FEASIBILITY OF SUPERABSORBENT POLYMER RECYCLING IN DISPOSABLE ABSORBENT HYGIENE PRODUCTS

A total life cycle approach

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Abstract

The objective of this work is to evaluate the life cycle impacts of recovering superabsorbent polymers from absorbent hygiene products (AHPs). AHPs, which include baby diapers, feminine hygiene products, and adult incontinence pads, have a considerable environmental impact. While convenient, these single-use products, which typically contain combinations of polypropylene, polyethylene, elastics, cellulose, and superabsorbent polymers (SAPs), are disposed by the billions worldwide. Current practice of AHP disposal results in the loss of valuable materials like SAPs, generation of large volumes of municipal solid waste, and increased manufacturing burdens. Though manufacturers have taken significant strides to reduce the environmental impact of AHPs through product design, developing a potential circular economy of AHPs will be crucial to reducing total life cycle impacts. This is more important than ever, since the disposable diaper industry is reporting exponential growth and its global production is expected to exceed US $71 billion/year by 2022.

While recognition of AHP impacts is increasing, it is important to consider that the most significant life cycle impacts of AHPs stem from resource extraction, production, and manufacturing, not disposal itself. The SAPs in these products are a particular focus as they contribute substantially to these upstream life cycle impacts. SAPs can make up as much as one third of the total mass of AHPs and are responsible for the highest proportion of greenhouse gas emissions of AHP materials. We aim to shed light on how we might lessen upstream impacts by focusing on the potential for SAP recovery and re-use. We evaluate three end-of-life options for baby diapers in Europe using a life cycle approach in order to explore alternative options to conventional disposal of AHPs.

This research analyzes the environmental trade-offs associated with AHP waste under the following three scenarios: 1) baby diaper disposal via landfill or incineration in a standardized European context; 2) diaper recycling without SAP recovery; and 3) diaper recycling with SAP recovery. Environmental impacts of these scenarios were modeled in the LCA software SimaPro using the ReCipe 2016 impact assessment framework. Results show that SAP recovery has potential to decrease life cycle emissions by 54% compared to standard landfilling and incineration and by 35% when compared to the recycling technologies assessed in the study. SAP recovery and reuse also results in large potential offsets of energy and water burdens involved in SAP manufacturing. By assessing these environmental impacts, we aim to clarify the point at which SAP recovery demonstrates potential for circular economy.

Acknowledgements

I would like to thank Dr. Jose Alfaro for making this research possible. I first met with Dr. Alfaro to discuss this project in the fall of 2017 and he has provided continuous support and guidance on this research ever since. Dr. Alfaro took me in as an undergraduate studying microbiology and has helped broaden and transform my skills through this project and others to sustainability, LCA, and engineering. I am also particularly thankful for Dr. Alfaro's industry experience which has guided this research and helped craft the presentation of this data to industry partners. I would like to acknowledge Dr. Alfaro's excellent mentorship and advisement on this project which has spanned multiple years (and multiple countries). I would also like to thank Dr. Geoffrey Lewis for providing my first formal introduction into the world of LCA and SimaPro though his class Advanced LCA Methods & Tools. Without this training, this environmental analysis would have looked much different. Dr. Lewis also provided support through the Center for Sustainable Systems by recommending relevant papers, helping me to think critically about LCA methods, and taking time to prepare me for multiple presentations and an international conference. His guidance was always accessible, and I am very thankful to have consulted with him on this research. I would also like to thank Dr. Nicole Ryan and Stefania Almazan Casali for their guidance on several presentations, for help preparing me to present this research in Beijing last summer, and for moral support on many occasions.

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Introduction

This analysis seeks to assess potential improvements to the sustainability of disposable baby diapers by creating a circular economy of the valuable materials, namely the superabsorbent polymers (SAPs), that make a major contribution to environmental impacts at the beginning of the life cycle. Disposable diapers are not new to the world of life cycle assessment (LCA). One of the first and most well-known examples of LCA compares disposable and cloth diapers [1]. Though cloth diapers are an arguably viable way to reduce environmental impacts, this analysis will be restricted to single-use baby diapers, referred to from here on as disposable baby diapers. The disposable versus cloth diaper debate has yielded no clear answers. Instead, consumers are left to weigh tradeoffs. With cloth diapers, the main environmental impact is the electricity and water used in washing; for disposable diapers, the main environmental impact is in the raw material production [2]. Regardless of the environmental impacts and tradeoffs between cloth and disposable diapers, market trends indicate consumers aren't willing to do without their disposable diapers any time soon. In fact, the industry is reporting exponential growth and population trends suggest this growth will continue [3]. Therefore, this paper aims to address circular economy-based solutions (e.g., material recovery and reuse) as a way to improve the environmental performance of these products.

Manufacturers have taken significant strides to reduce the environmental impact of disposable diapers through product design. In the past two decades, for example, the average weight of a baby diaper has been cut nearly in half [4]. This reduction is attributed largely to the introduction of SAPs ($(C_3H_3NaO_2)_n$), cross-linked poly-acrylic acid [5] with a high water absorbing capacity [4]. SAPs are produced from fossil feedstock (i.e., propylene) and are widely used in both hygiene, medical, and agricultural applications [6]. SAPs first appeared in the 1950s for use in contact lenses; since then they have expanded into several other industries, with a total production of around 1.5 million tons in 2005 [6]. While the weight of nearly every other diaper material has declined, the amount of SAP has increased from 0.7 grams in 1987 to 11.1 grams in 2011 [4]. Although product design remains an important method for achieving sustainability goals, addressing life cycle impacts of disposable diapers, namely greenhouse gas emissions, water consumption, and other air emissions, are needed to curtail the rising environmental impacts. Further, technologies for recycling and mitigating the loss of high economic value materials at the end-of-life may produce improvements more quickly than product material innovations.

Attempts to prevent this material loss and create alternatives to standard disposal of diapers have seen mild success. Largely, recycling efforts appear to be centered on recycling of the plastic fractions of a diaper or energy recovery. Knowaste Ltd. developed technology to successfully recycle the plastic and fiber fractions of disposable diapers in the UK, Canada, the Netherlands, and California, though the company is no longer operational [7]. In the Knowaste process, post-consumer diapers were sterilized and the fiber and plastics separated [7]. With this technology, the SAP remained with the cellulose fiber. Knowaste packaged fibers for reprocessing and the remaining plastics were sent to a granulator and washing system and ultimately converted into pellets for use in roof tiles and other plastic items [7]. Operational costs were unsustainably high and plans for a new plant in London, U.K. were rejected in 2017, primarily due to odor concerns [8]. In Italy, FaterSMART and Contarina SpA have developed an industrial scale recycling facility that utilizes a process of sterilization, drying, and separation to recover secondary materials [9, 10]. The recovered materials are viable for use in several applications including textiles, fertilizers, paper, and other AHPs [9]. A Singaporean company, Diaper Recycling Technology Pte Ltd., employs vertical stacking technology for plastic purification and pulp-SAP separation, ideal for recycling with constrained space [3]. They have claimed to recover 99% of key materials after recycling, specifically the SAP, plastic, and cellulose [3]. Finally, a Japanese company, Super Faiths Inc. is capable of processing 300-600 kg of used diapers daily by producing pellet fuel [3].

Challenges to commercial diaper recycling have included lack of consumer buy-in, logistical hurdles regarding the separate collection service, complex facility requirements, high operational costs, energy intensive operations, low quality and economic value of recovered materials, and low demand for recovered materials [3, 11, 12]. It is also important to note that the majority of these recycling facilities exist primarily in developed nations, despite the larger burdens and the larger health and social costs related to inadequate diaper disposal in developing countries. [3, 13].

The focus only on end-of-life with these diaper recycling technologies has some environmental benefits and results appear promising. A Deloitte life cycle assessment of the Knowaste process cited a 71% decrease in carbon emissions at end-of-life, approximately 22,536 metric tons of greenhouse gas emissions saved per 36,000 metric tons of AHP waste [14]. However, greenhouse gas (GHG) burdens for the end-of-life stage are minimal in comparison to manufacturing [4]. Approximately 63% of CO_2eq (carbon dioxide equivalent) emissions are attributed to production and manufacturing stages of disposable diapers [4] and thus the environmental benefits of this energy and cost intensive recycling are minimal when the burdens avoided are contained in the end-of-life stage. Furthermore, the assumption that recovered plastics and other materials will replace virgin materials is arguable, as GHG savings will only result if demand for recovered materials results in displacement of virgin materials [15], something that might only happen for very high value materials.

To address these recycling shortcomings, high manufacturing burdens should be the focus of efforts to reduce GHG impacts of AHPs. SAPs present an opportunity for reuse due to their high contribution of GHG emissions in diapers and their high economic and feedstock value [4]. Recovering SAP for reuse in its original application could create a direct market and potentially reduce manufacturing costs. Efforts to date to recycle or recover SAP have been limited. Some research has gone into removing the fossil feedstock by developing a bio-based SAP, but production currently reduces global warming potential while increasing other impacts due to high energy demand when the feedstock is side streams from pulp mills [16]. Methods to clean up used SAP, such as dimethyl ether extraction of SAP, centrifugation extraction of SAP, and thermal dehydration have shown promise in removing the water from used SAP [17].

