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LIFE CYCLE ASSESSMENT OF SURGICAL DRAPES AND TAPES: REUSABLE AND DISPOSABLE

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Chapter 1 SURGICAL DRAPES AND TAPES – CRADLE-TO-END-OF-LIFE ANALYSIS

Introduction

Surgical drape systems are covering materials that are taped to patients and equipment during surgical procedures to protect the workers and patients from the transfer of microorganisms, body fluids, and particulate matter. These drapes are available in reusable and disposable alternatives. The selection between reusable and disposable materials has historically been based on factors such as cost, performance, and comfort. Increasingly, environmental sustainability is also being considered as a key decision-making factor.

The most common analysis tool used to evaluate the environmental benefits and impacts of products is the life cycle assessment (LCA). A life cycle assessment includes a goal and scope definition, a life cycle inventory (LCI) analysis, a life cycle impact assessment (LCIA), and an interpretation of the results. Life cycle inventory analysis is the estimation of energy use and material use (and loss) of each manufacturing plant or node, such as a fabric manufacturing plant or a refinery for oil. Each plant or node is referred to as a gate-to-gate (GTG) life cycle inventory (LCI). The GTGs are added together to give a cradle-to-gate (CTG) LCI, from the cradle (natural materials in the earth) to the gate (a final product, such as a reusable surgical drape). Additional GTGs cover the use and end of life phases. Energy use is given as electricity, the use of steam (from boilers), or high temperature furnaces (e.g. for metals); whereas material use is given by the mass balance on each process or service. Individual emissions in the LCI are weighted and summed to determine total impact in environmental categories, such as global warming impact. These environmental impacts comprise the LCIA.

Comparative life cycle studies by McDowell (1993), Carre (2008), van de Berghe and Zimmer (2010), Overcash (2012), and Vozzola (2018) compared reusable and disposable surgical gown systems. Studies by Jewell and Wentsel (2014) and Vozzola (2018) compared reusable and disposable isolation gown systems. All of these studies found that reusable medical textile systems provided substantially better environmental profiles than disposable systems. However, the previous literature has not typically included the environmental impacts of surgical drapes and tapes.

Goal

The European Chainge Consortium (see annex for the partners of the consortium) commissioned Environmental Clarity, Inc. to quantify and compare the cradle-to-end-of-life environmental impacts of reusable and disposable surgical drape and tape systems. The objectives of the study were (1) to compare three environmental indicators (energy consumption, water consumption, and solid waste generation) and 11 environmental impacts from CML (abiotic depletion (of minerals), abiotic depletion of fossil fuels, global warming, ozone layer depletion, human toxicity, fresh water ecotoxicity, marine aquatic ecotoxicity, photochemical oxidation (smog formation), acidification, and eutrophication) of reusable and disposable surgical drapes and tapes; (2) to clearly show what parts of the life cycle are important to the result; and (3) to provide a sensitivity analysis for important parameters.

Reusable and disposable surgical drape and tape systems were compared using life cycle guidelines set forth by the International Organization for Standardization (ISO) in ISO 14040 and ISO 14044 (ISO, 2006). The life cycle assessment results are intended to be used by the Chainge Consortium and other industry partners to build and promote a sustainable pathway for high performance textiles in the health care industry.

Scope

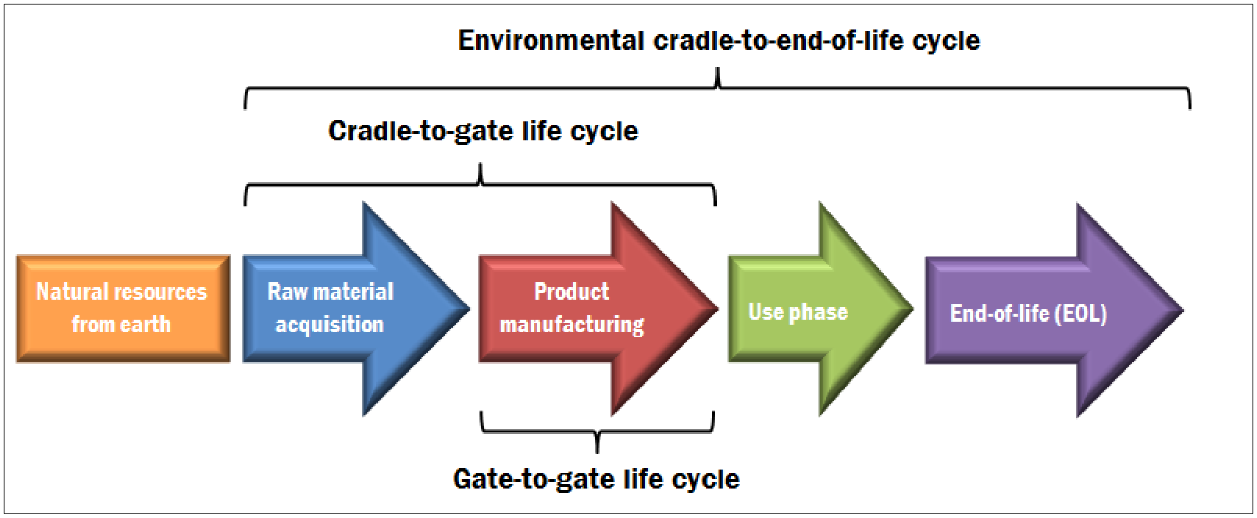
Product Systems to be Studied

The full life cycle inventory analysis of surgical drapes and tapes encompassed the phases illustrated in Figure 1.1:

1. The full supply chain from natural resources (oil, natural gas, ores, etc.) from the earth to the surgical drape and tape products, known as cradle-to-gate.
2. The use and/or reuse of drapes and tapes, which was in the health care setting and included laundry, sterilization, and wastewater treatment.
3. The end-of-life disposition in which drapes and tapes were managed when no longer functional.

When combined, the life cycle inventory was a full cradle-to-end-of-life (CTEOL) profile of surgical drapes and tapes.

Figure 1.1 Life cycle scope for product analysis



Functions of Product Systems

The surgical drape was defined as a medium sized top drape, with an area of 4 m^2. Each drape had 60cm of tape applied to it. Based on input from the Chainge Consortium, two surgical drape systems were selected for evaluation in this life cycle assessment: one market-representative reusable drape system and one market-representative disposable drape system. The reusable drape system includes a drape that is laundered after each use and reused. It also includes a tape that is removed in the laundry. New tape is applied for each subsequent use. The disposable drape system includes both a drape and tape that are disposed of after each use. The drape systems examined in this study are outlined in Table 1.1.

Table 1.1 Surgical drape systems evaluated in life cycle study

Type	Critical Zone Primary Fabric Material	Non-Critical Zone Primary Fabric Material(s)	Weight, g
Reusable*	Knit PET and ePTFE (50%) Knit PET and PU (50%)	Woven PET**(PES, polyester)	576
Disposable	PP film	SMS PP	245

* Market analysis found a 50/50 market share of ePTFE and PU reusable drapes
PET = polyethylene terephthalate, ePTFE = expanded polytetrafluoroethylene, PU = polyurethane, PP = polypropylene, SMS = spunbond-meltblown-spunbond
** PET is an acronym of polyethylene terephthalate. PET is often referred to as PES in Europe, and is often referred to as polyester when used in textiles in the United States.

Surgical tapes are used to attach surgical drapes to patients and equipment. The tapes were also included in the analysis. The tapes examined in this study are outlined in Table 1.2. Based on input from the Chainge Consortium, about 60 cm of tape is used with each reusable and disposable drape use.

Table 1.2 Surgical tape systems evaluated in life cycle study

Type	Carrier material	Roll Size	Roll Weight, kg
Tape for reusable drapes	Tissue	5 cm * 100 m	1.009 kg
Tape for disposable drapes	Polyester	5 cm * 200 m	1.753 kg

Functional Unit

The functional unit was defined as 1,000 surgical drape uses. Disposable (single-use) drapes were considered to be used one time before disposal. Thus, 1,000 disposable drape uses included the manufacture, use, and disposal of 1,000 drapes and the associated surgical tape. The disposable drapes and associated tapes were considered to be sterilized before use. Thus, the use phase included the sterilization of 1,000 drapes and the associated surgical tape. Reusable (multi-use) drapes were considered to be used 60 times before disposal. Thus, each 1,000 reusable drape uses included the manufacture and disposal of 16.7 drapes. The surgical tape used with reusable drapes is disposable, and so manufacture of the associated tape required for 1,000 drape uses was also included. The reusable drapes were considered to be laundered and sterilized before each use including the first. Thus, the use phase included the laundry of 1,000 drapes and the sterilization of 1,000 drapes and the associated surgical tape. Each surgical procedure may use more than one drape. This study assumes that the number of drapes used would be the same whether reusable or disposable drapes were used.

System Boundaries

The life cycle boundary for reusable surgical drape analysis is depicted in Figure 1.2 and the boundary for disposable surgical drape analysis in Figure 1.3. Each Figure shows the material flows included in the life cycle study, from natural resources to end-of-life. The dashed line represents the boundary. In the reusable system, the tapes are applied at the laundry, and the cleaned drapes are sterilized at the laundry prior to transport to the point of use. After each use, the disposable packaging, tape core, and release liner from the tape is disposed of in the landfill, and that activity is included in the study. After 60 uses, the drapes are recovered and reused or recycled into other products. This results in an environmental benefit. However, the benefit as well as the activities related to recovery and reprocessing are excluded from this study, as those are attributed to the product that utilizes the drapes.

In the disposable drape system, tape is applied after manufacture, and each drape is then sterilized and shipped to the point of use. Each drape use results in disposal of the drape, packaging, and complete tape system.

Allocation Procedures

Mass allocation was used in this life cycle assessment. Thus, for processes that produced multiple usable products, the life cycle inventory parameters were assigned to each product based on the percentage of total mass produced in the process.

LCIA Methodology and Types of Impacts

Three environmental indicators were selected for evaluation in this study.

- **Natural resource energy (NRE) consumption, MJ NRE**
  Natural resource energy is the total energy of all fuels used to provide energy in a process and includes the higher heating value (HHV) of fuel combusted per unit of energy transferred to the process (efficiency) plus the energy used to deliver fuel to the point of use (often known as precombustion or delivered energy). A complete description of the types of energy included in this report, including the relationship between process energy and NRE, is given in the Life Cycle Inventory Analysis section below. The heating value of fuels combusted for energy is an indicator of environmental emissions, as the majority of environmental impacts often result from energy consumption.

- **Blue water consumption, kg blue water**
  Blue water is the total of all water evaporated during production or physically incorporated into the product (Aviso et al., 2011). Thus, blue water does not include non-contaminated water returned to the environment (i.e. from steam heating or cooling water conditions) or contaminated water that is returned to the environment via a wastewater treatment process (i.e. from laundry).
- **Solid waste generation, kg waste generated at point of use**
  Solid waste generation is the total solid waste generated at the health care facility using the surgical drapes and includes the drapes, tapes, biological waste on the drapes, and non-recycled packaging.

Additionally, 11 environmental impact categories were evaluated using the CML impact assessment method.

- **Global warming potential (GWP), kg carbon dioxide equivalent (kg CO_2eq)**
  Global warming potential, also known as greenhouse gas (GHG) emissions, is often dominated by energy use. The energy portion can be estimated using the representative ratio of 0.06 kg CO_2eq/MJ NRE combustion. However, this life cycle assessment included a more detailed calculation using the CML 3.01 (2013) methodology. The GWP is the carbon dioxide (and CO_2eq of other greenhouse gasses) produced from all combustion processes for energy production plus any process emissions. CML 3.01 assigns specific impact factors to each chemical emission (CO_2 = 1, methane = 25, nitrous oxide = 298, etc.).

- **Abiotic depletion, kg antimony equivalent (kg Sb eq)**

Abiotic depletion characterizes the use of non-fossil raw materials. More rare elements are given a higher equivalent factor. For example, gold is given a factor of 52 Sb eq. More widely available atoms are given a lower value.

- **Abiotic depletion, fossil fuels, (MJ LHV)**
  Fossil abiotic depletion characterizes the consumption of fossil fuels. Each MJ low heat value (LHV) of fuel corresponds to 1 MJ of abiotic depletion.
- **Ozone layer depletion (ODP), kg chlorofluorocarbon 11 equivalent (kg CFC-11 eq)**
  Ozone layer depletion quantifies damage to the ozone layer, by chemicals such as chlorofluorocarbons (CFCs). The characterization model is developed by the World Meteorological Organization (WMO).
- **Human toxicity (HTP inf), kg 1,4-dichlorobenzene equivalents, (kg 1,4-DB eq)**
  Characterisation factors, expressed as Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon.
- **Fresh water ecotoxicity (FAETP inf), marine aquatic toxicity (MAETP), and terrestrial ecotoxicity (TETP inf), kg 1,4-dichlorobenzene equivalents, (kg 1,4-DB eq)**
  Each of these impact categories is based on USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon.
- **Photochemical oxidation (smog formation), kg ethylene equivalents (kg C2H4 eq)**
  Model developed by Jenkin & Hayman and Derwent
- **Acidification, kg sulfur dioxide equivalents (kg SO2 eq)**
  Includes fate, average Europe total, A&B. Model developed by Huijbregts
- **Eutrophication, kg phosphate equivalent (kg PO4—eq)**
  Describes fertilization of water systems. Model developed by Heijungs et al.

More information on this LCIA methodology is available at http://cml.leiden.edu/software/data-cmlia.html.

