ecoinvent v. 3.3.

Future-Fiber Scenario

Appendix Table 10: Inputs and Outputs for the Consumer Soil Production from Econova (Future-Fiber Scenario)

Econova-Consumer Soil							
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Peat	-	25 120	Tonne	-	200
		Bark Mulch	-	7 700	Tonne	-	2.5
		Fiber Mulch	-	41 500	Tonne	-	2.5
		Compost	-	4 800	Tonne	-	10
		Plastic	-	2	Tonne	-	100
		Sand	-	16 500	Tonne	-	100
		Lime	-	483	Tonne	-	100
		Fertilizers	-	300	Tonne	-	100
	Energy	Electricity	-	0.45	GWh	-	-
		Machine Operation	-	1 500	Hours	-	-
Outputs	Material	**Soil (Bags)**	**Main Product**	**96 400**	**Tonne**	**Market**	**200**

Appendix Table 11: Inputs and Outputs for the Bulk Soil Production from Econova (Future-Fiber Scenario)

Econova-Bulk Soil							
		Flow	**Origin/ Class.**	**Amount**	**Unit**	**Use/ Destination**	**Transp. (km)**
Inputs	Material	Peat		2 160	Tonne	-	200
		Bark Mulch	IS-Holmen	5 470	Tonne	-	2.5
		Fiber Mulch	IS-Holmen	23 200	Tonne	-	2.5
		Compost	IS-Municipal Waste	6 600	Tonne	-	10
		Plastic	-	15 000	Tonne	-	50
		Sand	-	6 000	Tonne	-	100
		Lime	-	130	Tonne	-	100
		Fertilizers	-	240	Tonne	-	100
	Energy	Machine Operation	-	1 500	GWh	-	-
Outputs	Material	**Soil-Bulk**	**Main Product**	58 800	**Tonne**	**Market**	100