As the technology to recover SAP develops, it is important to clarify the question - at what point is SAP viable for recovery and reuse? Given the uncertainties involved in SAP recovery and reuse, this paper analyzes the environmental benefits and tradeoffs of a potential SAP recovery process to help clarify the point at which SAP recovery could result in decreased manufacturing burdens and recuperation of valuable materials. Metrics chosen to compare scenarios include global warming potential (GWP), m^3 of water consumption, and cumulative energy demand both for the full life cycle and for the end-of-life scenarios alone. Sensitivity analyses for grid mix and percentage of SAP recovery were employed to further explore scenarios.

Methods

Modeling different disposable diaper life cycle scenarios was done using the software SimaPro version 9.0.0.48 and the ecoinvent database version 3.5 [18]. Below we describe the assumptions made and materials required to evaluate the environmental tradeoffs between three scenarios: standard diaper disposal as part of municipal solid waste (MSW), diaper recycling based on a process that recovers plastics but uses SAP and cellulose as a waste-to-energy stream, and an idealized diaper recycling process that recovers both SAP and plastics. The two diaper recycling scenarios are further divided: one scenario assuming all recovered materials close the loop (avoided burden method) and another assuming some materials are not of sufficient quality to replace primary production (denoted NAB for no avoided burden). This modeling strategy allows for analysis of the materials driving the environmental impacts as well as a nuanced analysis of environmental tradeoffs between the end-of-life scenarios. Life cycle assumptions, including boundaries, methods, materials, and disposal scenarios are outlined below.

LCA assumptions:

Figure 1 shows the system boundary for this analysis. In the interest of comparing the contribution of each diaper material as well as three different end-of-life scenarios for disposable baby diapers, only materials, energy, and related resource consumption were included, in addition to the disposal scenarios at the end-of-life. Diaper materials were assumed to remain the same between different diaper disposal scenarios. Packaging and distribution of diapers were not included in the analysis as both were assumed to remain constant for each of the three scenarios and neither are considered main drivers of environmental impacts. Transport from curb-side to a disposal facility was also not accounted for, despite the fact that novel recycling processes will likely require a separate collection service from current curbside pickup of MSW [4]. Ultimately, transportation represents a small fraction of emissions in the life cycle of a diaper [4] and appears to be negligible in comparisons of landfill, incineration, and recycling processes [12]. Dashed lines back to materials represent the potential flow of recovered materials back to close the loop when accounting for avoided burdens.

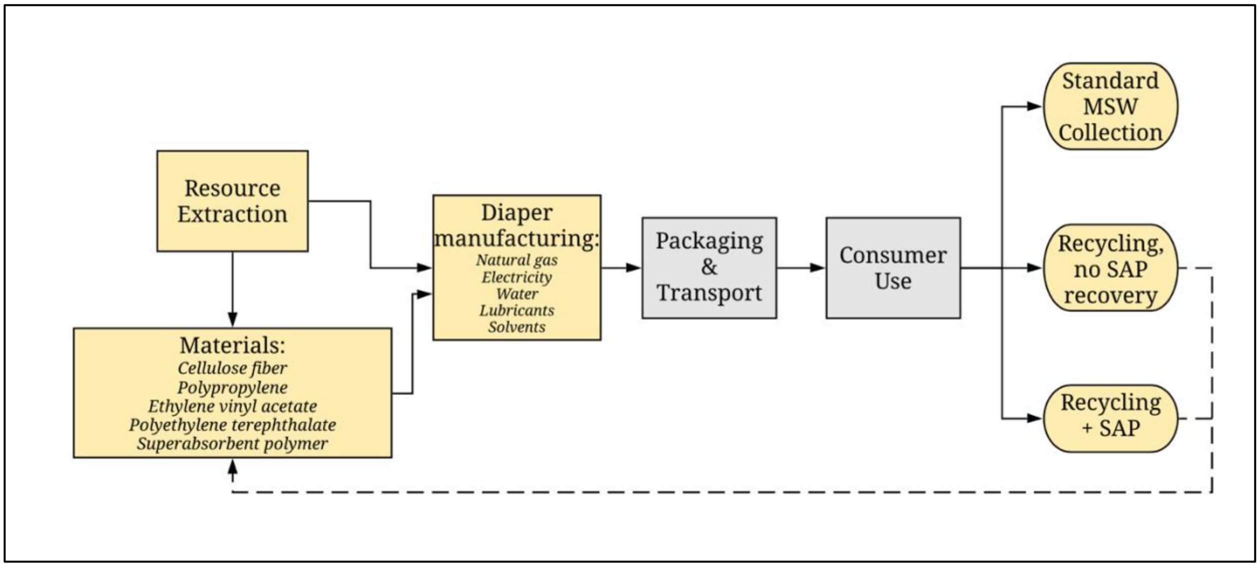


Figure 1. Life Cycle Overview *Life cycle boundaries showing the focus of the LCA (in yellow) and the excluded steps (in grey).*

The manufacturing and disposal of baby diapers was assumed to take place in the Netherlands. The Netherlands was selected for modeling for several reasons. First, the Netherlands is a leader in waste management practices and recycling [19]. Secondly, the Netherlands is a likely location for diaper recycling in the near future. Amsterdam has already attracted industry to work on a pilot diaper recycling project [20]. All materials and processes therefore assume parameters specific to the Netherlands whenever possible. When data for the Netherlands were unavailable, SimaPro data for other European countries (primarily Switzerland) were used as proxy. While supported generally by the literature, this method results in an estimation of the impacts of baby diaper production that may not reflect conditions outside of Europe. The functional unit in this analysis is one standard baby diaper weighing approximately 0.027 kg. For end-of-life scenarios, it was assumed that consumer use, or what the industry calls “insult,” added 50% of the initial weight. Added weights vary widely in the literature [3, 11] but 50% added weight was chosen after conversations with industry experts.

LCA methods:

Using the ecoinvent database in SimaPro, life cycle analyses were calculated using the ReCiPe 2016 v1.1 endpoint method, hierarchist version [21]. The following sections present the methods for evaluating disposable diaper inputs in the manufacturing stage and the end-of-life stage for three different disposal scenarios.

Manufacturing

The average disposable baby diaper consists of cellulose, SAP, plastics, and adhesives. The production of materials needed to construct a disposable diaper were accounted for in the manufacturing stage of the life cycle. The composition of diapers and the relative percent contribution of mass per item for SAP, cellulose, glue (modeled using ethylene vinyl acetate), polypropylene, and polyethylene terephthalate, were determined through conversations with an industry partner. SAP, or cross-linked poly-acrylic acid, was modeled using the 'Acrylic acid, at plant/ RER U' ecoinvent process representing acrylic acid production in Europe [18]. Energy and emissions were added to model the extra polymerization processes on top of acrylic acid production. These energy and emissions (specifically SO_2eq, CO_2eq, C_2H_4eq and PO_4eq emissions) data were gathered from a study on fossil-based production of sodium polyacrylate in the Netherlands [16, 22]. Values for production energy and masses of the remaining materials – water, lubricants, and solvents – were taken from the literature and added to the manufacturing stage [4]. Table 1 displays the materials and energy for the manufacturing that were included in the SimaPro model. Values for each material and process are included in the appendix.

Table 1. Materials and Process Inputs to Manufacture 1 Diaper

Materials	Processes
Cellulose fiber Polypropylene Ethylene vinyl acetate Water Lubricating oil Solvents Polyethylene terephthalate Superabsorbent polymer Insult	Natural gas Electricity

Disposal scenarios

Three disposal scenarios were evaluated. The *Standard MSW Collection* scenario assumes diapers are disposed in MSW. The second scenario *Recycling, no SAP recovery* is based on a process similar to the Knowaste technology where some materials are recovered but where SAP is incinerated along with the cellulose. The third scenario *Recycling + SAP recovery,* assumes the same recycling process as the *Recycling, no SAP recovery* scenario but with additional recovery and direct re-use of the SAP. In the second and third scenarios, *Recycling, no SAP recovery* and *Recycling + SAP recovery,* the disposal scenarios are further divided into two parts. Part 1 includes the avoided burdens or recovered materials from the recycling process that were assumed to offset virgin material production and will be included only in scenarios that use the avoided burden method. Part 2 includes resources required by the recycling plant and is included for all recycling scenarios, regardless of allocation method. In total, this method results in five disposal scenarios: *Standard MSW Collection, Recycling, no SAP recovery NAB, Recycling, no SAP recovery, Recycling + SAP recovery NAB, and Recycling + SAP recovery.*

Standard MSW Collection

Disposable baby diapers in the Netherlands are considered MSW [4]. MSW disposal was modeled using data for Switzerland (CH) due to lack of data on incineration and landfill in the Netherlands. The split between Standard Incineration (CH) and Landfill (CH) was assumed to be 92.1% and 7.9% respectively for the Netherlands (Table A2). The incineration waste scenario in ecoinvent version 3 is considered applicable to modern incineration practices in Europe [18]. No recycling processes were accounted for in MSW processing. Figure 2 shows the outline of the life cycle for this *Standard MSW Collection* disposal scenario. As was outlined in the LCA assumptions, resource extraction, manufacturing, and end of life were accounted for.