Data Requirements

The LCI data used in the surgical drape and tape life cycle assessment were obtained from the Environmental Clarity, Inc. LCI Database (Griffing and Overcash, 2018). The LCI data are transparent with a strong emphasis on process or design-based methodology. Detailed reports for all gate-to-gate life cycle inventories used in this life cycle assessment are available from Environmental Clarity. Each LCI report includes a summary of the process mass and energy flows as well as a review of literature pertinent to the process.

Figure 1.2 Life cycle boundary for reusable surgical drape system, 1,000 uses

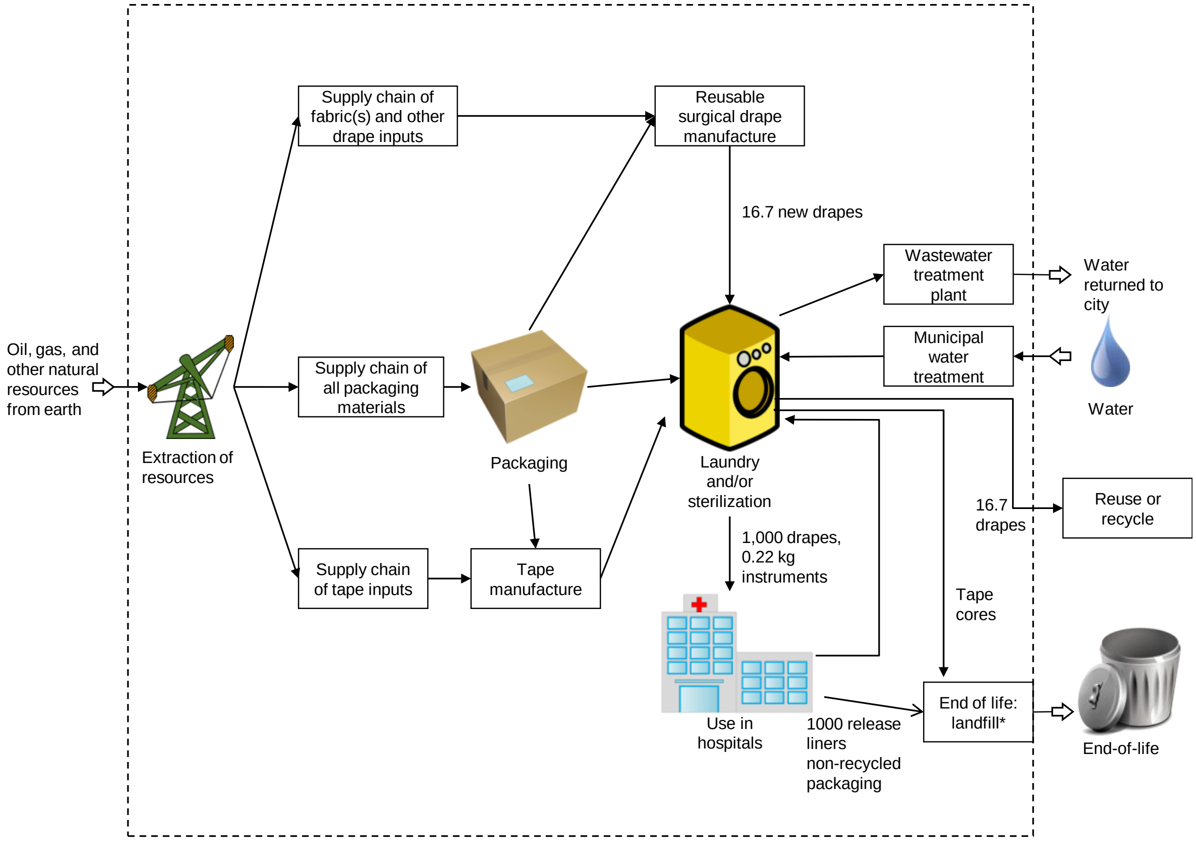
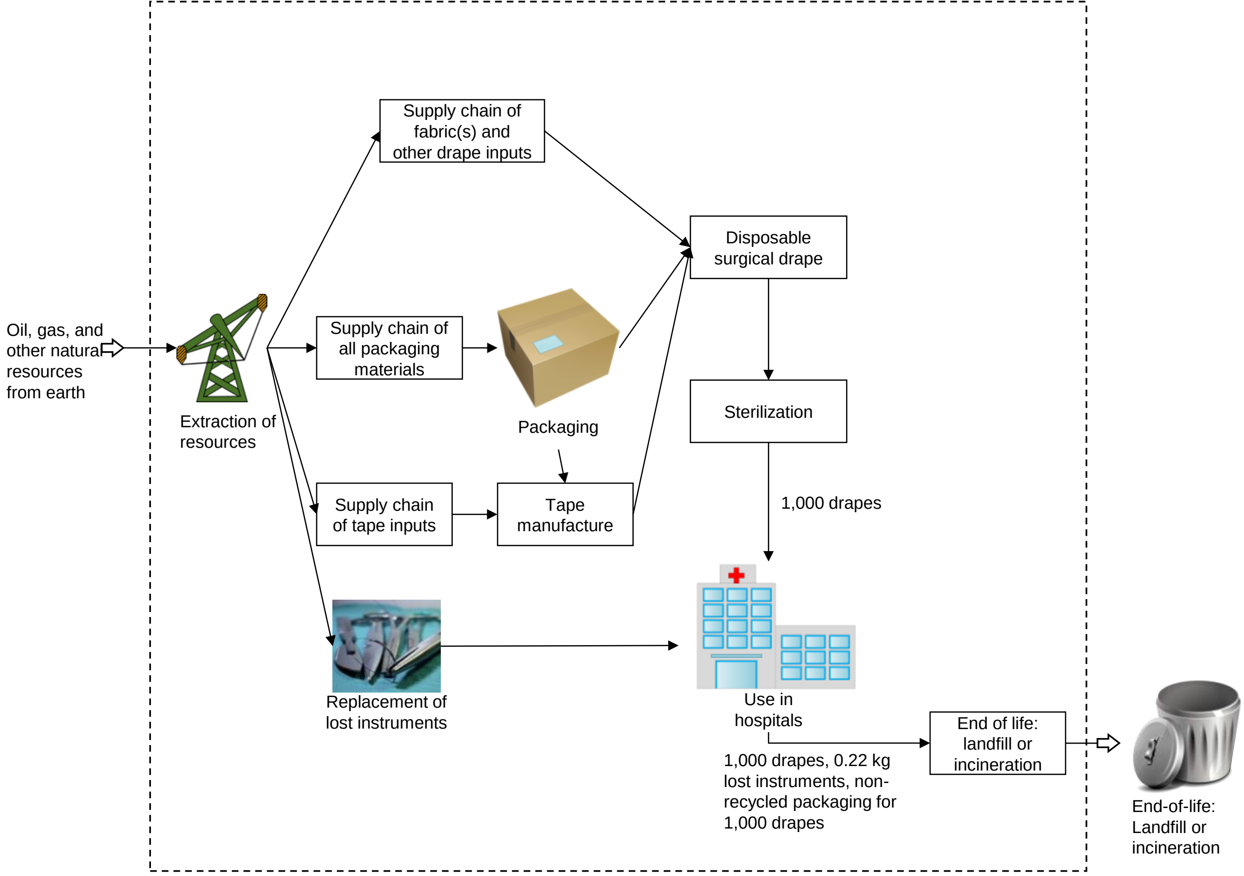


Figure 1.3 Life cycle boundary for disposable surgical drape system, 1,000 uses



Assumptions

A number of assumptions were made to conduct this life cycle assessment. A list of some of the more important assumptions is included below. Data supporting many of the assumptions were obtained from industry contacts, especially including but not limited to member companies of the Chainge Consortium. To protect intellectual property, data ranges are used and the data are not associated with any specific company. The words “company,” “companies,” or “industry experts” represent data obtained from these or other industrial contacts.

Drape weight – Representative weights for medium sized surgical top drapes were selected based on a review of about nine drapes from six suppliers. The nine top drapes ranged in size from 3.1 m^2 to 5.2 m^2, with an average area of 4 m^2. The weights used in this study were selected based on the fabric weights of the drapes examined, scaled to a size of 4 m^2. The 4 m^2 reusable drape was found to have a representative weight of 576 g. The 4 m^2 disposable drape was found to have a representative weight of 245 g.

Drape materials – Surgical drapes are manufactured from a number of woven and nonwoven fabric materials. The fabrics examined in this study are shown in Table 1.1. The fabric selections were based on manufacturer specifications and industry input. Substitution of similar fabric materials is not expected to have a significant impact on the results.

Reusable drape uses before end-of-life – Reusable surgical drapes are typically rated by the manufacturer for 75-100 uses before downgrade. However, the average use rate is always lower due to losses, damage, etc. A use rate of 60 cycles was selected as a conservative estimate based on industry data. This use rate is consistent with that found for reusable surgical gowns.

Locations of drape manufacture – Surgical drapes are manufactured in a number of locations worldwide. For the purposes of this report, specific locations were selected to show examples of the transport required for the drape supply chain and final delivery. Disposable drapes were proposed to have the fabric, fabric supply chain, and cut, sew, and trim operations in Asia with transportation to the Netherlands via ocean ship and articulated trailer. Fabrics for reusable drapes had a portion of the production and supply chain in Asia, and a portion in Europe. About 70% of the PET microfiber fabric or fiber was produced in Asia, and the remainder was produced in Europe. Thus, transport for 70% of the PET mass from Asia to a port in Rotterdam, the Netherlands was included. All of the fabric is transported from the Netherlands to Ukraine by train for cut/sew/trim operations. The drapes are then transported from Ukraine to laundries in Western Europe via articulated trailer. Note that the transport scenario had a small impact on the LCA results, accounting for about 10.7% of the total NRE for reusable drapes and 16.4% of the total NRE for disposable drapes. For the purposes of natural resource energy calculation and the CML LCIA calculations, energy modules from Europe were used for all stages of the life cycle. Although disposable drapes are often produced in Asia, Asia-specific energy modules were used in a sensitivity analysis, but were not used in the representative case LCIA.

Fabric waste – Fabric loss from trimming was 3 wt % for disposable and reusable drapes. All scrap fabric was considered a benign outflow. Thus, the environmental burden for manufacturing the scrap was allocated to the surgical drape manufacturing. Any credit for reusing or recycling the scrap would be attributed to the firm reusing the scrap.

Surgical tape use – Surgical tapes are used to attach surgical drapes to patients and medical equipment. The amount of tape used may vary based on the size of the drape and surgical procedure being performed. Based on industry input, about 50-70 cm tape (5 cm width) is expected to be used with one surgical top drape. In this study, 60 cm tape was shown as representative. Variation in tape use is not expected to have a significant impact on the results.

Surgical tape materials – The main components of surgical tapes are adhesives, carrier fabrics, and siliconised release paper. The adhesives are typically hot melt pressure sensitive adhesives (HMPSAs). The carrier fabric is either tissue (paper) or polymer (plastic) based. Brief descriptions of the tapes examined in this study are given in Table 1.2, with complete descriptions in Chapter 4. Substitution of similar tape materials is not expected to have a significant impact on the results.

End-of-life – Disposable drapes are landfilled or incinerated for energy production at end-of-life. In this report, landfilling via typical municipal solid waste collections is shown. Reusable drapes are made available for recycling into other products. Emissions from collection and recycling activities as well as the environmental benefit from displacing virgin materials were assigned to the product that utilizes the recycled materials. Thus no credits or emissions were assigned to the reusable drapes. The impact of landfilling reusable drapes was calculated as a separate scenario. Landfill collections for disposable drapes were based on post-consumer waste landfill transport model. The tapes, including tissue carrier and adhesive, used with reusable drapes dissolve in the laundry step and create wastewater treatment energy, but have no landfill burden. The release liner is removed at the hospital, and sent to landfill for both reusable and disposable drapes. The release liner is assumed to be inert in the landfill. The tapes used with disposable drapes are sent to the landfill with the drapes.

Laundry – Laundry data such as energy consumption, water consumption, and detergent use are typically available on a per unit weight basis. Thus, the laundry LCI data were scaled based on the weight of drapes washed as opposed to the number of drapes washed, which was subsequently calculated. The laundry LCI is based on robust data from over 20 industrial laundry facilities in North America and Europe.

Sterilization method – Disposable drapes and associated tapes were considered to be sterilized via ethylene oxide sterilization. Reusable drapes and associated tapes were considered to be sterilized via steam sterilization. The geographic location of the sterilization operation had no impact on the sterilization method and associated transport scenarios.

Cutoff for materials used in small quantities – Some materials used in small quantities were excluded from the life cycle inventory calculations. In general, within gate-to-gate life cycle inventories material inputs totaling less than 5 wt % relative to the final product were excluded. However, some materials used in quantities below this threshold were included either for clarity or because these were determined to have a large impact on the results.

Loss of instruments – Laundry operators regularly recover and return lost medical instruments and other items found while processing reusable surgical textiles such as gowns, drapes, and mayo stand covers. Thus, it is reasonable to expect that similar items are sent to the landfill with disposable surgical textiles. In this study, manufacturing of these lost items (approximated as stainless steel bowls) was accounted for as part of the disposable system. Based on data from laundry operators, 0.220 kg stainless steel/1,000 surgical drapes was included as an additional input in the disposable system. The small amount had a negligible impact on the environmental life cycle results. However, the monetary value of these items is often significant. For example, a case study conducted at the University of Maryland Medical Center estimated that the hospital saved $39,000 in returned medical instruments in 2010 (Practice Greenhealth, 2011). Figure 1.4 shows examples of medical instruments found and returned from the laundry process. The instruments in each image were recovered over a period of two to four months from the laundry of one or two hospitals with an estimated value of $2,500 to $6,000. Note that the instruments are found not only in drapes but also in mayo stand covers and gowns. Thus, the full benefit of recovering lost items from operating rooms is realized when using reusable forms of all textiles (gowns, drapes, mayo stand covers, towels, etc.).