Appendix 2-Results

Contribution of Firms to Overall Impacts

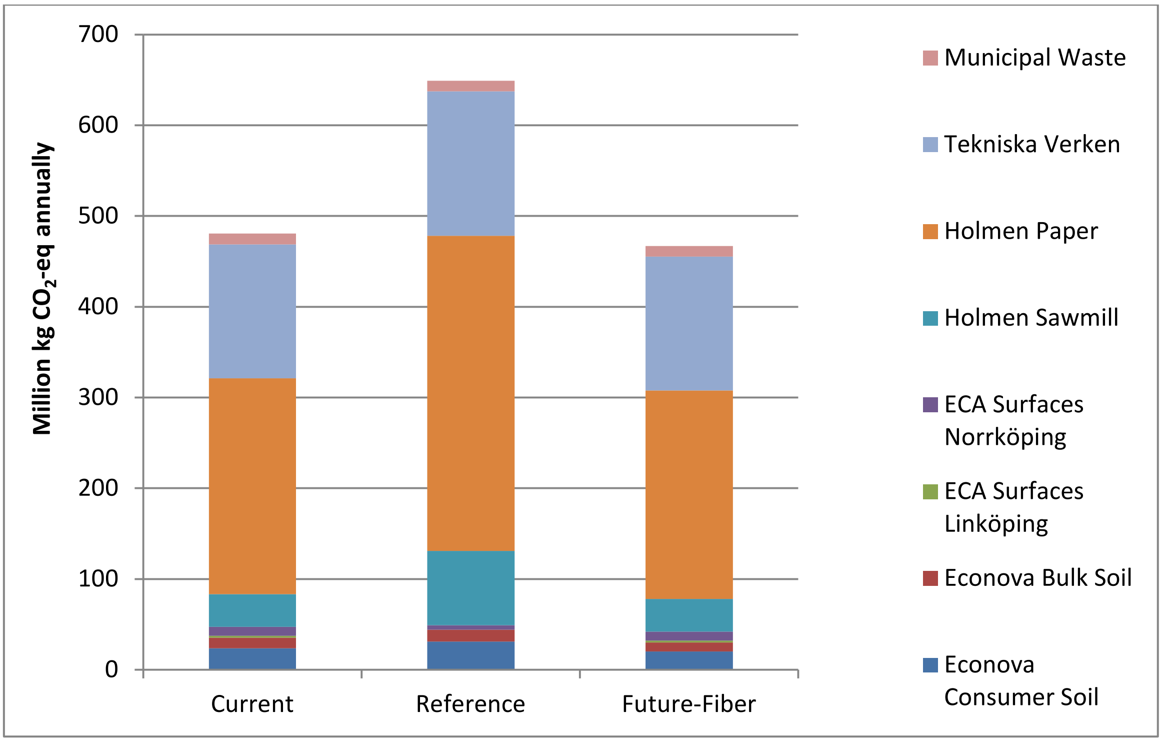

Figure A 1: Review of Climate impacts of the individual firms in the Current, Reference, and Future-Fiber Scenarios (shown in Million kg CO_2-eq annually)

Appendix Table 12: Review of Climate impacts of the individual firms in the Current, Reference, Reference-Asphalt and Future-Fiber Scenarios (shown in Million kg CO_2-eq annually)

		Current	*Reference*	*Future-Fiber*	*Reference Asphalt*
Econova	Econova Consumer Soil	24	31	20	31
	Econova Bulk Soil	11	13	9	13
ECA	ECA Surfaces Linköping	2	0	2	0
	ECA Surfaces Norrköping	10	5	10	2
Holmen	Holmen Sawmill	36	82	36	69
	Holmen Paper	238	347	228	335
Energy	Tekniska Verken	147	159	147	154
Other	Municipal Waste	12	12	12	12

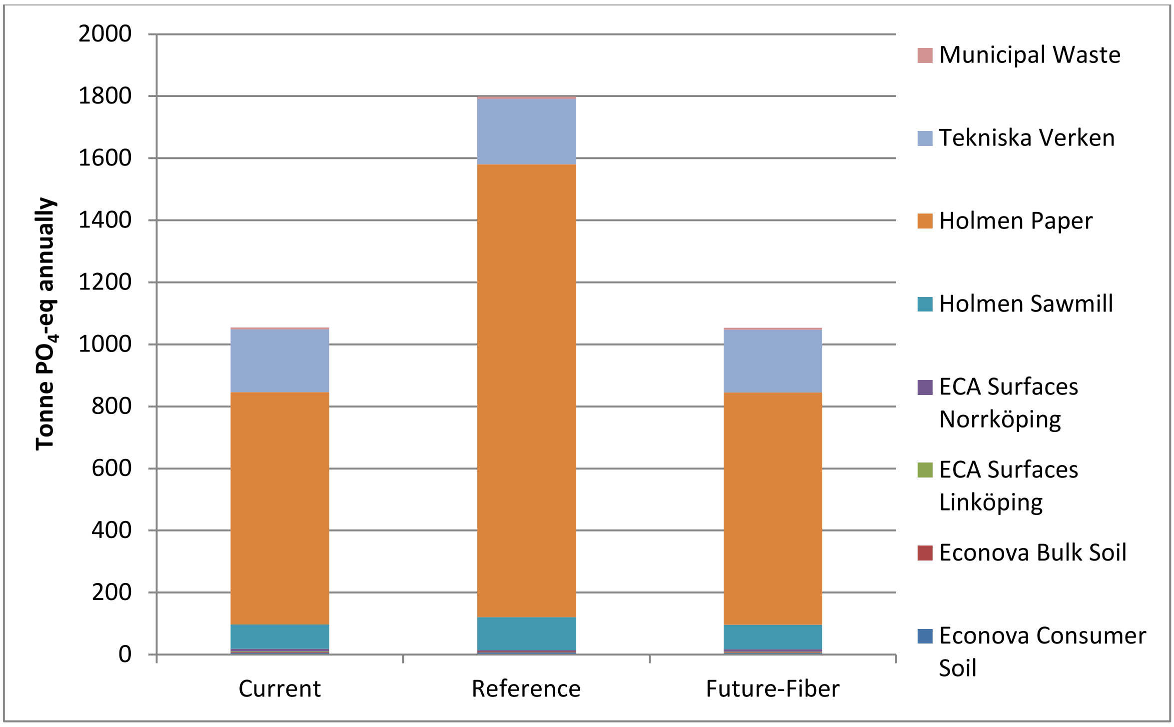

Figure A 2: Review of Eutrophication impacts of the individual firms in the Current, Reference and Future-Fiber Scenarios (shown in tonnes PO_4-eq annually)