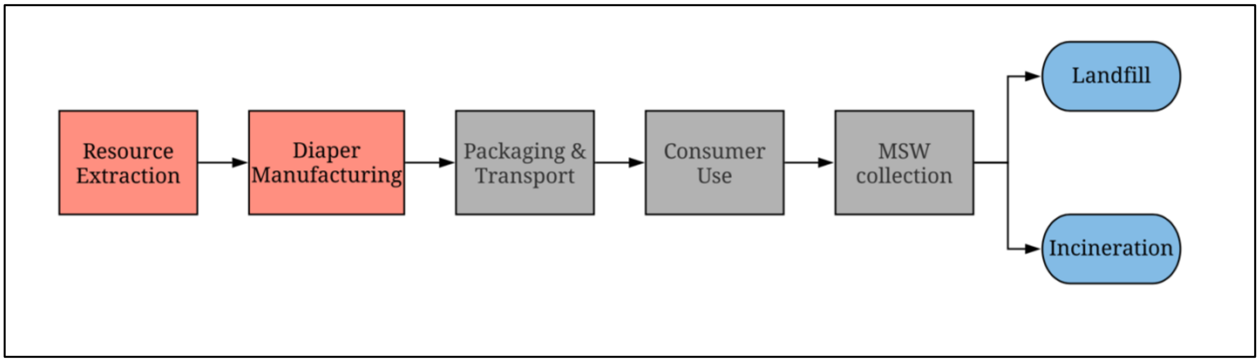


Figure 2. ***Standard MSW Collection*** **Scenario** *Modeling of the Standard MSW Collection scenario accounts for manufacturing (red) and end-of-life (blue).*

Recycling, no SAP recovery

Data for the *Recycling, no SAP recovery* scenario are based on a 2016 life cycle analysis of a potential recycling technology[12] but presents emissions and energy inputs for a prototype recycling process that did not achieve commercial deployment. The process involved a flow of 500 kg of AHP waste sterilized via electric autoclave [12]. After autoclaving, wastewater from the autoclave process is sent to municipal treatment and remaining materials are sent to a sorter where they are separated into recovered cellulosic and plastic fractions, and solid residues for disposal [12]. The plastics are sent to the existing plastic recycling processor but the cellulose and SAP are sent through a gasifier, combustor, and steam generator for energy recovery, with gaseous emissions treated in an air pollution control (APC) system [12]. Treated ash from the gasifier is used in the production of materials for road backfilling, and residues from the APC are disposed of in a landfill [12]. Plastics sent to recycling and materials recovered after gasification were assumed to be “avoided burdens” and thus the model accounted for replacement of their primary production [12]. As stated previously, this assumption is optimistic for low value materials and most plastics since recovered material is often of lower quality [15]. Furthermore, markets for recovered materials are unreliable due to supply and demand dynamics [15]. Figure 3, which displays the steps in this life cycle scenario, represents this uncertainty with a dashed line from recycling to resource extraction.

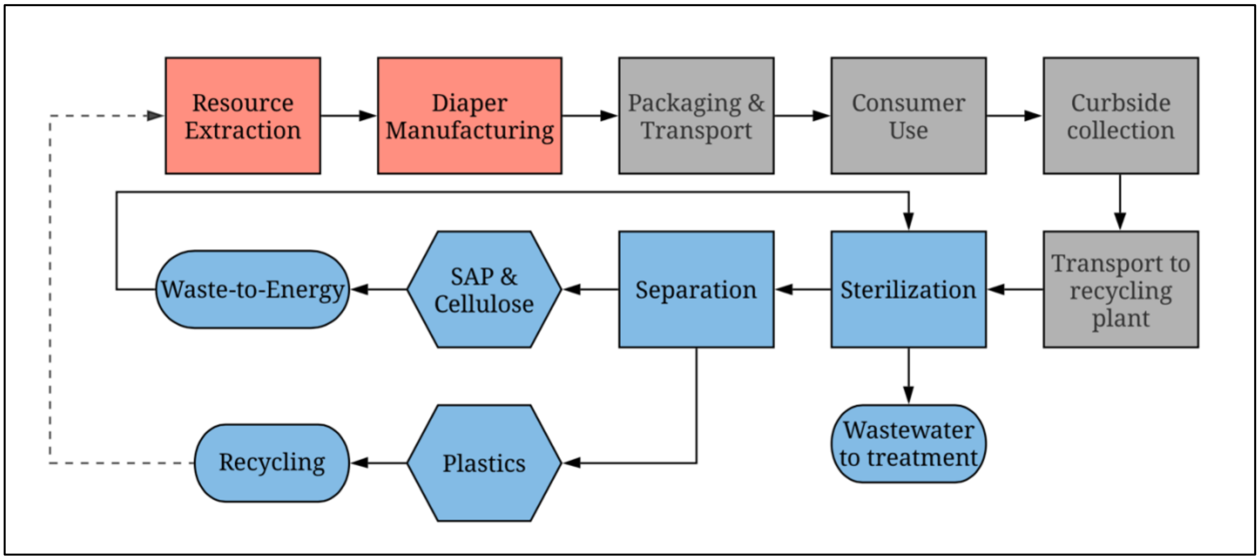


Figure 3. *Recycling, no SAP recovery* Scenario. *Modeling of the Recycling, no SAP recovery scenario accounts for manufacturing (red) and end-of-life (blue).*

To model the uncertainty in these recovered products, estimates for the *Recycling, no SAP recovery* scenario were calculated two ways: one utilizing the avoided burden method and one where credits are not given for recovered materials (marked as *NAB* for No Avoided Burdens). Table 2 lists flows for one baby diaper in the Netherlands. Within Table 2, Part 1 describes the materials recovered as avoided burdens. Part 2 describes resources and energy required by the recycling plant as well as the waste outflows: air emissions and waste to treatment.

Recycling + SAP recovery

The energy and material burdens of SAP recovery are unknown. Modeling of SAP recovery represents a best-case scenario of 100% SAP recovery in order to assess the utility of efforts to recoup SAP for direct re-use. The *Recycling + SAP recovery* scenario considers SAP as an avoided burden. In Figure 4, recovery of the SAP was modeled as an addition to the *Recycling, no SAP recovery* process. One critical distinction, however, is that SAP recovery is assumed to directly impact initial resource consumption related to materials (Figure 4). To uncover the best-case scenario for SAP recycling, 1 kg of recovered SAP is assumed to offset 1 kg of primary SAP production. SAP was assumed to always displace primary production in both allocation methods (*Recycling + SAP recovery NAB and Recycling + SAP recovery)*. This allows for assessment of the difference between direct re-use of SAP without accounting for other avoided burdens versus recovery of SAP in addition to credits for other avoided materials. Table 2 shows both avoided burdens of the recycling process as well as inputs and outputs.

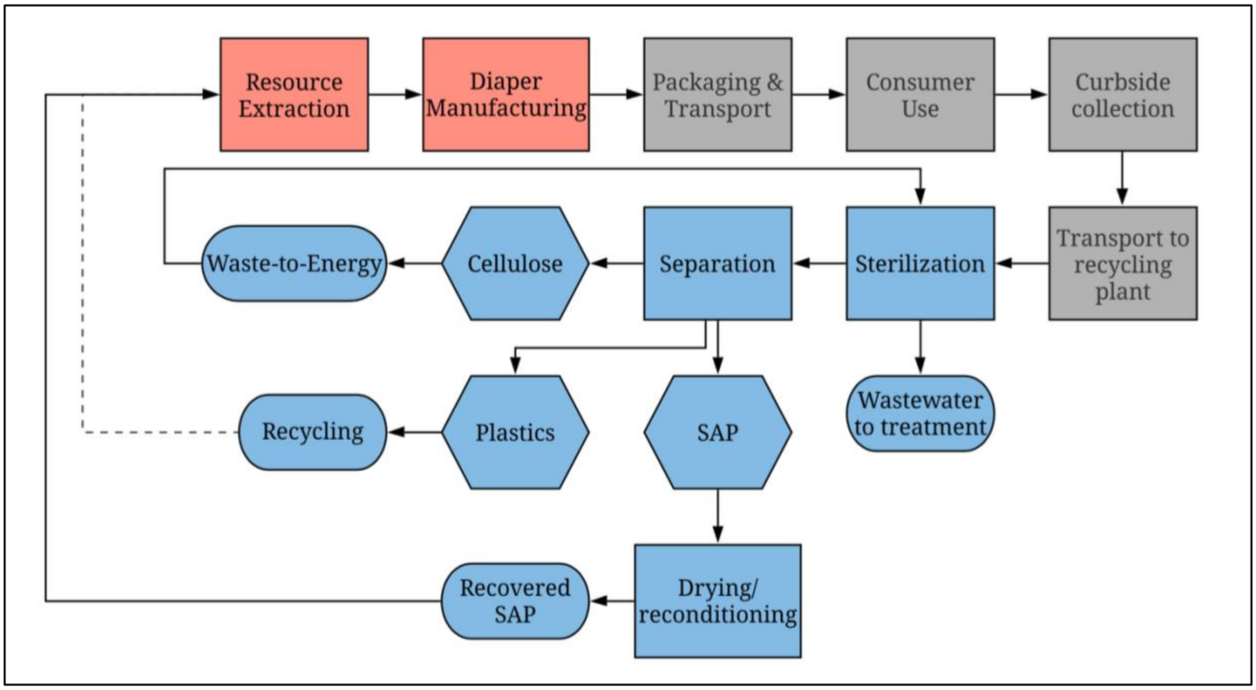


Figure 4. *Recycling + SAP Recovery* Scenario. *Modeling of the Recycling + SAP recovery scenario accounts for manufacturing (red) and end-of-life (blue).*

Table 2: ***Recycling, no SAP recovery and Recycling + SAP Recovery*** **Scenarios*:* Processes and Avoided Materials for 1 Diaper.** *Part 1 includes the avoided materials and is included only in the avoided burden scenarios. Part 2 consists of the resources required by the recycling plant and is included for both the avoided burden and NAB recycling scenarios.*