Figure 1.4 Medical instruments found and returned during the laundry process

Limitations

This LCA was conducted for industry representative surgical drape systems: a reusable drape system (with woven PET non-critical zones and 50% knit PET/ePTFE critical zone and 50% knit PET/PU critical zone) and a disposable drape system (SMS PP non critical zones and PP film critical zones). Individual drapes may utilize slightly different masses of materials, or utilize different materials altogether. The results of this LCA can be adjusted to account for different drape weights. However, the LCA is not directly applicable to drapes of other materials. The energy indicator results in this report show the relative impact of various components of the system, allowing the reader to interpret the potential impacts of major system changes.

Two surgical tape systems were examined, one for use with disposable drapes and one for use with reusable drapes. Individual tapes may utilize slightly different masses of materials, or utilize different materials altogether. The results of this LCA can be adjusted to account for different tape weights used with surgical drapes. However, the LCA is not directly applicable to tapes of other materials.

European energy modules were used for all production systems. In the case of materials or garments manufactured in Asia, using a European energy module is expected to underestimate most environmental impacts. In other words, the energy mix currently in use in Asia is expected to result in larger environmental impacts for disposable drape systems than reported in this study. The impact of manufacture in Asia is estimated as a sensitivity study using best estimates of Asian energy modules.

This LCA was conducted for drapes and tapes and does not include other garments used in health care settings such as gowns, face masks, gloves, etc.

Type of Critical Review

This life cycle assessment report was reviewed by four members of the Chainge Consortium. All included life cycle inventories were reviewed internally by Environmental Clarity. A portion of the life cycle inventories were reviewed externally by industry experts. The results of this study are intended to be summarized for internal and external use by the Chainge Consortium.

Life Cycle Inventory Analysis

Methodology

Surgical drapes are evaluated first on a life cycle inventory basis. The life cycle inventory results include material inputs, material outputs, and energy consumption for each gate-to-gate step in the cradle-to-end-of-life cycle of surgical drape systems.

The functional unit used was 1,000 surgical drape uses. To gain further insights and provide transparency to the reader, the LCI information is displayed in three formats throughout this report:

1. The cradle-to-gate energies per 1,000 kg of each chemical or material in the supply chain. This provides the reader with an understanding of the energy intensity (MJ/kg material) regardless of how much or how little is used in the supply chain.
2. The cradle-to-gate energies required to manufacture each drape, when expressed per 1,000 drapes manufactured. This format accounts for the weight of each drape and allows for comparison of the energy intensity (MJ/drape manufactured) regardless of how many times each drape is used.
3. The energies required per 1,000 drape uses, which is the most important basis for comparison. This format represents the direct cradle-to-end-of-life cycle results for reusable and disposable drapes. This format accounts for the functional unit used to compare surgical drapes, and allows for comparison of the energy intensity (MJ/drape use).

The total energy in LCI Tables and Figures is divided into six subcategories, based on the demands of the various manufacturing plants,

1. Electricity
2. Steam – typically used in the heating range of 25-207 °C
3. Dowtherm – typically used in the heating range of 207-400 °C
4. Non-transport direct use of fuel – typically used in the heating range above 400 °C
5. Transport fuel
6. Heat potential recovery – for cooling processes in which sufficient temperature is present to allow calculation of the percent of heat recovery. The potential recovery reflects significant heat integration in plants. It is reported as a negative energy input, which lowers the net or total plant manufacturing energy. With no heat integration, the total energy is calculated as the net energy in the Tables plus the positive value of the potential energy recovery and thus is a higher energy value. This transparency allows the reader to understand the range of values that might result based on the range of heat integration in plants.

In other Tables and Figures the data are provided for the two types of total energy,

1. Process energy – defined by ISO 14040 and ISO 14044 as the "energy input required for operating the process or equipment within a unit process, excluding energy inputs for production and delivery of the energy itself." Thus, process energy is the direct energy consumed by the process in each and all of the supply chain chemical and material plants. These energies relate to the distinctive unit processes (reactors, heat exchangers, pumps, distillation columns, etc.) required for each GTG LCI and are determined directly in

relation to these unit processes. These reflect the direct process energies as purchased at plants.

2. Natural resource energy (NRE) – the total of all fuels used to produce each of the six process energies. The natural resource energy is calculated from process energy by first including the higher heating value (HHV) of fuel combusted per unit of energy transferred to the process (efficiency) plus secondly the energy used to deliver fuel to the point of use (often known as precombustion or delivered energy). The factors used for the efficiency and precombustion are shown in Table 1.3 of this report as scale-up factors and can thus be used to convert, in a transparent fashion, process energy into natural resource energy. These factors can also be modified by the reader and a clear effect seen on the results.

Table 1.3 Scale-up factors from process energy to natural resource energy

Scale-up factors	Electricity	Dowtherm	Steam	Non-transport direct use of fuel	Transport fuel	Heat potential recovery	Coal	Natural gas	Crude oil
Precombustion factors, MJ fuel extracted per MJ delivered (The excess is consumed in delivery)	1.1	1.15	1.15	1.15	1.20	1.15	1.20	1.10	1.20
Generation/combustion factors, MJ HHV fuel delivered per MJ energy to process	2.91*	1.25	1.25	1.00	1.00	1.25	--	--	--
Total scale up factor (precombustion times generation/combustion)	3.20*	1.44	1.44	1.15	1.20	1.44	--	--	--

*The electricity scale up factors are representative of European electricity production based on values from the European Reference Life Cycle Data System (ELCD) low voltage European electricity and Ecoinvent medium voltage European electricity. The scale up factors used for United States electricity production are 3.13 and 3.44, respectively.

Based on Ecoinvent modules for market electricity use in China and average electricity use in Europe, Chinese electricity use results in 80% more fossil fuel consumption and 126% more CO2eq emissions than average European electricity. Good market representative modules for steam production in China or Asia were not available. Based on ecoinvent modules for steam production in Europe and the rest of the world (ROW), the average for ROW was 15% higher fossil consumption and 27% higher CO2 equivalent emissions. These factors were used to estimate the impact of production in Asia.

The LCIA calculations were done in SimaPro 8.0.3 (2014). The inventory portion of these calculations was done using European energy modules and a European impact assessment method. The specific modules used were from Ecoinvent, and are specified in Table 1.4. Electricity and heat are specified in consistent units in the Environmental Clarity and Ecoinvent databases. However, transport is converted to MJ at the GTG level in the Environmental Clarity system, and stored at the metric ton-km in the ecoinvent system. Thus, the transport was converted back to ton-km and road based transport was used.

Table 1.4. Energy modules used for LCIA

Our energy	In SimaPro
heating natural gas	Heat, natural gas, at industrial furnace >100kW/RER S
Electricity	Electricity, medium voltage, production RER, at grid/RER S
Heating steam	Heat, in chemical industry {RER}| market for | Alloc Def, S
Diesel (process)	Heat, light fuel oil, at industrial furnace 1MW/RER S
Diesel (in GTG transport)	Use Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, S CED is 2.79 MJ CED/tkm. We have 1.2 MJ nre/MJprocess. Thus, we use (1 / 1.87 MJ NRE * 1.4 MJ NRE/MJ process)=0.75 tkm/MJ.
Diesel (transport)	Use Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, S CED is 2.79 MJ CED/tkm. We have 1.2 MJ nre/MJprocess. Thus, we use (1 / 1.87 MJ NRE * 1.2 MJ NRE/MJ process)=0.75 tkm/MJ.
Direct fuel	Heat, natural gas, at industrial furnace >100kW/RER S
Dowtherm	For each MJ of Dowtherm heat, we use 1.25 MJ Heat, natural gas, at industrial furnace >100kW/RER S

At this level of transparency and detail, the reader must carefully look at each type of information and system to understand the full life cycle results. This level of data also allows the reader to more easily utilize the data for other analyses, such as varying the drape and tape materials or weights. In addition, each surgical drape and tape manufacturing company can choose to modify these results for their specific products.

Basis for Reusable Surgical Drape LCI

The full cradle-to-end-of-life (CTEOL) cycle included a series of components that were summed together to provide the life cycle energy profile. The functional unit was 1,000 drape uses in health care settings, which for the reusable system was determined by the average number of cycles.

The evaluation of the life cycle of 1,000 reusable surgical drape uses included the manufacture of 16.7 new drapes each used for 60 cycles. The components for the reusable surgical drape LCI are given in Table 1.5 and are described as follows:

1. Manufacture of 16.7 reusable surgical drapes (9.60 kg drapes) was evaluated as a cradle-to-gate (CTG) encompassing all material and energy consumption from natural resources through to the finished product.
2. Primary, secondary, and tertiary packaging for each of the 1,000 drape uses was included with all packaging materials (such as polyethylene) evaluated as CTG.
3. Manufacturing of the surgical tape required for 1,000 drape uses (6.05 kg tape) was evaluated as CTG.
4. Primary, secondary, and tertiary packaging for the surgical tape required for 1,000 drape uses was included with all packaging materials evaluated as CTG.

5. Before each use, each reusable surgical drape is cleaned at a laundry facility, evaluated as GTG washing and drying at a single site. For 1,000 reusable surgical drape uses this was laundry of 576 kg reusable drapes.
6. Production of water used for laundry was considered to be from conventional municipal water treatment plants and was included separately as a transparent LCI profile of the laundry process.
7. The water leaving the laundry site is not yet returned to regulatory approved standards of purity. Thus, the wastewater treatment of the organic burden from the laundry (and thus directly from hospital use) was evaluated from a life cycle perspective. The wastewater burden (3.30 kg COD/1,000 reusable drape uses) was based on measured chemical oxygen demand (COD) values from medical laundry facilities. Thus, the majority of the water involved in the reusable system is not consumed, but instead is returned at a socially acceptable condition. The evaporated water (blue water) loss (about 0.33%) was accounted as the water burden of the reusable laundry system. The metered water was also included in this report.
8. Before each use, each reusable surgical drape and surgical tape is sterilized at a steam sterilization facility, evaluated as GTG steam sterilization at a single site. For 1,000 reusable surgical drape uses this was sterilization of 582 kg drapes and tape.
9. The end-of-life phase for reusable surgical drapes included landfill disposal. Reusable drapes are largely synthetic polymers and so when these are landfilled, no significant decomposition is expected. The drapes are effectively inert in the landfill. However, transport to the landfill and landfill operations/capital infrastructures are incurred per unit mass of material landfilled. Thus, the 16.7 reusable surgical drapes were evaluated as 9.60 kg of landfilled plastic material. Landfilling of plastic packaging in the amount of 58.1 kg/1,000 drape uses was also included. Note that corrugated boxboard packaging was considered to be recycled.
10. When drapes are used in hospitals, contaminants and soil (biological waste, paper, dust, etc.) is deposited on the drapes. The amount of contaminants on used reusable drapes was estimated based on the chemical oxygen demand (COD) measured in the wastewater from reusable drape laundry. The COD was converted to total organic carbon (TOC) based on a factor of 0.2 kg TOC / 1 kg COD developed based on measured wastewater information in a previous surgical textile study. The TOC was assumed to be the same (on a TOC/drape basis) for all surgical drapes. The organic carbon for landfilled reusable drapes is delivered to a landfill. Based on the TOC, degradable biological waste in the amount of 0.0107 kg/16.7 reusable surgical drapes was considered sent to the landfill. This process resulted in a small energy credit because the biological waste generates gas, which is incinerated for energy recovery. The energy credit for this process is shown as a negative energy value in the "Total Net Energy" column of Table 1.6.
11. Reusable surgical drape and tape transportation in the use phase included transport to-and-from a laundry center and to-and-from a sterilization center. These transport values are included in the first line of Table 1.6.

Basis for Disposable Surgical Drape LCI

The functional unit for surgical drapes was 1,000 drape uses, which for the disposable system was 1,000 new drapes. The components for the disposable surgical drape LCI are given in Table 1.5 and are described as follows:

1. Manufacture of 1,000 disposable surgical drapes (245 kg drapes) was evaluated as a cradle-to-gate (CTG) encompassing all material and energy consumption from natural resources through to the finished product.
2. Primary, secondary, and tertiary packaging for each of the 1,000 drape uses was included with all packaging materials (such as polyethylene) evaluated as CTG.
3. Manufacturing of the surgical tape required for 1,000 drape uses (5.26 kg tape) was evaluated as CTG.
4. Primary, secondary, and tertiary packaging for the surgical tape required for 1,000 drape uses was included with all packaging materials evaluated as CTG.
5. Before each use, each disposable surgical drape and surgical tape is sterilized at an ethylene oxide sterilization facility, evaluated as CTG ethylene oxide sterilization at a single site. For 1,000 disposable surgical drape uses this was sterilization of 250 kg disposable drapes and tape.
6. The end-of-life phase for disposable surgical drapes and tape included landfill disposal. The disposable drapes are largely synthetic polymers and so when these are landfilled, no significant decomposition is expected. The drapes and tape are effectively inert in the landfill. However, transport to the landfill and landfill operations/capital infrastructures are incurred per unit mass of material landfilled. Thus, the 1,000 disposable surgical drapes and associated tape were 250 kg of landfilled plastic material. Landfilling of plastic packaging in the amount of 57.0 kg/1,000 drapes was also included. Note that corrugated boxboard packaging was considered to be recycled.
7. When drapes are used in hospitals, a small amount of contaminants or soil (biological waste, paper, dust, etc.) is deposited on the drapes. The amount of contaminants on used disposable drapes was estimated based on the chemical oxygen demand (COD) measured in the wastewater from reusable textile laundry. The COD was converted to total organic carbon (TOC) based on a factor of 0.2 kg TOC / 1 kg COD developed based on measured wastewater information in a previous surgical textile study. The TOC was assumed to be the same (on a TOC/drape basis) for all surgical drapes. The organic carbon for disposable drapes is delivered to a landfill. Based on the TOC, degradable biological waste in the amount of 0.643 kg/1,000 disposable surgical drapes was considered sent to the landfill. This process resulted in a small energy credit because the biological waste generates gas, which is incinerated for energy recovery. The energy credit for this process is shown as a negative energy value in the “Total Net Energy” column of Table 1.7.
8. Lost instruments occur during operating room cleanup after the patient has left. This was measured on a reusable system basis and was assumed to be approximately the same for disposable systems. In the disposable system these instruments are deposited in the landfill. The CTG production of the mass of stainless steel to replace this loss was included. This was approximated as a stainless steel bowl, recognizing those actual instruments lost may be more expensive items. About 0.220 kg stainless steel instruments per 1,000 disposable surgical drapes were estimated as the mass loss. Discussion of this part of the life cycle of disposable drapes is included in the end-of-life chapter.
9. Disposable surgical drape transportation in the use phase included transport to-and-from a sterilization center. This transport value is included in the first line of Table 1.7.