Appendix Table 13: Review of Eutrophication impacts of the individual firms in the Current, Reference, Reference-Asphalt and Future-Fiber Scenarios (shown in tonnes PO_4-eq annually)

		Current	Reference	Future-Fiber	Reference Asphalt
Econova	Econova Consumer Soil	6	8	5	31
	Econova Bulk Soil	2	3	2	12
ECA	ECA Surfaces Linköping	2	0	3	0
	ECA Surfaces Norrköping	8	4	8	13
Holmen	Holmen Sawmill	78	106	78	344
	Holmen Paper	749	1460	740	1820
Energy	Tekniska Verken	202	211	202	826
Other	Municipal Waste	7	7	7	26

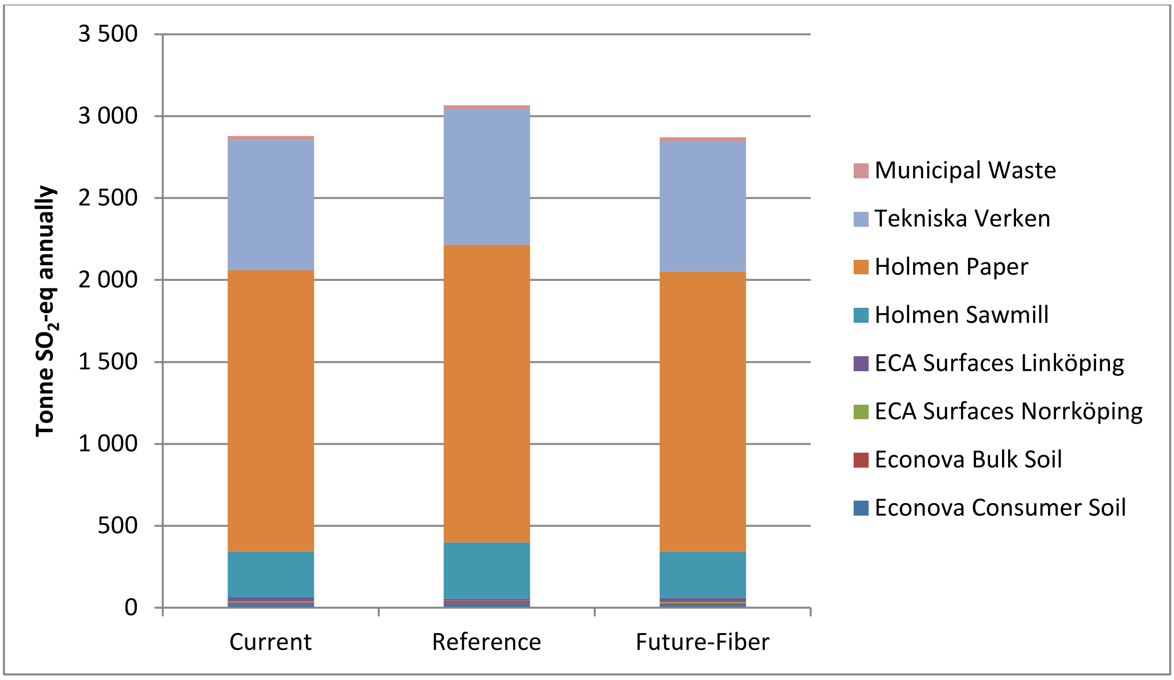

Figure A 3: Review of Acidification impacts of the individual firms in the Current, Reference and Future-Fiber Scenarios (shown in tonnes SO_2-eq annually)

Appendix Table 14: Review of Acidification impacts of the individual firms in the Current, Reference, Reference-Asphalt and Future-Fiber Scenarios (shown in tonnes SO_2-eq annually)