> ***Recycling, no SAP recovery*** **Scenario*:*** *Avoided burden method = Part 1 + 2; NAB method = Part 2 only*
>
> ***Recycling + SAP Recovery*** **Scenario:** *Avoided burden method = Part 1 [including SAP] + Part 2; NAB method = Part 2 + [SAP] as the only avoided burden.*

Part 1	**Part 2**			
Avoided materials	*Resources*	*Energy*	*Emissions*	*Waste*
[SAP] Polypropylene Aluminum, primary Aluminum, secondary Steel, converter Steel, electric Gravel Polyethylene terephthalate	Water	Methane Electricity	Carbon dioxide Carbon monoxide Oxygen Nitrogen, total Nitrogen oxides Ammonia Sulfur dioxide Hydrogen chloride Particulates, SPM Dioxins (unspec.)	Treatment, sewage, to wastewater treatment Disposal, inert waste Disposal, hard coal ash Disposal, municipal solid waste to sanitary landfill

Results and discussion

The LCA results for a standard baby diaper comparing the three disposal scenarios are presented in terms of three environmental metrics: GWP as kg CO_2eq, m^3 of water consumption, and cumulative energy demand in MJ per diaper. For each metric, results are presented in terms of the entire life cycle as well as for the end-of-life scenarios only. To begin evaluating GWP impacts, we assessed the relative contribution of the manufacturing versus end-of-life impacts for all five disposal scenarios, as shown in Figure 5. Results are presented in terms of percent contribution of each disposal scenario to the total life cycle GWP. End-of-life impacts contribute significantly less than manufacturing impacts to full life cycle GWP. In the *Standard MSW Collection* scenario, approximately 71% of the total life cycle GWP comes from manufacturing. As more materials are recovered, the end-of-life contribution to total GWP lessens, as seen in the

Recycling, no SAP recovery NAB scenario. In the *Recycling, no SAP recovery* scenario, avoided burdens at end-of-life completely cancel out the GWP emissions coming from end-of-life. In the *Recycling + SAP recovery NAB* and *Recycling + SAP recovery* scenarios, avoided burdens lead to GWP "savings" at end-of-life, resulting in a negative contribution for end-of-life. Manufacturing burdens are thus higher than the full life cycle burdens, leading to percentage contributions over 100%.

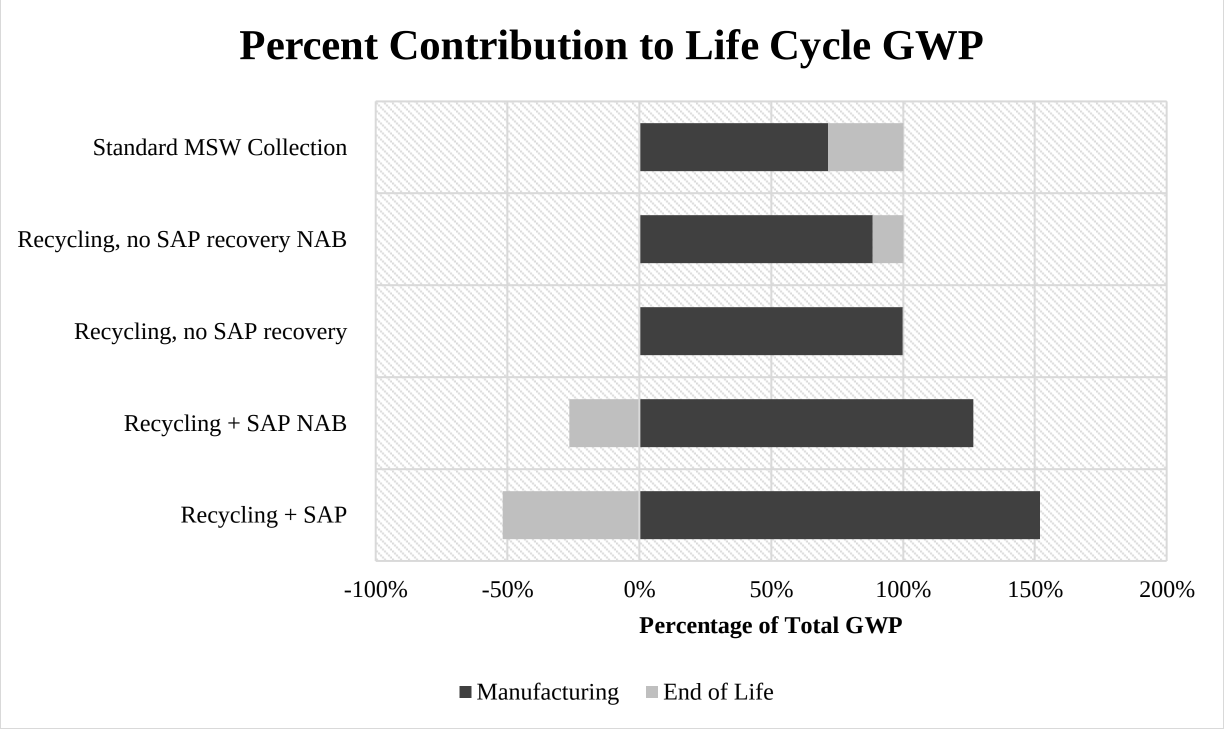


Figure 5. Manufacturing versus End-of-life GWP Impacts

Though Figure 5 does not indicate the values of GWP between the life cycle scenarios, it illustrates the burden of manufacturing GWP relative to end-of-life GWP. For the *Standard MSW Collection scenario*, the unequal burden between manufacturing and end-of-life demonstrates that the most important life cycle stage, from a GHG emissions standpoint, is manufacturing. These findings, consistent with relative life cycle stage impacts in the literature [4], highlight the importance of placing focus on manufacturing GWP impacts. Even for the *Recycling + SAP recovery NAB* and *Recycling + SAP recovery* scenarios, the end-of-life savings of CO_2eq are less than half of manufacturing emissions.

Within manufacturing, the contributions to GWP are divided as shown in Table 3. SAP and energy from natural gas and electricity to assemble the diaper, contribute 34.5% and 34.4% of the GWP respectively. Plastics are the third biggest contributor to GWP within the manufacturing stage with a 25.2% share of emissions. Finally, cellulose and other materials contribute the rest of the GWP impacts, at 1.9% and 4.0% respectively.

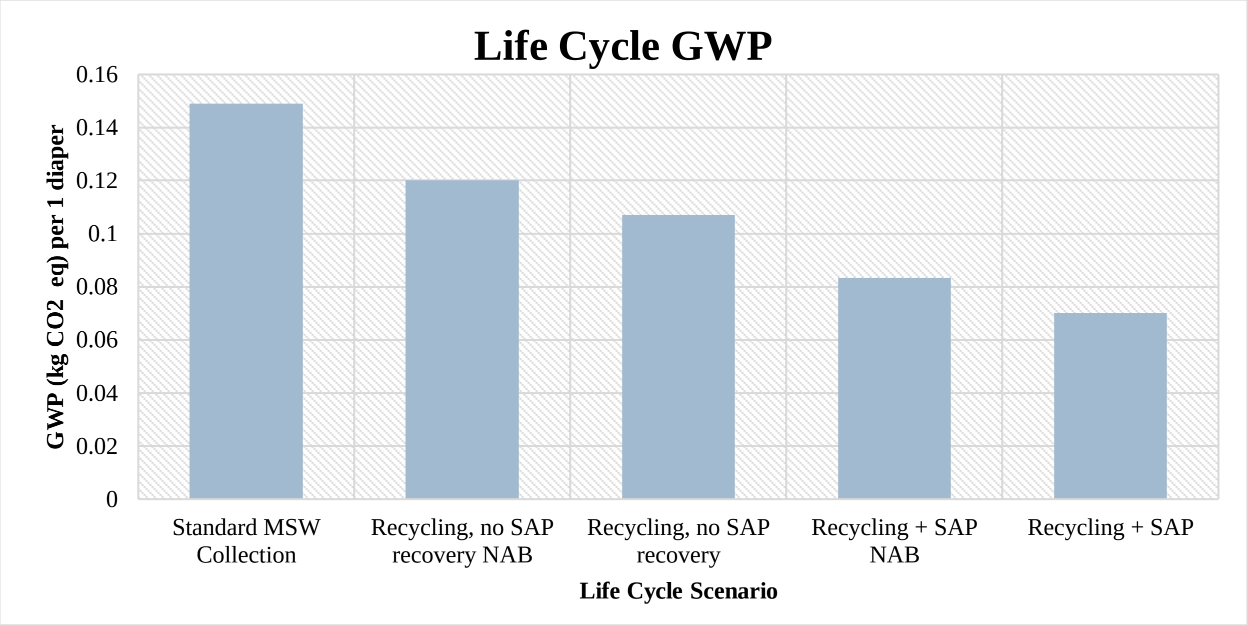
Table 3. Global Warming Potential (GWP) Impacts for Diaper Production and Manufacturing by Material and Process

	SAP	**Energy**	**Plastics**	**Cellulose**	**Other materials**
GWP (CO_2eq)	34.5%	34.4%	25.2%	1.9%	4.0%

The high contribution of CO_2eq emissions from SAP production and processing highlights the environmental value in addressing SAP production. Given that SAP makes up approximately 20% of the weight of a diaper in this model, its impact on emissions is disproportionate; addressing these emissions could significantly lower the full life cycle GWP.