LCI Results of cradle-to-end-of-life

A comparison of the architecture of the reusable and disposable surgical drapes is given in Table 1.5. Using a 1,000 surgical drape uses basis, the life cycle inventory of the reusable and disposable alternatives are shown in Table 1.6 and Table 1.7, respectively. The mass of each contributing part of the CTEOL is shown on these Tables as well as the process energy and the natural resource energy. This transparent format allows a clear comparison. The energy results are scalable based on mass architectures. Thus, mass architectures can be changed and clear impacts seen on the energy results. The NRE results are discussed and the drape systems are compared more directly in the LCIA section.

Detailed descriptions of how each of these mass architecture values were calculated are included in later chapters. For example, the packaging for drape systems is broken down into primary, secondary, and tertiary packaging systems. A portion of these systems, such as the primary plastic bags and inserts that wrap each drape are produced from virgin materials and disposed of after each use. Thus, production matches transport for these packaging materials. Other items, such as boxboard, wooden pallets, aluminum and plastic totes, are used many times and / or recycled after use. Thus, the production of materials does not match mass transported during the use phase. For example, an aluminum cart weighing 72 kg is used to transport 200 drapes to and from the hospital (360 g/drape). Thus, the transported mass is much greater than the mass manufactured for each drape use.

Table 1.5 Comparison of reusable versus disposable systems for surgical drapes

LCI Component	**Reusable Architecture**	**Disposable Architecture**
Manufacture of drape	9.60 kg manufactured/1,000 drape uses as 16.7 drapes at 0.576 kg/drape (60 cycles for 1,000 drape uses)	245 kg manufactured/1,000 drapes at 0.245 kg/drape
Primary, secondary, and tertiary packaging for drape	59.0 kg manufactured/1,000 drape uses; 420 kg transported	88.3 kg manufactured/1,000 drapes; 101 kg transported
Manufacture of tape	6.05 kg manufactured/1,000 drape uses	5.23 kg manufactured/1,000 drapes
Primary, secondary, and tertiary packaging for tape	0.608 kg manufactured/1,000 drape uses; 1.23 kg transported	0.353 kg manufactured/1,000 drapes; 0.743 kg transported
Laundry	1,000 drapes, composed of 576 kg used linen, 288 kg water, 23.0 kg inorganic waste, and 1.73 kg organic waste	N/A
Water for laundry (11 kg metered water/kg laundered)	6,342 kg metered/1,000 drapes; 173 kg consumed (blue water)/1,000 drapes	N/A
Wastewater treatment to restore water	3.30 kg chemical oxygen demand/1,000 drape uses	N/A
Sterilization	1,000 drapes and associated tape, composed of 576 kg linen and 6.05 kg tape, steam sterilization	1,000 drapes and associated tape, composed of 245 kg linen and 5.23 kg tape, ethylene oxide sterilization
Landfill of biological waste	0.0107 kg/1,000 drape uses	0.643 kg /1,000 drapes
Landfill of plastic surgical drapes, tape, and packaging	68.0 kg/1,000 drape uses	307 kg/1,000 drapes
Replacement of lost instruments	N/A	0.220 kg/1,000 drapes, stainless steel surgical bowl

Table 1.6 Cradle-to-end-of-life (CTEOL) of 1,000 reusable surgical drape uses (60 cycles), process energy and natural resource energy

Modules comprising the major components of surg drape reuse 1000 uses, 07/22/2018	Description	Mass architecture of surg drape reuse 1000 uses, kg/1000 uses	Process energy, MJ/1000 uses reusable surgical drape							Natural Resource energy, MJ/1000 uses reusable surgical drape
			Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy	Total Net Energy
gate-to-gate data										
use phse transport, gtg	transport of drapes and tapes to and from laundry	1,000	0	0	0	0	865	0	865	1,038
laundry process, gtg	washing and drying process for 1,000 drapes	576	578	0	0	3,313	0	0	3,890	5,659
cradle-to-gate data										
manufacture and delivery of surg drape reuse ePTFE, ctg	8.33 new drapes (500 uses)	4.80	213	49.1	272	70.5	45.4	-85.9	564	1,156
manufacture and delivery of surg drape reuse PU, ctg	8.33 new drapes (500 uses)	4.80	211	48.4	270	71.2	45.1	-86.4	559	1,144
packaging for new reusable surgical drapes, ctg	16.7 new drapes	0.974	0.650	0	0.469	10.2	0.192	-0.583	11.0	13.9
packaging for laundered drapes, ctg	1000 drapes from laundry and back	58.0	248	0	282	662	72.2	-180	1,084	1,787
tape used with reusable drapes, ctg	600 m (by 5 cm) surgical tape used to tape 1,000 drape uses.	6.05	27.9	0.144	148	63.1	12.1	-58.7	193	305
packaging for tape, ctg		0.608	0.157	0	0.217	6.03	0.0453	-0.0984	6.35	7.66
Water for laundry, ctg	treatment for metered water used in laundry	6,342	5.11	0	0	0	0	0	5.11	16.3
WWTP disp, COD, ctg	based on COD value in waste water from 1000 drapes	3.30	13.1	0	0	0	0	0	13.1	41.9
steam sterilization of drapes, ctg		582	36.6	0	22.1	229	0	0	288	413
landfill of packaging, ctg	all disposable packaging. Drapes are excluded (an additional 9.6 kg potential)	61.1	2.96	0	0	20.4	0	0	23.4	33.0
landfill of biological waste on drapes, ctg		0.0107	5.19E-04	0	0	3.59E-03	0	-0.0303	-0.0262	-0.0378
		7,064								
		1,000								
		Total ctgs	758	97.6	995	1,133	175	-412	2,747	4,918
		Total gtgs	578	0	0	3,313	865	0	4,755	6,697
		Total Process Energy, MJ/1000 kg surg drape reuse 1000 uses	1,336	97.6	995	4,446	1,040	-412	7,502	1.16E+04

Table 1.7 Cradle-to-end-of-life (CTEOL) of 1,000 disposable surgical drape uses, process energy and natural resource energy

Modules comprising the major components of surg drape disp 1000 uses, 07/22/2018		Mass architecture, kg/1000 uses	Process energy, MJ/1000 uses disposable surgical drapes							Natural resource energy, MJ/1000 uses disposable surgical drapes
			Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy	Total Net Energy
gate-to-gate data										
surg drape disp 1000 uses, gtg	no operations, collection of ctgs only	1,000	0	0	0	0	0	0	0	0
cradle-to-gate data										
surg drape disp PP, ctg	1,000 new drapes, includes transport from Asia to kit packer and then to hospital	245	2,324	1,381	773	3,643	2,478	-999	9,600	1.63E+04
surg drape disp pack, ctg	packaging for 1,000 new drapes	88.3	243	0	279	958	70.9	-176	1,375	2,112
S070 tape, ctg	600 m surgical tape used to tape 1,000 drape uses	5.26	19.5	5.18	52.3	60.3	17.6	-34.7	120	186
S070 pack, ctg	packaging for surgical drapes	0.353	0.0922	0	0.118	3.52	0.0266	-0.0609	3.69	4.45
sterilization, EtO, textiles, ctg		250	9.98	0	5.71	20.1	1.52	-15.4	21.9	43.0
LF disp, plastic, ctg	landfill of drapes and tapes	307	14.9	0	0	103	0	0	118	166
LF disp, biological waste, ctg	landfill of biological waste	0.643	0.0312	0	0	0.215	0	-1.82	-1.57	-2.27
stainless steel bowl, ctg	approximated impact of replacing lost equipment	0.220	0.902	0.0368	0.121	0.796	0.497	-0.161	2.19	4.39
		897								
		1,000								
		Total ctgs	2,613	1,386	1,110	4,788	2,568	-1,227	1.12E+04	1.88E+04
		Total gtgs	0	0	0	0	0	0	0	0
		Total Process Energy, MJ/1000 kg surg drape disp 1000 uses	2,613	1,386	1,110	4,788	2,568	-1,227	1.12E+04	1.88E+04

Life Cycle Impact Assessment (LCIA)

The three environmental indicators selected for comparison of reusable and disposable surgical drape systems in this study were: natural resource energy consumption, blue water consumption, and solid waste generation. The indicators are described in-depth in the "LCIA Methodology and Types of Impacts" section above. The LCIA results for the two drape systems are presented in Table 1.8, followed by a detailed description of the calculations for each environmental indicator.

Table 1.8 Cradle-to-end-of-life evaluations of reusable (60 cycles) and single use surgical drapes, environmental indicators

Environmental indicator	**Units, per 1,000 drape uses**	**Reusable**	**Disposable**	**Reduction (improvement) from selecting reusable system, % of disposable system**	**Increase from selecting disposable system, % of reusable system**
Natural resource energy	MJ	11,615	18,774	38%	62%
Blue water consumption	kg	117	304	62%	160%
Health care facility solid waste generation for disposal*	kg	61.1	308	80%	404%

*Solid waste includes drapes, tapes, biological waste, and plastic and paper packaging. Note that corrugated boxboard is not included as solid waste as it considered 100% recycled.

Natural Resource Energy Consumption

The NRE consumption for 1,000 uses of surgical drape was calculated from the process energy consumption and the scale-up values from Table 1.3. The NRE is summarized in Table 1.9.

For the reusable drapes, about 50% of the NRE use was from laundry operations. About 20% was from manufacture of the drapes. Drapes with the PU and ePTFE barrier had nearly equal energy consumptions. This was due partly to the small relative impact of the barrier material to the rest of the drape. More details are given in the drape manufacturing Chapter. Packaging materials for transport from laundry to point of use were about 16% of NRE, and transport itself was about 9%. Other materials and operations combined resulted in 7% of NRE use.

For the disposable drapes, about 87% of NRE was from drape manufacture. This included transport of the drapes from the point of manufacture in Asia to the kit packer and then to the hospital. This transport resulted in 1,926 MJ of fuel use or 2,311 MJ of NRE, which is about 12% of the total. About 11% of the NRE was due to packaging, and the other operations combined resulted in about 2% of the NRE.

Table 1.9 Natural resource energy consumption, MJ/1,000 uses surgical drapes

	NRE, MJ/1,000 drape uses (%)	
Life cycle stage	Reusable	Disposable
Drape manufacture and supply chain[1], CTG	2,300 (19.8%)	16,260 (86.6%)
Drape packaging and supply chain, CTG	1,801 (15.5%)	2,112 (11.2%)
Tape manufacture and supply chain, CTG	305 (2.6%)	186 (1.0%)
Tape packaging and supply chain, CTG	7.66 (0.1%)	4.45 (0.0%)
Laundry, CTG	5,717 (49.2%)	0
Sterilization, CTG	413 (3.6%)	43.0 (0.2%)
Use phase transport[1], GTG	1038 (8.9%)	0 (0%)
End-of-life, CTG	33 (0.3%)	168 (0.9%)
Total NRE	**11,615**	**18,774**

1. Transport of disposable drapes to kit packers and then to hospital is considered part of the drape manufacture and supply chain. Transport of reusable drapes to cut-sew-trim and then to laundry is also part of the manufacture and supply chain category. Reusable transport from laundry to hospital and back is part of use phase.

Blue Water Consumption

For reusable and disposable surgical drapes, water use occurs in the manufacturing supply chain, the laundry phase, and the sterilization phase.

The life cycle evaluation of water consumption in individual manufacturing plants must be more transparent than simply a catalogue of water supplied to or wastewater sent from such facilities. Water utilized in manufacturing gate-to-gate life cycle inventories consists of the following:

1. Water utilized in steam heating or cooling water circulations. This water plays a role in the energy balance of the manufacturing plant and is generally non-contaminated water.
   a. Water in heating and cooling circuits that is removed to keep ion or salt buildup within acceptable limits. This is often referred to as blowdown since this water is removed from the circuit and sent to wastewater treatment.
   b. Water in heating and cooling circuits that is lost through evaporation to the atmosphere.
2. Water that comes in direct contact with the chemical reactions and separations, material processing (such as cooling spray for grinding), or is otherwise utilized in direct contact with the product. This water is contaminated and under the U.S. regulatory environment is sent to a wastewater treatment plant.
3. Water consumed or produced in chemical reactions or in relation to the incoming raw materials or outgoing product as moisture level.