		Current	Reference	Future-Fiber	Reference Asphalt
Econova	Econova Consumer Soil	24	31	21	31
	Econova Bulk Soil	9	12	7	12
ECA	ECA Surfaces Norrköping	5	0	9	0
	ECA Surfaces Linköping	25	12	25	13
Holmen	Holmen Sawmill	280	340	280	340
	Holmen Paper	1 710	1 820	1 700	1 820
Energy	Tekniska Verken	790	830	790	830
Other	Municipal Waste	25	26	25	26

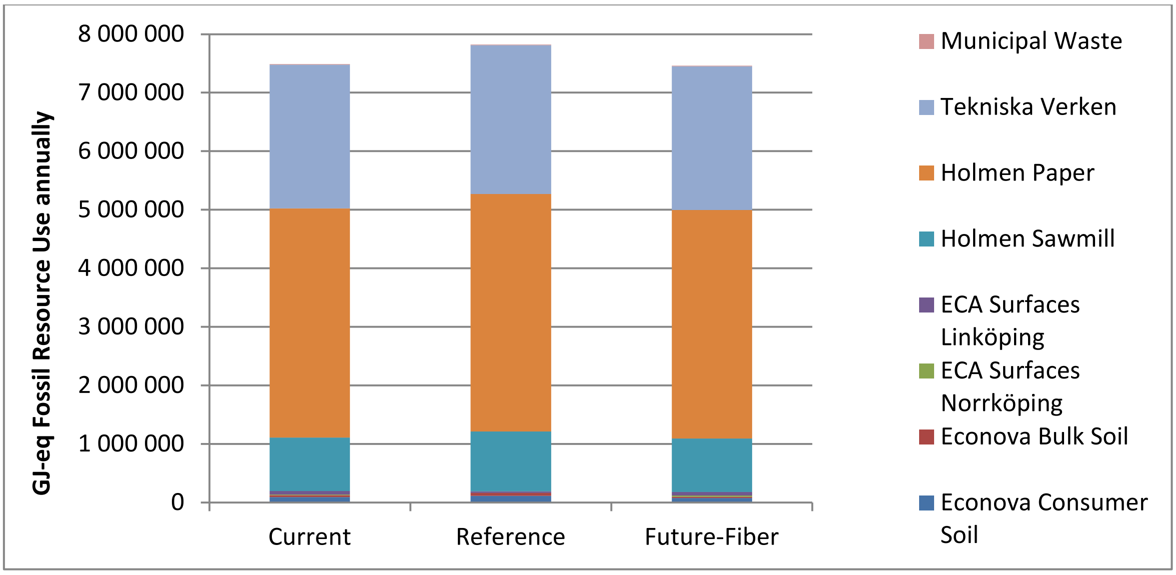

Figure A 4: Review of the abiotic resource depletion (measured in GJ fossil resource use annually) of the individual firms in the Current, Reference and Future-Fiber Scenarios

Appendix Table 15: Review of the abiotic resource depletion (measured in GJ fossil resource use annually) of the individual firms in the Current, Reference, Reference-Asphalt and Future-Fiber Scenarios

		Current	Reference	Future-Fiber	Reference Asphalt
Econova	Econova Consumer Soil	92 630	118 190	76 510	118 190
	Econova Bulk Soil	33 210	45 760	25 330	45 760
ECA	ECA Surfaces Norrköping	12 680	-	21 370	-
	ECA Surfaces Linköping	59 940	28 630	57 090	38 930
Holmen	Holmen Sawmill	913 530	1 023 160	913 530	1 130 630
	Holmen Paper	3 912 700	4 056 170	3 899 340	4 155 600
Energy	Tekniska Verken	2 453 380	2 542 140	2 453 380	2 725 520
Other	Municipal Waste	9 710	10 190	9 710	10 190

Appendix Table 16: Transportation for the different clusters, and for the Current, Reference, Future-Fiber and Reference-Asphalt scenarios (measured in tonne-km annually).

	Current	Reference	Future-Fiber	Reference Asphalt
Econova	43 101 460	57 382 110	34 206 970	57 382 110
Econova ECA	1 813 950	600 000	1 813 950	680 400
Holmen	391 558 180	400 995 000	391 615 830	397 245 000
Tekniska Verken	253 003 980	267 515 050	253 003 980	267 515 050
Municipal Waste Management	1 872 000	2 064 000	1 872 000	2 064 000

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