In terms of the amount of CO_2eq for one diaper, Figure 6 demonstrates the full life cycle and end-of-life impacts for each scenario. The *Standard MSW Collection* scenario leads to 0.149 kg CO_2eq per diaper for the life cycle (or equivalently, 5.52 kg CO_2eq per kg of diaper), with 0.0425 kg CO_2eq coming from end-of-life. The *Recycling, no SAP recovery NAB* scenario reduces this full life cycle impact to 0.12 kg CO_2eq, due to 0.0425 kg - 0.0137 kg or 0.0288 kg CO_2eq reduced at the end-of-life. The *Recycling, no SAP recovery* scenario further reduces this impact to 0.107 kg CO_2eq. Recycling the SAP reduces the CO_2eq further to 0.0835 kg for *Recycling + SAP recovery NAB* and 0.07kg CO_2eq for *Recycling + SAP recovery.*

a.



b.

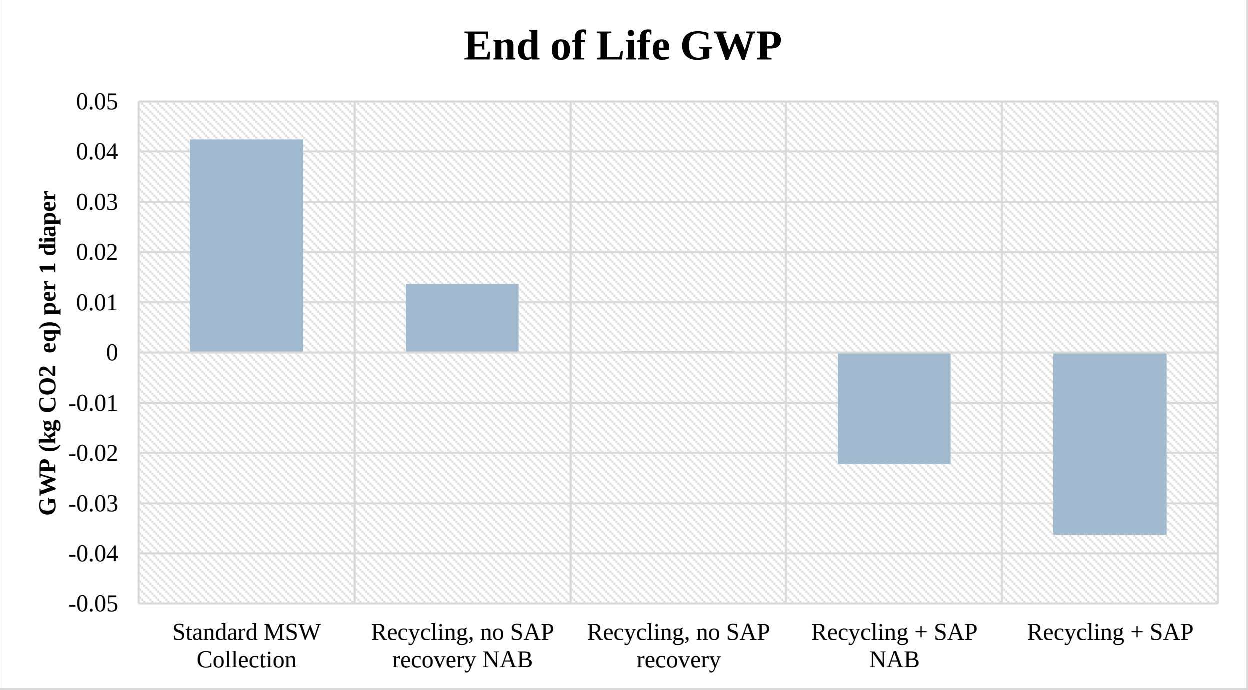


Figure 6. Global Warming Potential (GWP) Impacts per Diaper for the Life Cycle (a) and End-of-life (b)

As Figure 6 illustrates, the higher the mass of material that is recovered (from the *Standard MSW Collection scenario* to the *Recycling, no SAP recovery* and *Recycling + SAP recovery)* and offset (from NAB to the avoided burden approaches), the bigger the decrease in end-of-life impacts. From *Standard MSW Collection* to the *Recycling + SAP recovery* scenario, there is a 54% decrease in GWP and a 35% decrease in GWP between the current *Recycling, no SAP recovery* scenario to the potential *Recycling + SAP recovery* scenario (Figure 6a). The recovery of the SAP would contribute substantially to a decrease in GWP emissions. The allocation method appears to change GWP results by 10% between the *Recycling, no SAP recovery NAB* and *Recycling, no SAP recovery* scenarios and by 15% between the *Recycling + SAP recovery NAB* and *Recycling + SAP recovery* scenarios (Figure 6a). This becomes evident in the end-of-life scenarios, where offsetting CO_2eq is minimal until primary materials are displaced. In end-of-life, GWP for both *Recycling + SAP recovery* scenarios is negative, due to the assumed offsetting of impacts resulting from displaced primary production (Figure 6b).

Water consumption for the full life cycle and end-of-life is presented in Figure 7. For the full life cycle, water consumption is higher than *Standard MSW Collection* in both *Recycling, no SAP recovery* and *Recycling, no SAP recovery NAB* scenarios as well as in the *Recycling + SAP recovery NAB* scenario. *Standard MSW Collection* consumes 0.0791 m^3 of water in the life cycle with 0.00319 m^3 (or 4%) of this water resulting from landfilling and incineration. For the *Recycling, no SAP recovery NAB* and *Recycling, no SAP recovery* scenarios, water consumption is higher at 0.107 m^3 and 0.09 m^3 respectively. When SAP is recycled, water consumption is reduced to 0.0856m^3 for *Recycling + SAP recovery NAB* and to 0.0682m^3 for *Recycling + SAP recovery.* Due to displaced manufacturing of SAP, the *Recycling + SAP recovery* scenario has a negative impact at the end-of-life (Figure 7b).

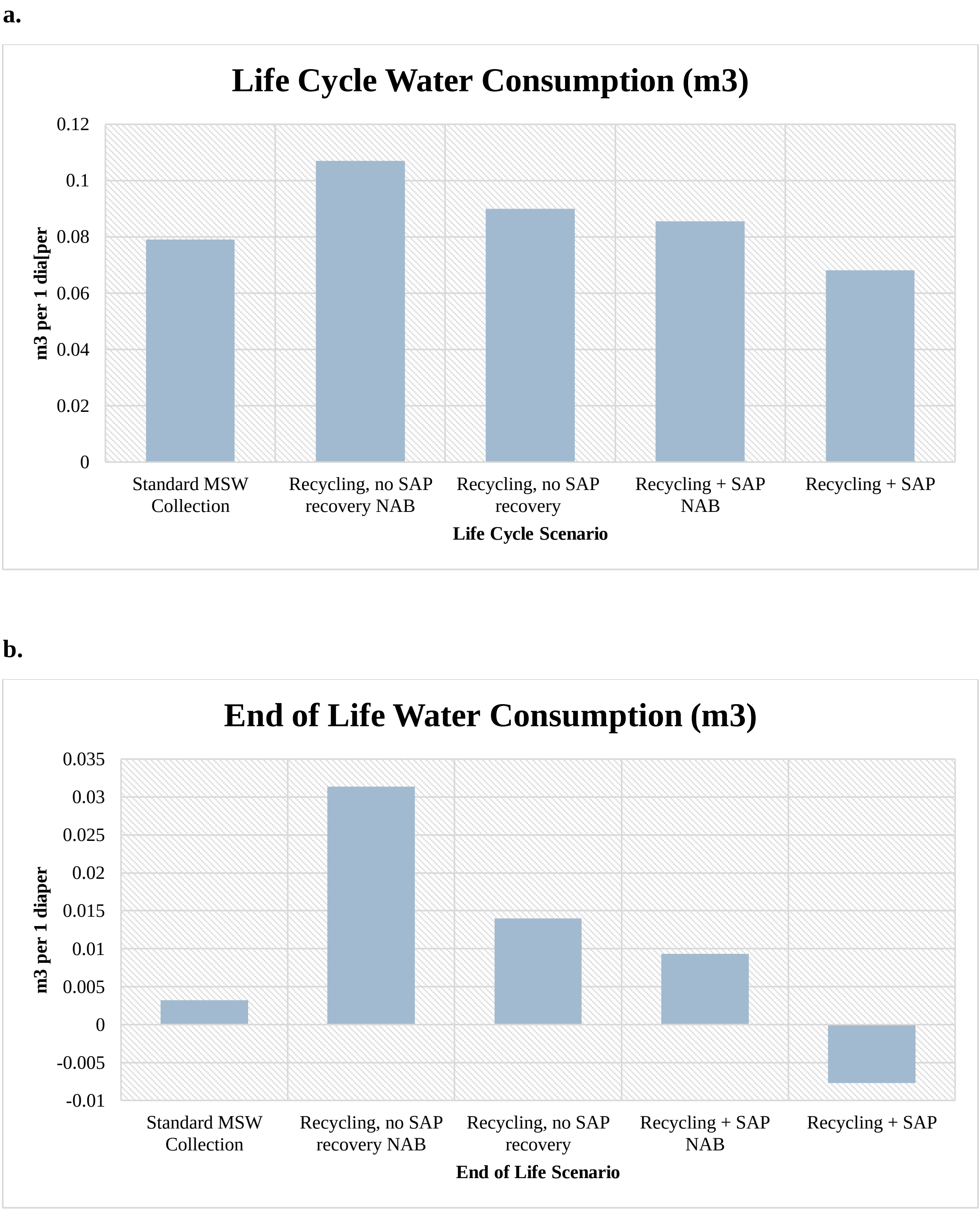
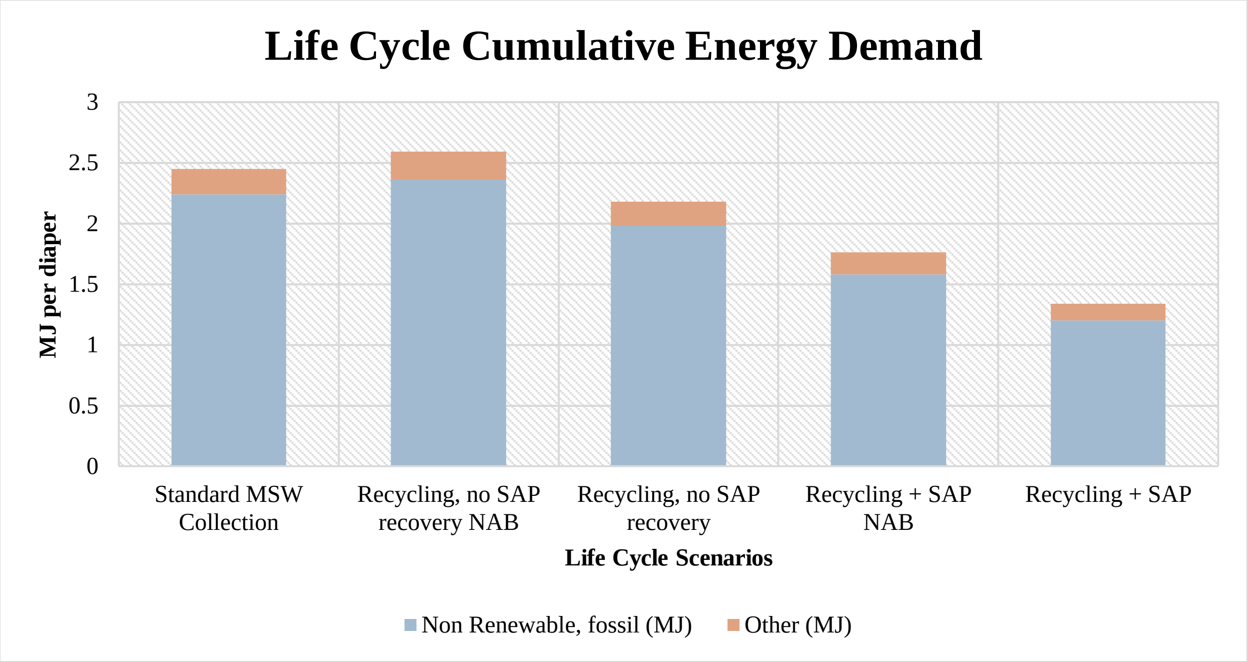