These categories of water can be utilized to establish water use based on principles developed for water footprint assessment (Aviso et al., 2011; Hoekstra and Chapagain, 2007). The critical assumption for this water analysis is that contaminated water is sent to treatment plants that use physical and biological means to restore the water to regulatory standards for safe human contact. These Federal and State standards are used to issue permits for discharge to surface waters in the U.S. These standards also apply to municipal wastewater treatment plants to which an industry may discharge wastewater that is subsequently treated to the required levels. It is further assumed that industry and municipalities are in compliance with these permits, as these waters are returned to surface water resources. For most chemical and materials manufacturing GTG LCI, the water utilization assessment categories (Aviso et al., 2011) of direct relevance are:

1. Gray water – the water, if any, that is used to dilute pollutants in a wastewater treatment plant to produce an effluent meeting the regulated standard concentrations for discharge to surface water. The assumption of compliance with wastewater treatment plant permit requirements means that gray water is essentially zero for many manufacturing processes, since regulated standards for water discharge are already met. In other words, much manufacturing water use is like rented water, as it is returned in acceptable condition after use and discharge to surface waters and is thus not consumed.
2. Blue water – the water evaporated or incorporated into the product (net of water consumed in product minus water generated from inputs to product). These losses are water not directly available locally to replenish surface waters. The return of water due to rainfall from this evaporated water is not considered sufficient for the water balance on the manufacturing plant and thus is considered blue water or consumed water.

Therefore, the analysis of water consumption of each manufacturing plant GTG also includes the requisite wastewater treatment plant for achieving regulated discharge standards. This manufacturing plant boundary allows the water consumption to only include blue water, and thus is substantially less than water metered to the plant (the typical method for evaluating water consumption). The LCI water consumption for a manufacturing plant is thus 1b) above and can be estimated in a transparent way from the LCI of each GTG analysis.

Water consumption (blue water) analysis involves three steps of calculations. First, the water lost to evaporation is estimated in relation to flows in two circulating systems:

a. Cooling water loop in which water in the outer shell of a heat exchanger removes heat from processes and then goes to a cooling tower where that heat is discharged to the atmosphere. These cooling towers have evaporative losses, estimated from several sources in Table 1.10, kg water evaporated/kg water flow in the cooling circuit.
b. Heating loop in which steam is used in the outer shell of a heat exchanger to add heat to processes, is condensed to water isothermally, and then returns to a boiler system to be converted back to steam. These boilers have evaporative losses estimated from several sources in Table 1.10, kg water evaporated/kg water flow in the steam circuit. Heating at higher temperatures that cannot use steam (instead using fluids like Dowtherm or direct flame heating of air) are assumed to not have evaporative water losses.

Table 1.10 Water loss as evaporation in heating and cooling circuits of manufacturing plants, estimates from various sources

Source	Cooling Circuit				Steam Heating Circuit			
	Evaporative Loss		Blowdown loss* to wastewater treatment plant		Evaporative Loss		Blowdown loss to wastewater treatment plant	
	kg/kg circuit flow	kg/MJ cooling	kg/kg circuit flow	kg/MJ cooling	kg/kg circuit flow	kg/MJ steam heating	kg/kg circuit flow	kg/MJ steam heating
[1]	0.006	0.066			0.08	0.060		
[2]	0.001							
[3]	0.0035-0.004		0.014-0.016					
[4]	0.016-0.02		0.064-0.08					
[5]					0.1-0.2		0.04-0.08	
[6]					0.15		0.075	
VJR	**0.01**	**0.068**	**0.05**	**0.34**	**0.15**	**0.052**	**0.06**	**0.031**

*approximately 80% of total make up is blowdown, Cirelli, 2011.
[1] Jimenez-Gonzalez and Overcash, 2000; [2] Carre, 2008; [3] Albemarle Company, 2011 (based on total makeup); [4] Chemtura, 2011; [5] KEI Steam Solutions; [6] Cleaver Brooks; VJR = value judged representative

In the second step, results in Table 1.10 are used transparently with standard conditions in the operation of heat exchangers for cooling and heating to calculate water loss per MJ heating or cooling. For the representative cooling heat exchanger, water enters at 20 °C and exits at 50 °C, while for the heating heat exchanger steam enters at 207 °C and leaves as a condensate at 207 °C. These conditions have been applied uniformly across all GTG LCI studies in this report and thus can be compared for the entire life cycle evaluation. Also, the effect of changing these standard conditions can be evaluated transparently. The MJ heating or cooling/kg water in the circuit are:

- Cooling:

$$1\ kg\ water * \frac{4.19\ kJ}{kg\ water \cdot {}^{\circ}C} * (50\ {}^{\circ}C - 20\ {}^{\circ}C) * \frac{1\ MJ\ cooling\ water}{0.85\ MJ\ in\ process}$$

$$= \frac{\mathbf{0.148\ MJ\ process\ cooling}}{\mathbf{kg\ water\ in\ cooling\ circuit}}$$

- Heating (isothermal at 207 °C):

$$\frac{\mathbf{1.94\ MJ\ process\ heating}}{\mathbf{kg\ water\ in\ steam\ circuit}}$$

Combining the evaporative losses from Table 1.10 with the MJ heating or cooling/kg water, the kg evaporated water/MJ heating or cooling is calculated, Table 1.11.

Table 1.11 Evaporative losses per MJ heating or cooling

	Cooling	Heating
kg water evaporated/kg water flow in circuit	0.01	0.15
MJ heating or cooling/kg water in circuit	0.148	1.94
kg water evaporated/MJ heating or cooling in circuit	**0.0676**	**0.0773**

The third step is to evaluate if water is consumed or generated by chemical reactions in the manufacturing process. Additionally, if water is imported through raw materials input to the manufacturing plant or exported in the product, this part of the water balance must be completed (net kg water generated or consumed in plant). Often as a preliminary evaluation, the net kg water generated or consumed is assumed to be zero as is the case for the manufacturing of surgical drapes.

Utilizing these relationships, the water consumption (blue water) for the manufacturing phase and use phase (laundry and sterilization) of surgical drapes are estimated, Table 1.12. The process cooling water (MJ) and the process heating steam (MJ), determined routinely in each GTG LCI, give the water for reusable and disposable surgical drapes. The laundry water use for 1,000 drape uses is also included. The laundry water loss to evaporation is 0.44 kg water / kg drape (dry weight). Additionally, 0.5 kg water content in the soiled drapes arrives at the laundry on the drapes as received. The soil is comprised of tissue, blood, sweat, and other liquids. When disposable drapes are used, this water is not recovered. When reusable drapes are used, this water is recovered in the laundry and sent through the WWTP and back into the water supply. Thus the net water use in the laundry is 0.44 – 0.5 = -0.06 kg water / kg drape. The total water consumed (blue water) indicates that the reusable system is about 62% lower (an improvement) over the comparable disposable drapes. However, there is a large amount of water evaporated and also recovered from the drape soil. These largely offset, but this results in a high level of uncertainty in the net blue water use.

Table 1.12 Estimation of blue water or evaporated water from manufacturing and use (laundry) of surgical drape systems

Reusable surgical drape system, CTG	Value / 1,000 drape uses	Water Use / 1,000 drape uses
Cooling water, manufacturing CTG	1,111 MJ	Evaporated water, [1,111 * 0.0676 kg water evaporated/MJ cooling] = 75.1 kg water
Steam, manufacturing CTG	995 MJ	Evaporated water, [995 * 0.0773 kg water evaporated/MJ heating] = 76.9 kg water
Laundry, GTG	6,342 kg water	Evaporated water, [576 kg drape * 0.44 kg water evaporated / kg drape] = 253 kg water – 576*0.5 kg water recovered / kg drape=-288 kg water. Net blue water = 253kg – 288 kg = -35 kg
Total blue water use for reusable surgical drape system		**117 kg blue water**
Disposable surgical drape, CTG	Value / 1,000 drape uses	Water Use / 1,000 drape uses
Cooling water, manufacturing CTG	3,228 MJ	Evaporated water, [3,228 * 0.0676 kg water evaporated/MJ cooling] = 218 kg water
Steam, manufacturing CTG	1,110 MJ	Evaporated water, [1,110 * 0.0773 kg water evaporated/MJ heating] = 85.8 kg water
Total blue water use for disposable surgical drape system		**304 kg blue water**

Solid Waste Generation

The solid waste generated at the health care facility includes drapes, tapes, and packaging which are incinerated for energy production or sent to a landfill. The solid waste generation for surgical drape systems is summarized in Table 1.13. Note that corrugated boxboard is considered to be recycled for both the reusable and disposable surgical drape cases. Thus, of the packaging, only the plastic portion is incinerated or landfilled. In the reusable drape system, the tape release liner and core are solid waste. However, the tape adhesive and carrier are dissolved in laundry.

Table 1.13 Solid waste generation at the health care facility

	Solid waste, kg/1,000 uses surgical drapes	
	Reusable	Disposable
Drapes	0 (9.60) **	245
Packaging for drapes	58.1	57.0
Surgical tape	2.96 *	5.26
Packaging for tapes	0.0377	0.0217
Biological waste on drapes	0.0107	0.643
Total solid waste	**61.1**	**308**

* Surgical tape used with reusable surgical drapes disintegrates in the laundry and is not delivered as solid waste. The plastic core and the release liner are disposed as solid waste.

** Reusable drapes are generally recycled. However, if these are not recycled in a specific scenario, these contribute 9.6 kg / 1000 uses.

Reusable surgical drape systems were thus found to reduce solid waste generation to the landfill by 80% compared to disposable drape systems. Conrardy et al. (2010) conducted a concept comparison between operating rooms using reusable surgical gowns, back table covers, towels, Mayo stand covers and basins, bowls, and pitchers versus disposable alternatives. The study found a 65% reduction in regulated medical waste from selective reusables.

Impact Assessment using CML

In addition to the three environmental indicators evaluated above, the CML version 3.01 impact assessment method (CML-IA, 2013), which was developed by Leiden University in the Netherlands, was used to compare 11 environmental impact categories. The results are shown in Table 1.14.

Table 1.14 Cradle-to-end-of-life evaluations of reusable (60 cycles) and single use surgical drapes, environmental impacts, CML v3.01.

Environmental impact	Units, per 1,000 drape uses	Reusable	Disposable	Reduction (improvement) when selecting reusable system, % of disposable system	Increase when selecting disposable system, % of reusable system
Global warming (GWP100a)	kg CO2 eq	670	1072	38%	60%
Acidification	kg SO2 eq	1.69	3.60	53%	113%
Eutrophication	kg PO4--- eq	0.708	1.37	48%	93%
Ozone layer depletion (ODP)	kg CFC-11 eq	1.34E-04	9.88E-05	-36%	-26%
Photochemical oxidation	kg C2H4 eq	1.59	11.7	86%	637%
Fresh water aquatic ecotox.	kg 1,4-DB eq	123	402	69%	227%
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.09E+05	7.78E+05	47%	90%
Terrestrial ecotoxicity	kg 1,4-DB eq	0.866	1.09	20%	26%
Human toxicity	kg 1,4-DB eq	981	2.84E+04	97%	2797%
Abiotic depletion (fossil fuels)	MJ	9,965	1.55E+04	36%	56%
Abiotic depletion	kg Sb eq	3.44E-04	7.97E-04	57%	131%

Life Cycle Interpretation

Reusable surgical drape systems outperformed disposable surgical drape systems in all three environmental indicators studied, Figure 1.5. The reusable system used about 38% less energy (NRE) when compared to the disposable system. The reusable system also used about 62% less water (blue water) and avoided 80% of solid waste when compared to the disposable system. The reduction in all categories is due to the large impact of manufacturing and transport energies of the disposable drapes. The blue water savings for reusable drapes is slightly larger than energy savings. The majority of blue water use in drape manufacture is from losses in the industrial cooling water system. The majority of energy use for reusable drapes is in the laundry process, which does not have a cooling water need. The evaporative losses in laundry are offset by recovery of water from soil in the laundry. This recovery is based on the measured water content of soiled drapes and surgical gowns as received at the laundry. This leads to a large savings in blue water, but there is significant uncertainty.

For the impact assessment (Table 1.14), the improvement from selecting reusable drapes was 20-60% in most categories. This is consistent with the NRE improvement of 38%. Four categories that differed significantly from this range are ozone layer depletion, human toxicity, photochemical oxidation (smog formation) and fresh water ecotoxicity. In the ozone layer depletion category, the reusable drapes had 36% greater impact than disposable drapes. This category was strongly influenced by process emissions of methyl chloride and chlorodifluoromethane. These chemicals are emitted in the production of ePTFE, which appears in the critical zone of reusable drapes and in the tape system. In the human toxicity category, the reusable drapes had a 97% reduction in impact relative to the disposable drapes. The large impact for disposable drapes in this category was dominated by ethylene oxide (ETO) emissions in the sterilization process. In the photochemical oxidation (smog) category, disposable drape emissions were dominated by process emissions in propylene production. Reusable drapes used much lower quantities of ethylene and propylene. The fresh water aquatic toxicity of the disposable drape system was impacted to emissions of copper chloride and copper phthalocyanine, which are emitted during production of the blue dye that was chosen as representative dye for disposable drapes.

The uncertainty in these impact assessment categories is much greater than the uncertainty in the environmental indicator NRE. This is based on both uncertainty in process emissions, which can vary depending on the methods of emissions control used at the point of use, and on uncertainty in the impact factors themselves. However, this analysis showed several potential process emissions of concern. Overall, there were improvements in 10 out of 11 impact categories.

Importance of drape weight

The LCI and LCIA results for the disposable surgical drape systems are highly dependent on the weight of the drape. For example, a 10% decrease in disposable drape weight results in about a 9% decrease in NRE consumption, water consumption, and solid waste generation. The weight of the reusable drape is also significant, since the laundry results are based on the weight of items laundered. Thus, a 10% decrease in reusable drape weight results in about a 8% decrease in NRE consumption and blue water consumption.

Importance of laundry efficiency

The LCI and LCIA results for the reusable surgical drape are highly dependent on the efficiency of the laundry process. For example, a 10% decrease in laundry energy consumption results in about a 5% decrease in NRE.

Blue water consumption and laundry

It is notable that the water output to the wastewater treatment plant from the laundry operation is higher than the water input to the laundry process. This is due to water present in the incoming soiled drapes and in the washing detergent. Essentially, water is recovered from the soiled drapes and the detergent and returned to the municipal water source for reuse. The water from the soiled drapes is shown as a blue water credit, because it is water that would be lost to the environment with disposable drape use. The amount of water on drapes after spinning or pressing and before drying is 0.4 to 0.6 kg/kg drape. The water content on the dried drapes is 0.05 kg / kg drape. Thus, the evaporated water is 0.35 to 0.55 kg / kg drape or 202 to 317 kg/1000 uses. The estimated blue water use was 0.44 kg / kg drape or 253 kg water/1000 uses. The amount of water recovered from the soiled drapes is 0.5 kg / kg drape or 288 kg/1000 uses. Thus, the net blue water consumption is -35 kg / 1000 uses, because more water is recovered than used. However, there is a high uncertainty in specific instances due to the variation between laundries. In the case of poor efficiency in a press and drapes returned very dry, the net water use could be as high as 317 kg/1000 uses. Thus, in an extreme case, the reusable drape system could use up to 50% more blue water than the disposable drapes system.

Production location of disposable drapes

About 10% of the NRE for disposable drapes was due to transport from Asia to Western Europe. If the drapes were produced in Europe, this would have a minor impact on the calculated improvement. The reusable drape system would still consume 32% less NRE than the disposable system. Reliable energy modules were not readily available for China. Thus, the results in this report were based on using European energy modules for both disposable and reusable drapes. As a sensitivity analysis, alternative scale-up factors for China were used to calculate NRE from process energies from drape and packaging materials. This resulted in an NRE of 26,000 MJ/1000 disposable drape uses. In this case, the net reduction in NRE for choosing reusable drapes would be 53%.

End use of reusable drapes

Reusable drapes weigh 9.6 kg / 1000 uses. The disposable components of packaging and tape combine to 61.1 kg / 1000 uses. Thus, if the reusable drapes were landfilled at end of use, the impact on solid waste disposal would be small. The savings would be 77% relative to disposable drapes.

Summary of results

The three environmental indicators are summarized graphically in Figure 1.6, Figure 1.7, and Figure 1.8. The CML LCIA results are shown graphically in Figure 1.1.9. The results were broken out into process emissions and energy emissions.

The LCI indicators and LCIA results in this report are based on a relative approach and indicate potential environmental effects. The results do not predict actual impacts on category endpoints, the exceeding of thresholds, or safety margins or risks.

Figure 1.5 Environmental indicators for surgical drape systems, expressed as percent of disposable value

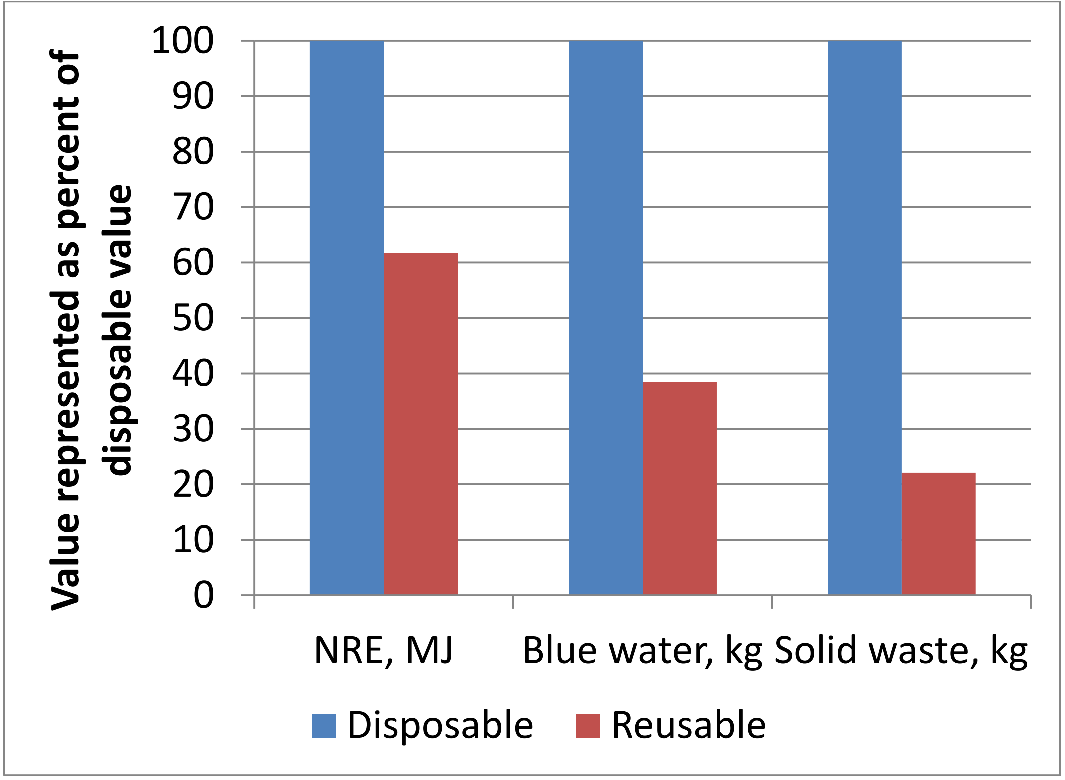


Figure 1.6 Natural resource energy consumption for surgical drape systems, MJ/1,000 drape uses

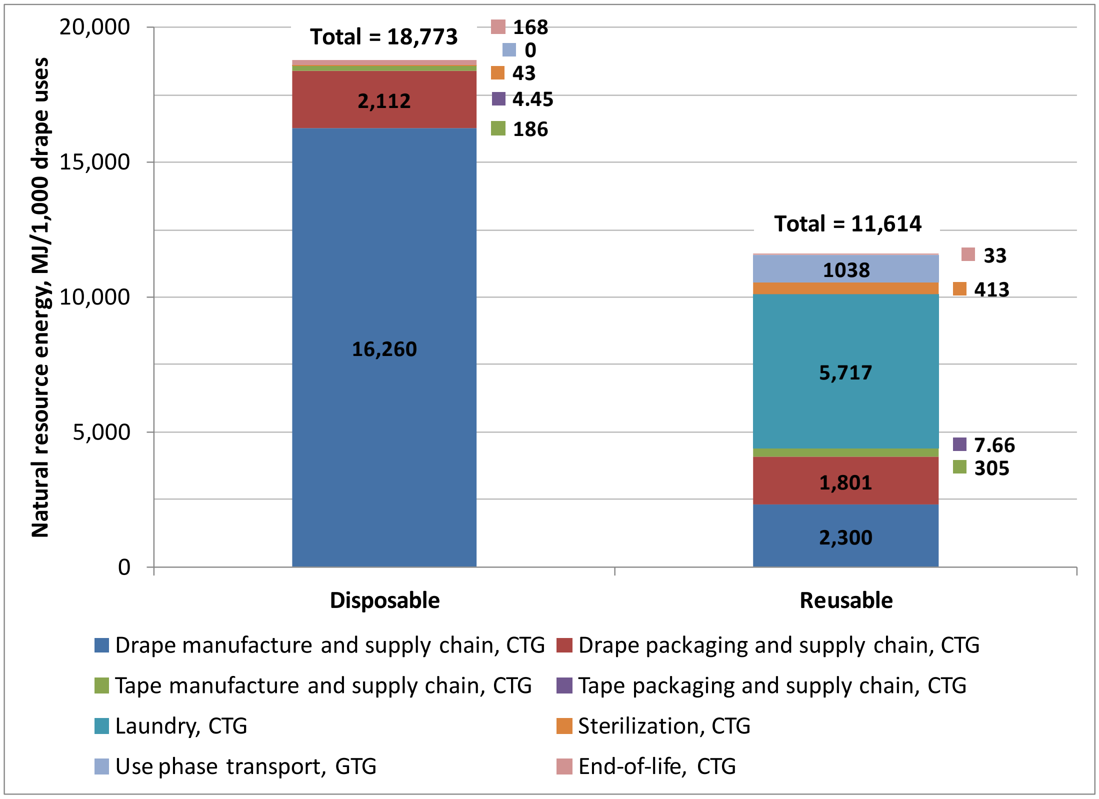


Figure 1.7 Blue water consumption for surgical drape systems, kg/1,000 drape uses