Figure 7. Water Consumption Impacts per Diaper for the Full Life Cycle (a) and End-of-life (b)

Water consumption, unlike GWP, shows increased impacts for the recycling scenarios. Unlike in landfilling or incineration, water is required in AHP processing to clean diapers before sterilization via autoclave [12]. Differences in water consumption between the *Standard MSW Collection* scenario and *Recycling, no SAP recovery NAB* are stark (Figure 7a). The water requirements to recycle diapers without taking any credits for avoided burdens significantly influences water consumption. Furthermore, this indicates that a recycling process that does not displace primary production may worsen water consumption compared to the standard MSW scenario. Direct re-use of SAP, however, may lessen the burdens of water required for treatment of AHP waste. As indicated in the *Recycling + SAP recovery NAB* scenario, accounting for SAP alone can result in 0.014 m^3 - 0.00936 m^3 or 0.00464 m^3 of water per diaper. However, even the *Recycling + SAP recovery NAB* scenario is more water intensive than the *Standard MSW Collection.* Unless water is saved due to replacement of some primary production of SAP *and* other recovered materials are taken into account (*Recycling + SAP recovery*), life cycle water consumption appears to be more intensive in diaper recycling (Figure 7a).

Cumulative energy demand, which represents direct as well as indirect use of energy over the life cycle, is evaluated for both the full life cycle and end-of-life (Figure 8). Here, *Recycling, no SAP recovery NAB* has the highest life cycle cumulative energy demand at 2.59 MJ per diaper (or equivalently, 95.9 MJ per kg of diaper), with approximately 6.3% resulting from end-of life (0.163 MJ per diaper). The *Recycling, no SAP recovery NAB* scenario has the highest end-of-life impact compared to any other scenario; *Standard MSW Collection* is the only other scenario with positive cumulative energy demand values at end-of-life (though smaller than *Recycling, no SAP recovery NAB* with 0.0171 MJ). The remaining recycling scenarios (*Recycling, no SAP recovery, Recycling + SAP recovery NAB* and *Recycling + SAP recovery)* have lower values for cumulative energy demand for the life cycle compared to *Standard MSW Collection* as a result of negative values at the end-of-life.

a.



b.

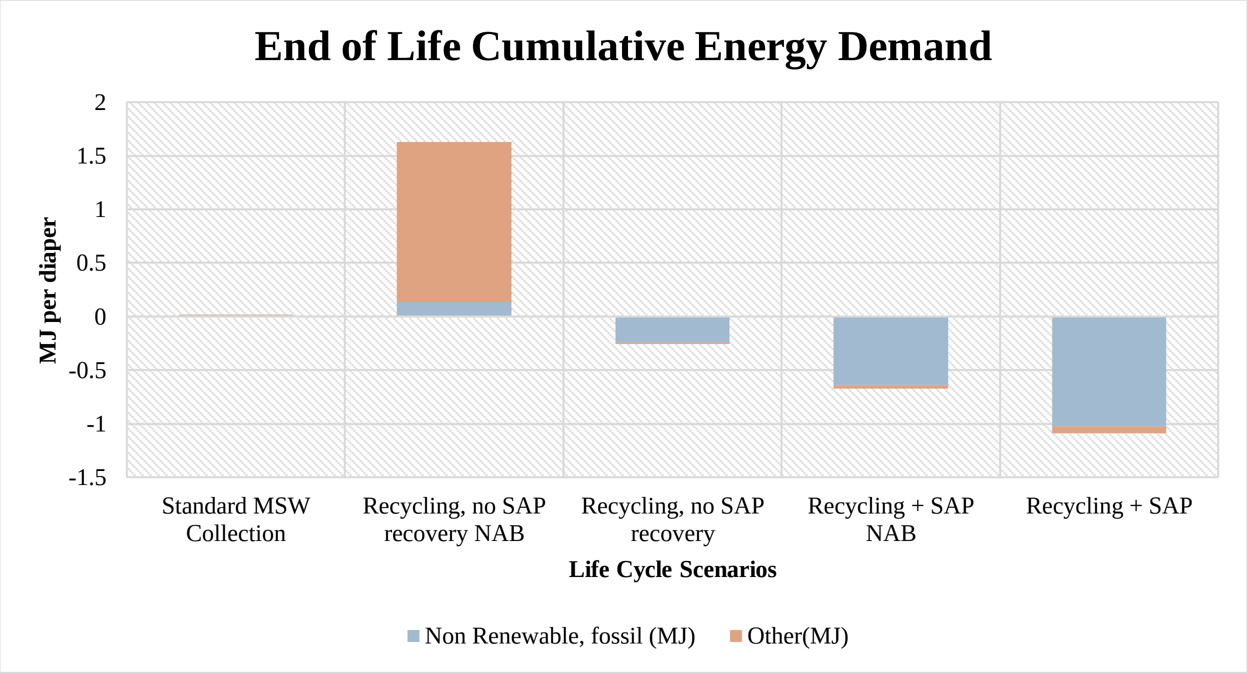


Figure 8. Cumulative Energy Demand Impacts per Diaper for the Full Life Cycle (a) and End-of-life (b)

The cumulative energy demand results underscore the importance of including avoided burdens in diaper recycling. As indicated in the water consumption analysis, if recovered materials from the *Recycling, no SAP recovery NAB* process are downcycled and do not displace primary production of material, environmental impacts, cumulative energy demand in this case, may be worse than *Standard MSW Collection.* The differing energy sources are also of note. Unsurprisingly, the majority of energy impacts originate from use of fossil fuel sources in the life cycle (Figure 8a). However, in the end-of-life stage, the *Recycling, no SAP recovery NAB* scenario shows energy consumption from other renewable sources, likely due to inputs of methane from biogas in the recycling process, not electricity (Figure 8). When accounting for the materials recovered in the *Recycling, no SAP recovery* process and the *Recycling + SAP recovery* process, there are energy "savings" in the form of fossil-based sources (Figure 8b).

It is important to note that the utility of cumulative energy demand as a standalone indicator has been questioned [23]. Cumulative energy demand is useful as an indicator of environmental burden, particularly when considering fossil-based energy sources [23]. Here, the cumulative energy demand of fossil resources in the full life cycle and relative absence of fossil-based sources in end-of-life helps to explain the reasons for high burdens in manufacturing and production (Figure 8b). The high percentage of fossil-based energy in the full life cycle raises the question of whether use of renewable sources in manufacturing (i.e., for electricity) can reduce environmental burdens of diapers. Since the grid in the Netherlands remains largely powered by fossil fuels, the environmental favorability of diaper recycling technology may increase in countries with more renewables in their grid mix.