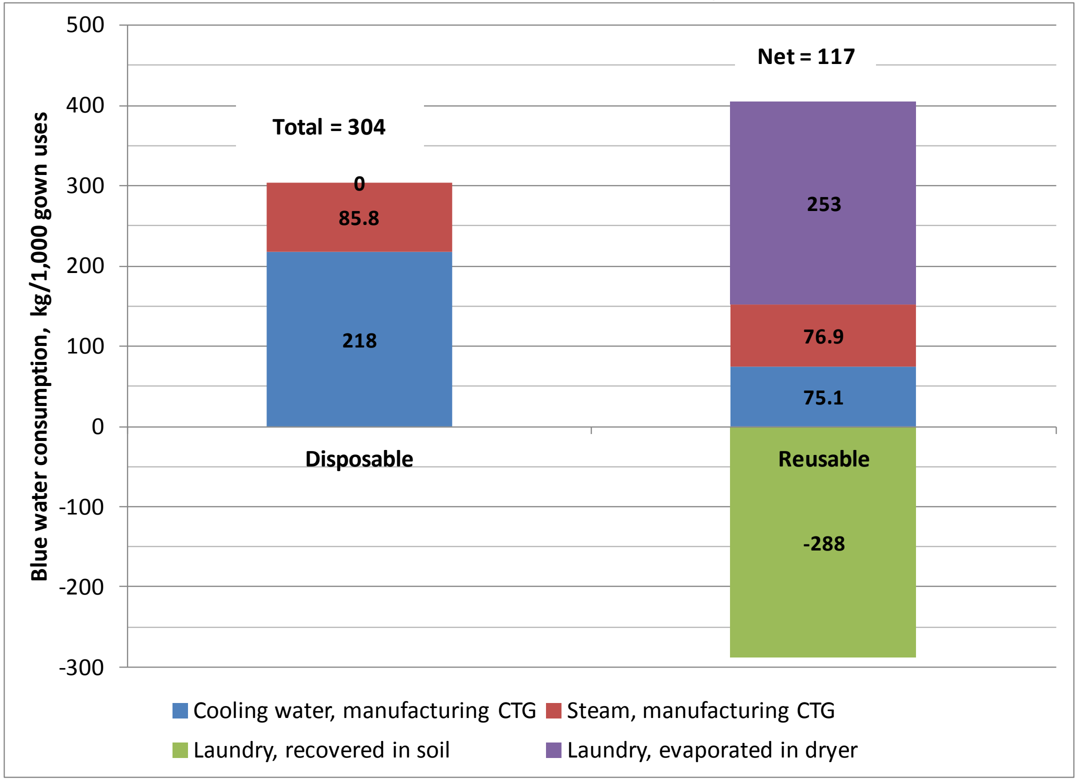


Figure 1.8 Solid waste generation for surgical drape systems

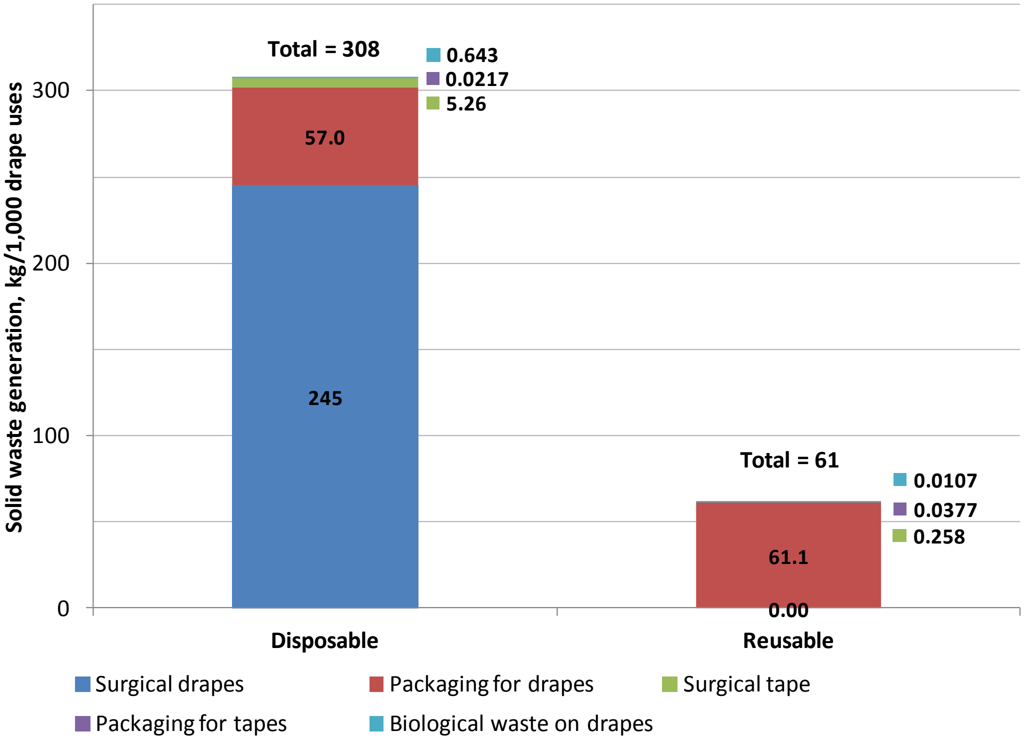
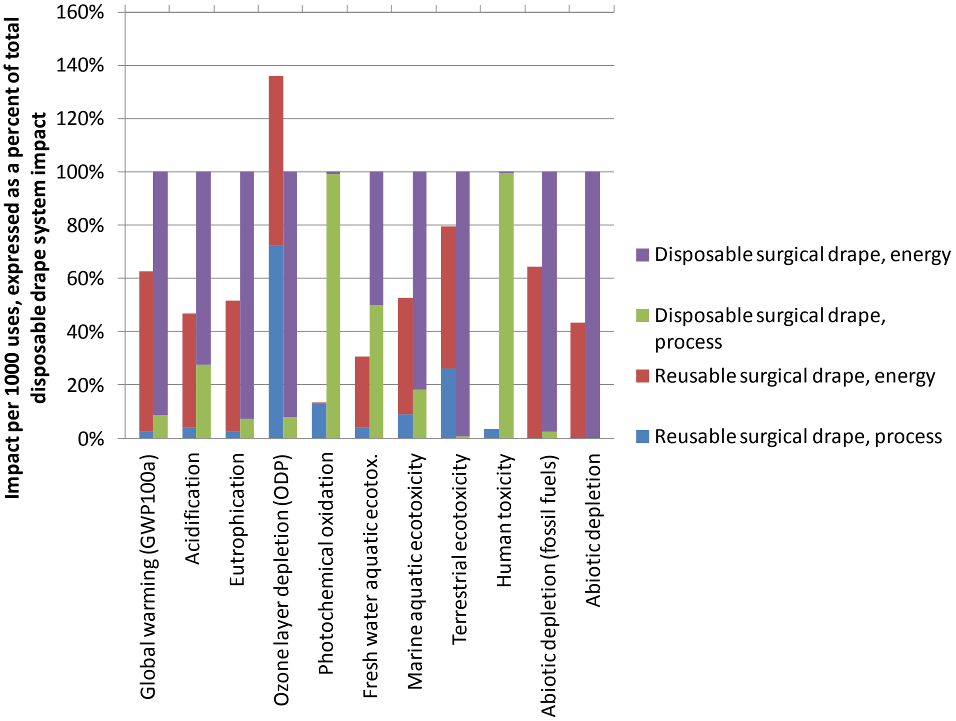


Figure 1.1.9 LCIA for reusable and disposable drape systems, per 1000 uses. European energy modules and CML impacts were used.



Conclusions

In a comprehensive life cycle evaluation of surgical drape systems there are 11 components that are analyzed as life cycle inventories for each of the drape systems (reusable and single use), Table 1.5. The components are combined according to the mass and energy flows linking the components, and the cradle-to end-of-life (CTEOL) energy results are documented, Table 1.6 and Table 1.7.

The environmental footprints of reusable and disposable surgical drape systems are evaluated by converting the mass and energy flows documented above into environmental indicators and impacts. Three environmental indicators (natural resource energy, blue water consumption, solid waste generation) and 11 environmental impacts from CML are documented, Table 1.8 and Table 1.14.

For the cradle-to-end-of-life cycle, the reusable surgical drape system results in reduced energy consumption relative to the disposable drape system. The reusable drape system uses 38% less energy when compared to the disposable surgical drape system, Table 1.8. Stated differently, selecting a disposable surgical drape system leads to an increase in energy consumption of nearly twice that from selecting a reusable surgical drape system. This is consistent with the partial life cycle studies previously reported in the literature for surgical gowns and other garments, and so it is now absolutely clear that the environmental benefit of reusable surgical drape systems is significant. The life cycle energy improvement has been quantified herein and can thus be used by health care facilities for their achievements in sustainability programs.

In addition, the blue water use for the reusable surgical drape system is found to be about 60% less than the disposable surgical drape system. This is contrary to much of the discussion in the literature and marketplace, which designates reusable garments as more water intensive. The literature or market descriptions often fail to include the water consumed in the supply chain. The literature or market descriptions often also do not use the principle of water footprint that designates blue water as the best consumption principle (Aviso et al., 2011).

Furthermore, the solid waste generation for disposal for the reusable surgical drape system is found to be significantly lower (80%) than the disposable drape system. Stated differently, selecting a disposable drape system results in an increase in solid waste of about 5 times that from selecting a reusable system.

Finally, an LCI done using European energy modules and the CML impact method showed that the reusable drape system had lower environmental impacts in 10 of the 11 categories. Ozone depletion, human toxicity, and fresh water ecotoxicity categories had strong contributions from process emissions. The ozone depletion category was the only category in which the disposable system outperformed the reusable system. This category was strongly influenced by potential emissions of methyl chloride and chlorodifluoromethane, which appear in the manufacture of ePTFE and the tape systems. The human toxicity category was dominated by emissions of ethylene oxide in the sterilization of disposable drapes. The fresh water ecotoxicity category was strongly influenced by emissions of copper ions in the representative dye production used. Each of these categories has a high uncertainty due to unknown emission controls and uncertainties in the impact factors of these chemicals. However, this analysis shows potential emissions of concern throughout the supply chains. The other impact categories are dominated by energy emissions and thus do not deviate significantly from what would be predicted from the NRE results.

There appear to be environmental benefits for many hospital covering items that are reusable versus disposable. Thus, adding the life cycle of other textile and non-textile items found in health care facilities (especially surgical gowns) would further strengthen the environmental benefits of reusable systems.

The remaining Chapters of this report include in depth analyses of the life cycle inventory data used in this study. Each Chapter explores the background and methodology used to develop one major component of the life cycle analysis. Results are given as material and energy balances on each system:

- Chapter 2 – Surgical drape manufacturing cradle-to-gate
- Chapter 3 – Drape packaging manufacturing cradle-to-gate
- Chapter 4 – Surgical tape manufacturing cradle-to-gate
- Chapter 5 – Tape packaging manufacturing cradle-to-gate
- Chapter 6 – Use phase (laundry and sterilization)
- Chapter 7 – End-of-life phase
- Chapter 8 – Transport

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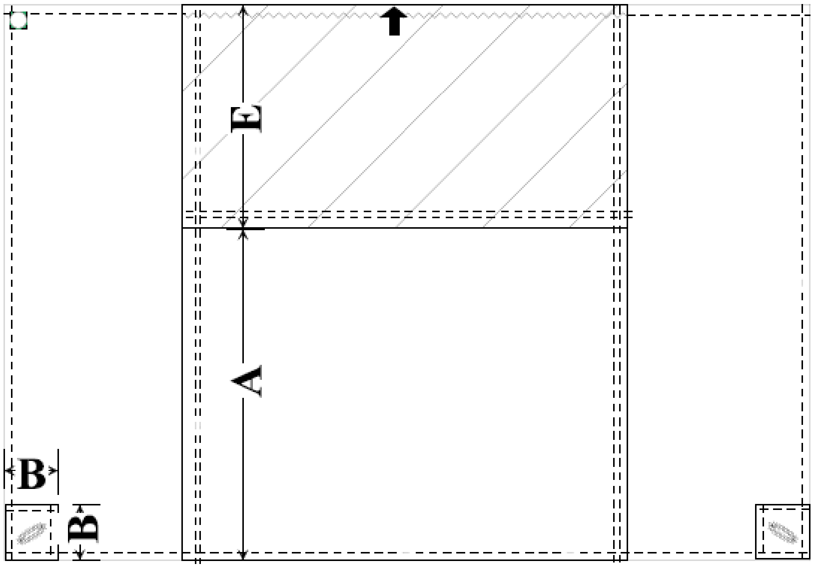
Chapter 2 SURGICAL DRAPE MANUFACTURING CRADLE-TO-GATE

Background

Reusable and disposable surgical drapes provide protection from fluid and bacterial contamination for health care workers and patients. Surgical drapes typically contain “critical” areas with maximum protection and “non-critical” areas with less protection. An example of a reusable surgical drape with breathable fluid protection barrier is shown in Figure 2.1. Disposable drapes have a similar design.

Figure 2.1 Reusable surgical drape with breathable fluid protection in critical zones (shaded section)



Reusable and disposable medical garments have two principal fabric materials, those for critical areas and those for non-critical areas. Different fabrics are typically used by various manufacturers for a variety of different products, built from these common fabric platforms. Thus, the objective of the life cycle study was to provide transparent life cycle information for many related products built on the life cycle inventories of these core fabrics, but focused on a surgical top drape, Table 2.1.

Table 2.1 Fabrics used for representative surgical top drapes in this life cycle inventory study

Drape	**Critical zone**	**Non-critical zone**
Disposable surgical drape	Polypropylene film	SMS PP
Reusable surgical drape	Knit PET and liquid resistant ePTFE or PU *	Woven PET

SMS = spunbond-meltblown-spunbond, PP = polypropylene, ePTFE = expanded polytetrafluoroethylene, PU = polyurethane

* Two critical zone materials examined: 1) ePTFE breathable barrier membrane, and 2) PU breathable barrier membrane

Methodology

The LCI results for fabrics and components are analyzed in two ways to allow better understanding and transparency:

1. On a uniform basis of 1,000 kg of the fabric or material, MJ/1,000 kg.
2. On the basis of the amount of fabric used in one 4 m^2 surgical top drape.

The results are discussed under separate sections below for reusable and disposable products.

The drape manufacturing cradle-to-gate analysis included the complete supply chain, from natural resources in earth to delivery of the drape to a laundry. This analysis included the cut, sew, and trim plant where drapes are manufactured from input materials. The cut, sew, and trim gate-to-gate (GTG) life cycle inventories (LCIs) were developed separately for the reusable and disposable drapes. In general, each drape assembly produced scrap of these same materials, Table 2.1. The scrap was considered a waste of the process (classified as a “benign outflow” for life cycle purposes). This means that the materials and energy required to manufacture the drape and the scrap were all allocated to the drape. In other words, no credit was assigned for the potential reuse of the scrap fabric for other purposes. If the scrap fabric were to be used to produce another product, the credit for reuse would be assigned to the firm reusing the scrap, as is conventional in environmental life cycle analysis. After the use phase, the reusable drapes are typically recycled. Any benefit associated with recycling the used drapes is excluded from the study as were the benefits from recycling the scraps from the cut/sew/trim operations.

Results

Reusable Surgical Drapes

The main components of reusable surgical top drapes are woven fabric and liquid resistant (LR) fabric, Table 2.2. Woven PET fabric is typically used in non-critical zones, with some differences in the weight per unit area. A tri-laminate, liquid resistant fabric is used in critical zones. The tri-laminate includes two layers of knit PET and one layer of a liquid resistant breathable barrier. The two LR barriers used in the industry are an expanded polytetrafluoroethylene (ePTFE) barrier and a polyurethane (PU) barrier. Based on input from the Chainge Consortium, the current European market share is about 50% ePTFE drapes and 50% PU drapes. This market share was represented in the life cycle study by including life cycle inventories for both barriers and weighting the results by the appropriate market share. Thus, the cradle-to-gate LCI for reusable surgical drapes was based on the woven PET fabric cradle-to-gate LCI and the LR fabric cradle-to-gate LCIs, and the gate-to-gate for cutting, sewing, and trimming the drapes.

Table 2.2 Fabric materials used in reusable surgical top drapes

Zone	**Material(s)**
Non-critical zones	Woven PET fabric (129 gsm)
Critical zones	Tri-laminate fabric composed of three layers: Inner layer: knit PET Breathable barrier film layer: ePTFE liquid resistant sheet or polyurethane breathable barrier membrane Outer layer: knit PET Adhesive between layers: polyurethane Total fabric material = 230 gsm

The cradle-to-gate LCI of 1,000 kg woven PET fabric (129 gsm) is shown in Table 2.3. Note that a woven PET fabric with a similar basis weight of 115 gsm (3.40 oz./sy) was used as representative and scaled appropriately. The top row is the woven fabric plant, preceded by the yarn production plant from PET fibers. Following are the gate-to-gates (GTGs) to get PET fibers from the inputs (e.g. terephthalic acid, sodium hydroxide, disperse yellow 23). Then, the cradle-to-gate LCI of each input is given, thus completing the supply chain back to natural resources from earth. The cradle-to-gate process energy and natural resource energy for the woven PET fabric (MJ/1,000 kg woven PET fabric) were 115,000 and 239,000, respectively.

The cradle-to-gate LCI of 1,000 kg LR ePTFE barrier fabric (230 gsm) is given in Table 2.4. Note that a LR ePTFE barrier fabric with a similar basis weight of 132 gsm (3.90 oz./sy) was used as representative and scaled appropriately. The top row is the tri-laminate plant, where two layers of knit PET are bonded to one layer of ePTFE film with polyurethane adhesive. Then, the cradle-to-gate of each of the fabrics and adhesive used in the tri-laminate plant is given, completing the supply chain back to natural resources from earth. The cradle-to-gate process energy and natural resource energy for the LR ePTFE fabric (MJ/1,000 kg woven PET fabric) were 92,100 and 193,000, respectively.