Sensitivity Analysis

In evaluating the feasibility of SAP recovery and reuse, differences in grid mix were examined, primarily since the electricity and energy used in manufacturing have a large impact on GWP (Table 4) and because grid mix for electricity used to process AHPs at end-of-life affects the environmental benefits of recovery, though electricity use in recycling processes is minimal compared to use in manufacturing [4, 12]. The Netherlands grid is more carbon-intensive than many other European grids with 83% of electricity production from fossil fuels and 5.8% from renewables in 2016 [24, 25]. The US, for comparison, has a higher share of renewables in final energy consumption at 9.5% [26]. Sensitivity analysis for grid mix (Figure 9) shows that using electricity from the Netherlands increases GWP emissions for the *Standard MSW Collection* scenario compared to a US grid but otherwise decreases GWP emissions slightly for all recycling scenarios.

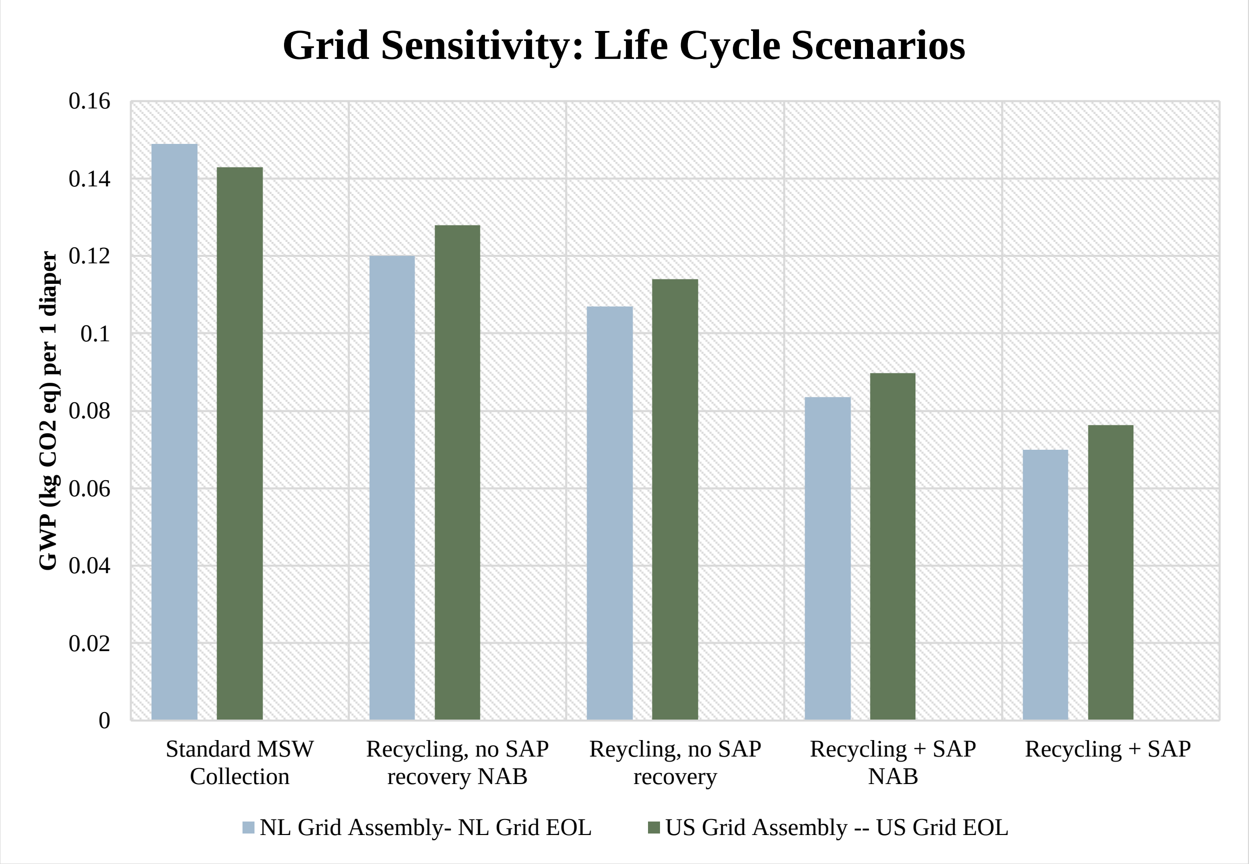


Figure 9. Sensitivity Analysis: Grid Mix. *Expected GWP for the full life cycle, manufacturing (Assembly) and end-of-life (EOL), with the Netherlands grid mix and the US grid mix.*

In the *Standard MSW Collection* scenario, the US scenario has a slightly lower GWP than the Netherlands, likely because 80% of MSW in the US is landfilled [18] and incineration of these materials in the Netherlands contributes more to GWP than landfilling [12] (Figure 6). However, despite a lower portion of renewables, the Netherlands shows a slightly lower GWP for the remaining disposal scenarios. This is due to differences in non-renewables in the grid mixes, specifically the higher consumption of coal in the US [27, 28]. Supply chain data indicating the countries where disposable diapers are assembled could shed more light on how differences in country grid mix may influence GWP and thus impacts of various material recovery technologies.

In addition to grid mix, another critical element in assessing the feasibility of SAP recycling is the feasibility of SAP recovery itself. Studies that have addressed SAP recovery have cited difficulties in separating SAP from the cellulose and fibers in disposable baby diapers [11] though there are other reports that claim nearly 99% recovery [3]. Sensitivity analysis shows the GWP reductions from SAP recovery are significantly lessened as recovery of SAP lessens (Figure 7).

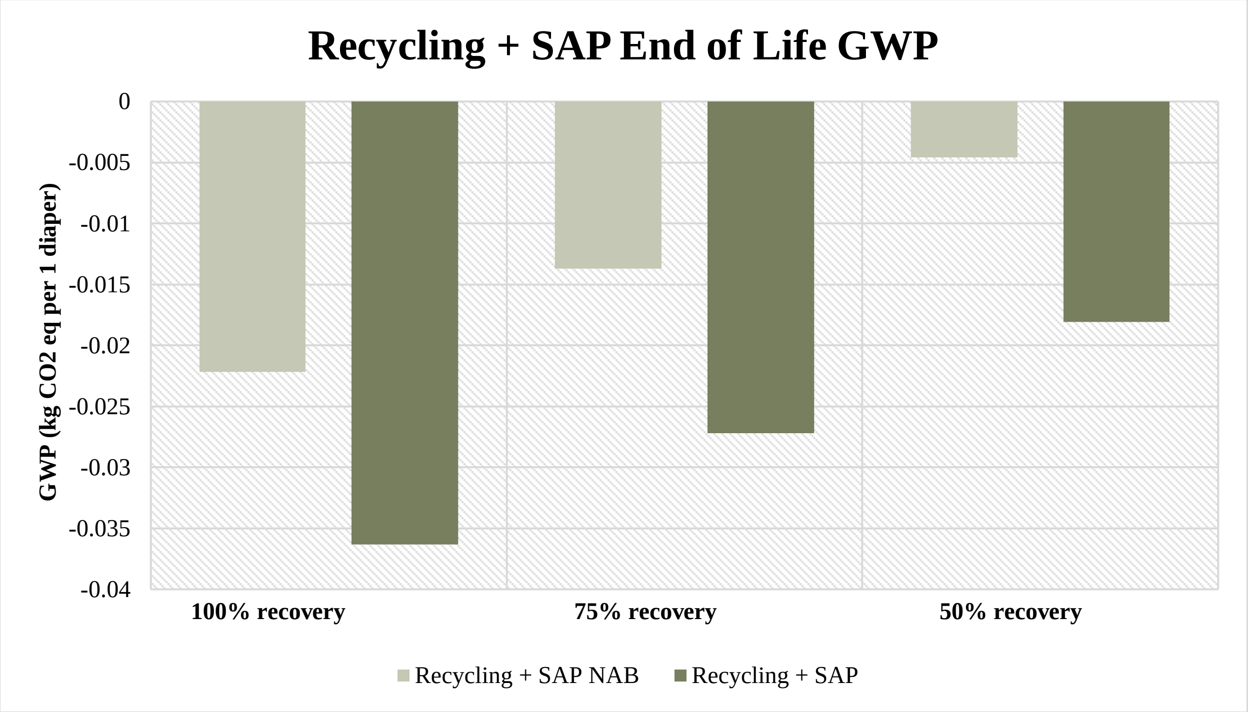


Figure 10. Sensitivity Analysis: Percentage SAP Recovery. *Impacts of SAP recovery percentage in terms of GWP for Recycling + SAP recovery NAB and Recycling + SAP recovery.*

With 50% SAP recovery, GWP approaches zero for the *Recycling + SAP recovery NAB* process, highlighting the importance of high SAP recovery. Successful SAP recovery is a significant barrier to SAP recycling feasibility, along with grid mix and energy needed for the recycling process. The reduced carbon savings shown here with 50% SAP recovery still assume the quality of recovered SAP is sufficient to offset 50% of virgin SAP production for one diaper. Poor performance factors (e.g., low recovery percentage, poor quality of recovered SAP, low percentage of renewables in the grid mix, and high energy inputs for recycling) challenge SAP recycling feasibility. Thus, these are factors that should be emphasized when evaluating any given technology.

To help evaluate how these factors will impact GWP savings, we have calculated the GWP "delta" or the emissions saved by recycling SAP. Since adding SAP as an avoided burden is the only difference between the *Recycling, no SAP recovery* and *Recycling + SAP recovery* process, the life cycle CO_2eq from the *Recycling, no SAP recovery* process minus the lifecycle CO_2eq from the *Recycling + SAP recovery* process yields the GWP "delta" (Equation 1).

Equation 1. Delta GWP. *Difference in global warming potential between Recycling, no SAP recovery process and Recycling + SAP recovery process.*

$$\Delta GWP = GWP_{\textit{Recycling}} - GWP_{\textit{Recycling+SAP recovery}}$$

$$0.107 \text{ kg } CO_2\text{eq} – 0.07 \text{ kg } CO_2\text{eq} = 0.037 \text{ kg } CO_2\text{eq per 1 diaper}$$

Given the *Recycling + SAP recovery* process does not account for the additional energy required to recover and reuse SAP, this delta (0.037 kg CO_2eq per 1 diaper) indicates the amount of buffer between the two processes (Equation 1). In other words, if energy required to recover SAP results in emissions of more than 0.037 kg CO_2eq per 1 diaper, then SAP recovery is no longer favorable in terms of GHG emissions.

Limitations

Several limitations are important to consider when evaluating the environmental benefits of SAP recovery and reuse. First, this analysis does not account for energy, water, or process materials necessary to recover SAP, as the technology remains at an early stage and these impacts are not well characterized yet. Materials and energy used to recover SAP could dramatically influence the results of this analysis and could result in worse environmental outcomes. This paper aims to guide decision-making around SAP recovery by providing information on the environmental benefits from SAP recovery alone. Inputs to recover SAP will reduce these benefits but should not lower them to the point where other methods of disposal have lower environmental impact. A related limitation is that SAP reuse is dependent on the feasibility of SAP recovery and the realizable recovery percentages are currently unknown. Recovery will vary by technology and it is important to consider that even with 50% SAP recovery, CO_2eq emission reductions are cut nearly in half. Additionally, due to data limitations for the Netherlands, estimates for some processes were gathered from other areas in Europe. It will be important to conduct more spatially specific analyses as SAP recovery technology develops.

Conclusions

This LCA provides novel information regarding the feasibility of SAP recycling and supports existing data showing 1) environmental burdens from the manufacturing and production of diapers far exceed those from end-of-life, and 2) SAP is the highest contributor to GWP impacts in diaper manufacturing. Results indicate that SAP recovery has potential to decrease life cycle GWP emissions by 54% when compared to standard landfilling and incineration and by 35% when compared to recycling technologies that focus on plastics and energy recovery. SAP recovery and reuse also appears to yield significant savings related to the energy and water burdens involved in SAP manufacturing. Despite uncertainties in SAP recycling, SAP reuse shows potential benefits considering the rising impacts of the disposable hygiene product industry and the growing efforts around impact mitigation. With regards to technology development, efforts to recover and reuse SAP should account for the 0.037 kg CO_2eq per diaper difference between current diaper recycling technologies and a diaper recycling processes with SAP recovery. Sensitivity analysis also emphasizes the importance of grid mix and the percentage of SAP recovery in determining GWP impact. These data in combination with the additional efforts required to recover the SAP will shape the favorability of the recycling process.

Given the challenges involved in diaper recycling, namely the costs, lack of end markets, and lack of infrastructure, efforts that recover a smaller fraction of materials or materials that are less intensive to produce appear to have limited value from a GWP perspective. While the aim of this work was to model savings from a highly favorable and direct reuse of SAP, direct reuse may not prove feasible due to cost, poor quality of recovered SAP, or logistical challenges. If SAP were instead to be recovered for use in another high-value application, savings would be dependent on whether demand for recovered SAP displaces production of another material. Despite technical challenges in SAP recovery, reducing production impacts or identifying other uses for post-consumer SAP still holds potential to lower emissions.

While technology appears to be a limiting factor, it is important to recognize there are also behavioral and social considerations that should be taken into account when evaluating diaper recycling or potential direct reuse of SAP. Some studies have found consumers are generally responsive to diaper recycling trials and post-consumer recycled products while others have indicated some consumer hesitation [12, 29]. These behavioral considerations should be carefully evaluated in conjunction with the environmental and economic impacts of diaper recycling and SAP recovery. All will impact the feasibility of minimizing the impacts from production and manufacturing of SAP and other materials used in disposable diapers.

Appendix

Table A1. Materials and Processes for 1 Diaper

Materials and Processes			
Materials		**Processes**	
SimaPro Name	***Amount (kg)***	***Name***	***Amount***
Cellulose fiber, inclusive blowing in, at plant/CH S	**0.0054**	Natural gas, burned in boiler atm. low-NOx condensing non-modulating < 100 kW/RER S	**0.02 MJ**
Polypropylene, granulate, at plant/RER S	**0.0054**		
Ethylene vinyl acetate copolymer, at plant/RER S	**0.00135**		
Water, de-ionised, at plant/CH S	**0.002**		
Lubricating oil, at plant/RER S	**0.0000033**		
Solvents, organic, unspecified, at plant/GLO S	**0.0000051**	Electricity, production mix NL/NL S	**0.05277 kWh**
Polyethylene terephthalate, granulate, at plant/RER S	**0.0054**		
Superabsorbent polymer	**0.00945**		
Insult	**0.0145**		

Table A2. *Standard MSW Collection* Disposal Scenario

Curbside collection NL	
SimaPro Name	***Amount***
Incineration/CH S	**92.1%**
Landfill/CH S	**7.9%**

Table A3a: *Recycling, no SAP recovery* Scenario for 1 Diaper: Part 1

Avoided burden method = Part A + Part B; NAB = Part B

Part 1	
Avoided materials	
SimaPro Name	Amount (kg)
Polypropylene, granulate, at plant/RER S	**0.0027**
Aluminum, primary, ingot, at plant/RNA	**0.0000078**
Aluminum, secondary, ingot, at plant/RNA	**0.00000957**
Steel, converter, low-alloyed, at plant/RER S	**0.0000383**
Steel, electric, un- and low-alloyed, at plant/RER S	**0.0000278**
Gravel, unspecified, at mine/ CH S	**0.00049**
Polyethylene terephthalate, granulate, amorphous, at plant/RER U	**0.0027**

Table A3b: *Recycling, no SAP recovery* Scenario for 1 Diaper: Part 2

Part 2							
Resources		*Energy*		*Emissions*		*Waste*	
SimaPro Name	Amount	SimaPro Name	Amount	SimaPro Name	Amount	SimaPro Name	Amount
Water, unspecified natural origin, NL	**0.0099994 m^3**	Methane, 96 vol-%, from biogas, from medium pressure network, at service station/CH S	**0.00006 kg**	Carbon dioxide	**0.0216 kg**	Treatment, sewage, to wastewater treatment, class 2/CH U	**0.22 m^3**
				Carbon monoxide	**0.0046 g**		
				Oxygen	**0.0032 kg**		
				Nitrogen, total	**0.064 kg**	Disposal, inert waste, 5% water, to inert material landfill/CH S	**0.000024 kg**
				Nitrogen oxides, NL	**0.0033 g**		
				Ammonia, NL	**0.0000026 g**	Disposal, hard coal ash, 0% water, to residual material landfill/NL S	**0.00021 kg**
		Electricity, production mix, NL/NL S	**0.00478 kWh**	Sulfur dioxide, NL	**0.000013 g**		
				Hydrogen chloride	**0.00001 g**	Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH S	**0.001087 kg**
				Particulates, SPM	**0.00035 g**		
				Dioxins (unspec.)	**0.000041 ng**		

Table A4a: *Recycling + SAP Recovery* Scenario for 1 Diaper: Part 1

Avoided burden method = Part A + Part B; NAB = Part B + 0.00945 kg SAP as an avoided burden.

Part 1	
Avoided materials	
SimaPro Name	Amount (kg)
Superabsorbent polymer	**0.00945**
Polypropylene, granulate, at plant/RER S	**0.0027**
Aluminum, primary, ingot, at plant/RNA	**0.0000078**
Aluminum, secondary, ingot, at plant/RNA	**0.00000957**
Steel, converter, low-alloyed, at plant/RER S	**0.0000383**
Steel, electric, un- and low-alloyed, at plant/RER S	**0.0000278**
Gravel, unspecified, at mine/ CH S	**0.00049**
Polyethylene terephthalate, granulate, amorphous, at plant/RER U	**0.0027**

Table A4b: *Recycling + SAP Recovery* Scenario for 1 Diaper: Part 2

Part 2							
Resources		*Energy*		*Emissions*		*Waste*	
SimaPro Name	Amount	SimaPro Name	Amount	SimaPro Name	Amount	SimaPro Name	Amount
Water, unspecified natural origin, NL	**0.0099994 m^3**	Methane, 96 vol-%, from biogas, from medium pressure network, at service station/CH S	**0.00006 kg**	Carbon dioxide	**0.0216 kg**	Treatment, sewage, to wastewater treatment, class 2/CH U	**0.22 m^3**
				Carbon monoxide	**0.0046 g**		
				Oxygen	**0.0032 kg**		
				Nitrogen, total	**0.064 kg**	Disposal, inert waste, 5% water, to inert material landfill/CH S	**0.000024 kg**
				Nitrogen oxides, NL	**0.0033 g**		
				Ammonia, NL	**0.0000026 g**	Disposal, hard coal ash, 0% water, to residual material landfill/NL S	**0.00021 kg**
		Electricity, production mix, NL/NL S	**0.00478 kWh**	Sulfur dioxide, NL	**0.000013 g**		
				Hydrogen chloride	**0.00001 g**	Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH S	**0.001087 kg**
				Particulates, SPM	**0.00035 g**		
				Dioxins (unspec.)	**0.000041 ng**		

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