The cradle-to-gate LCI of 1,000 kg LR PU barrier fabric (230 gsm) is given in Table 2.5. Note that a LR PU barrier fabric with a similar basis weight of 142 gsm (4.20 oz./sy) was used as representative and scaled appropriately. The top row is the tri-laminate plant, where two layers of knit PET are bonded to one layer of PU breathable barrier membrane with polyurethane adhesive. Then, the cradle-to-gate of each of the fabrics and adhesive used in the tri-laminate plant is given, completing the supply chain back to natural resources from earth. The cradle-to-gate process energy and natural resource energy for the LR PU fabric (MJ/1,000 kg woven PET fabric) were 87,700 and 182,000, respectively.

Each of the two barrier fabrics examined (ePTFE and PU) were composed of the same knit PET inner and outer layers. The only difference between the fabrics was the middle layer. For additional transparency, the cradle-to-gate life cycle inventories of the two middle layers examined (ePTFE film and PU breathable barrier membrane) are compared in Table 2.6 on a mass basis and Table 2.7 on an area basis. Polyurethane is used in both barriers. Polyurethane is a copolymer of an isocyanate monomer (poly methylene diphenyl diisocyanate, PMDI), polyether polyol, and a diol chain extender. The mass ratio of PMDI to polyol to diol differs based on the desired properties. The NRE for the ePTFE film and PU barrier membrane (MJ/1,000 kg) were 64,900 and 59,300, respectively. However, the ePTFE film has a fabric density of 10.5 gsm (0.31 oz./sy) and the PU barrier membrane has a fabric density of 21.0 gsm (0.62 oz./sy). Thus, the PU membrane requires twice as much mass to cover the same area. On an area basis, the NRE for the ePTFE film and PU membrane (kJ/m^2) were 681 and 1,246, respectively.

Table 2.3 Summary of cradle-to-gate life cycle inventory for 1,000 kg woven PET fabric (129 gsm)

Modules comprising the major components of 340PETwvnfab, 05/02/2018	Mass architecture of 340PETwvnfab, kg/1000 kg 340PETwvnfab	Process energy, MJ/1000 kg 340PETwvnfab						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
340PETwvnfab, gtg	1,000	8,243	0	3.54E+04	5,253	440	0	4.93E+04
340PETyarn, gtg	1,052	2.55E+04	0	145	0	463	0	2.61E+04
PET fiber, from TPA, gtg	1,093	3,863	0	0	0	481	0	4,344
PET pellet, from TPA, gtg	1,093	60.1	0	0	0	481	0	541
PET melt, from TPA, gtg	1,093	394	1,187	171	0	481	-413	1,819
cradle-to-gate data								
terephthalic acid, ctg	938	2,449	9,085	1.46E+04	6,322	1,735	-1.37E+04	2.05E+04
ethylene glycol, ctg	367	1,107	0	5,543	2,710	366	-3,394	6,333
Sodium hydroxide, ctg	657	3,120	0	2,588	0	289	-35.6	5,961
Total mass of ctg inputs	1,962							
Total mass of product, kg	1,000							

	Total ctgs	6,676	9,085	2.28E+04	9,032	2,390	-1.72E+04	3.28E+04
	Total gtgs	3.81E+04	1,187	3.57E+04	5,253	2,346	-413	8.21E+04
	Total Process Energy, MJ/1000 kg 340PETwvnfab	4.48E+04	1.03E+04	5.85E+04	1.43E+04	4,736	-1.76E+04	1.15E+05

Modules comprising the major components of 340PETwvnfab, 05/02/2018	Mass architecture of 340PETwvnfab, kg/1000 kg 340PETwvnfab	Natural Resource energy (nre*), MJ/1000 kg 340PETwvnfab						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
340PETwvnfab, gtg	1,000	2.64E+04	0	5.08E+04	6,041	528	0	8.38E+04
340PETyarn, gtg	1,052	8.17E+04	0	208	0	555	0	8.24E+04
PET fiber, from TPA, gtg	1,093	1.24E+04	0	0	0	577	0	1.29E+04
PET pellet, from TPA, gtg	1,093	192	0	0	0	577	0	769
PET melt, from TPA, gtg	1,093	1,260	1,706	246	0	577	-594	3,195
cradle-to-gate data								
terephthalic acid, ctg	938	7,837	1.31E+04	2.11E+04	7,270	2,082	-1.97E+04	3.16E+04
ethylene glycol, ctg	367	3,543	0	7,968	3,117	440	-4,878	1.02E+04
Sodium hydroxide, ctg	657	9,984	0	3,720	0	347	-51.2	1.40E+04
Total mass of ctg inputs	1,962							
Total mass of product	1,000							

	Total ctgs	2.14E+04	1.31E+04	3.27E+04	1.04E+04	2,868	-2.47E+04	5.58E+04
	Total gtgs	1.22E+05	1,706	5.13E+04	6,041	2,815	-594	1.83E+05
	Total Natural Resource Energy, MJ/1000 kg 340PETwvnfab	1.43E+05	1.48E+04	8.40E+04	1.64E+04	5,683	-2.53E+04	2.39E+05

Table 2.4 Summary of cradle-to-gate life cycle inventory for 1,000 kg liquid resistant ePTFE fabric (230 gsm)

Modules comprising the major components of 390LRfab, 05/02/2018	Mass architecture of 390LRfab, kg/1000 kg 390LRfab	Process energy, MJ/1000 kg 390LRfab						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
390LRfab, gtg	1,000	6.77	0	112	0	440	0	559
cradle-to-gate data								
220PETknitfab, ctg	567	2.30E+04	5,813	2.71E+04	7,882	2,578	-9,930	5.65E+04
110PETknitfab, ctg	284	1.27E+04	2,907	1.36E+04	3,941	1,289	-4,965	2.95E+04
LR ePTFE fabric, ctg	79.9	714	92.7	1,686	1,442	358	-1,214	3,078
polyurethane, ctg	69.6	676	23.6	1,299	942	207	-646	2,501
Total mass of ctg inputs	1000							
Total mass of product, kg	1,000							

Total ctgs	3.71E+04	8,836	4.37E+04	1.42E+04	4,432	-1.68E+04	9.16E+04
Total gtgs	6.77	0	112	0	440	0	559
Total Process Energy, MJ/1000 kg 390LRfab	3.71E+04	8,836	4.38E+04	1.42E+04	4,872	-1.68E+04	9.21E+04

Modules comprising the major components of 390LRfab, 05/02/2018	Mass architecture of 390LRfab, kg/1000 kg 390LRfab	Natural Resource energy (nre*), MJ/1000 kg 390LRfab						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
390LRfab, gtg	1,000	21.7	0	162	0	528	0	711
cradle-to-gate data								
220PETknitfab, ctg	567	7.36E+04	8,357	3.90E+04	9,064	3,094	-1.43E+04	1.19E+05
110PETknitfab, ctg	284	4.08E+04	4,178	1.95E+04	4,532	1,547	-7,137	6.34E+04
LR ePTFE fabric, ctg	79.9	2,284	133	2,424	1,658	429	-1,745	5,184
polyurethane, ctg	69.6	2,163	33.9	1,867	1,083	248	-929	4,467
Total mass of ctg inputs	1000							
Total mass of product	1,000							

Total ctgs	1.19E+05	1.27E+04	6.28E+04	1.63E+04	5,318	-2.41E+04	1.92E+05
Total gtgs	21.7	0	162	0	528	0	711
Total Natural Resource Energy, MJ/1000 kg 390LRfab	1.19E+05	1.27E+04	6.30E+04	1.63E+04	5,846	-2.41E+04	1.93E+05

Table 2.5 Summary of cradle-to-gate life cycle inventory for 1,000 kg liquid resistant polyurethane fabric (230 gsm)

Modules comprising the major components of 420 LR PU fab, 05/03/2018	Mass architecture of 420 LR PU fab, kg/1000 kg 420 LR PU fab	Process energy, MJ/1000 kg 420 LR PU fab						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
420 LR PU fab, gtg	1,000	28.5	0	105	0	440	0	574
cradle-to-gate data								
220PETknitfab, ctg	524	2.12E+04	5,370	2.51E+04	7,281	2,382	-9,173	5.22E+04
110PETknitfab, ctg	262	1.18E+04	2,685	1.25E+04	3,641	1,191	-4,587	2.72E+04
PU barrier membrane, ctg	148	1,209	172	3,303	2,907	445	-2,770	5,266
polyurethane, ctg	66.7	648	22.6	1,244	902	198	-619	2,396
Total mass of ctg inputs	1,000							
Total mass of product, kg	1,000							
	Total ctgs	3.49E+04	8,250	4.22E+04	1.47E+04	4,215	-1.71E+04	8.71E+04
	Total gtgs	28.5	0	105	0	440	0	574
	Total Process Energy, MJ/1000 kg 420 LR PU fab	3.49E+04	8,250	4.23E+04	1.47E+04	4,655	-1.71E+04	8.77E+04

Modules comprising the major components of 420 LR PU fab, 05/03/2018	Mass architecture of 420 LR PU fab, kg/1000 kg 420 LR PU fab	Natural Resource energy (nre*), MJ/1000 kg 420 LR PU fab						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
420 LR PU fab, gtg	1,000	91.2	0	151	0	528	0	770
cradle-to-gate data								
220PETknitfab, ctg	524	6.80E+04	7,720	3.61E+04	8,373	2,858	-1.32E+04	1.10E+05
110PETknitfab, ctg	262	3.77E+04	3,860	1.80E+04	4,187	1,429	-6,593	5.86E+04
PU barrier membrane, ctg	148	3,868	248	4,748	3,343	534	-3,981	8,759
polyurethane, ctg	66.7	2,073	32.5	1,789	1,038	237	-890	4,279
Total mass of ctg inputs	1,000							
Total mass of product	1,000							
	Total ctgs	1.12E+05	1.19E+04	6.06E+04	1.69E+04	5,059	-2.47E+04	1.81E+05
	Total gtgs	91.2	0	151	0	528	0	770
	Total Natural Resource Energy, MJ/1000 kg 420 LR PU fab	1.12E+05	1.19E+04	6.08E+04	1.69E+04	5,587	-2.47E+04	1.82E+05

Table 2.6 Mass balance and NRE for ePTFE film and PU breathable barrier membrane, 1,000 kg basis

	Mass, kg/1,000 kg		NRE, MJ/1,000 kg	
	ePTFE film	PU membrane	ePTFE film	PU membrane
Barrier assembly	--	--	987	2,341
PTFE	606	0	38,940	0
Polyether polyol	308	450	21,438	31,285
Polymeric MDI	78.3	450	3,154	18,139
1,4-butanediol	7.04	100	360	5,112
Dimethylformamide (solvent)	0	92.1	0	2,457
Total	1,000	1,092	64,879	59,334

Table 2.7 Material requirements and NRE for ePTFE film and PU breathable barrier membrane, 1 m^2 basis

	Mass, g/m^2		NRE, kJ/m^2	
	ePTFE film	PU membrane	ePTFE film	PU membrane
Tri-laminate assembly	--	--	10.4	49.2
PTFE	6.37	0	409	0
Polyether polyol	3.24	9.46	225	657
Polymeric MDI	0.823	9.46	33.1	381
1,4-butanediol	0.0740	2.10	3.78	107
Dimethylformamide (solvent)	0	1.94	0	51.6
Total	10.5	23.0	681	1,246

The reusable surgical top drape is thus a combination of critical zone and non-critical zone fabrics. The cradle-to-gate LCIs of these fabrics have been previously described. Reusable surgical drapes are laundered, sterilized, and returned for use, so the functional unit of 1,000 drape uses must incorporate these cycles. The field data indicated that 60 cycles was representative of surgical drapes, Chapter 1. At 60 cycles, 1,000 reusable surgical drape uses is 16.7 drapes used 60 times. Table 2.8 and Table 2.9 provide the cradle-to-gate results for 1,000 uses of each of the two reusable top drapes studied (manufacture and delivery to laundry only). The drape manufacturing (transportation, cut, sew, and trim plant) is the GTG row at the top of each Table, followed by the CTGs of the various fabrics and adhesives used in each drape. Note that the final results of the study incorporated the market share of each of the drapes for a total basis of 1,000 uses (50% ePTFE, 50% PU).

In Figure 2.2 and Figure 2.3, the fabric life cycle inventory energy intensities are portrayed graphically, MJ/1,000 kg of each material. In the comparison, the liquid resistant ePTFE and PU barriers and the polyurethane adhesive are about half as energy intensive as the woven and knit PET fabrics. Figure 2.4 and Figure 2.5 show the total cradle-to-gate LCI energy for each reusable drape manufacture, accounting for the amount of each material used. In this case, the energy required to manufacture the woven PET fabric is substantially larger than the energy requirements for the cut-and-trim operation, the knit PET fabric, the liquid resistant barriers, and the adhesive. The gtg for the cut-sew-trim operation includes transportation from manufacture of materials through cut-sew-trim and then to the laundry. Note that due to the small amount of liquid resistant barrier used relative to the drape weight, the LCIs for the ePTFE and PU drapes are very similar. From the Figures, it is clear that the cradle-to-gate energy required to manufacture and deliver reusable surgical drapes is the most influenced by the woven PET fabric supply chain. On a 1,000 drape uses basis, the overall process energy and natural resource energy requirements for the cradle-to-gate manufacture and delivery of reusable surgical drapes (MJ/1,000 uses reusable drape) were 1,124 and 2,301 respectively. These energies were calculated from the values given in Table 2.8 and Table 2.9 and the relative market share of each drape.

Table 2.8 Summary of cradle-to-gate life cycle inventory for 1,000 reusable surgical drape uses, drape manufacture and delivery, ePTFE drape

Modules comprising the major components of surg drape reuse ePTFE, 07/11/2018	Mass architecture of surg drape reuse ePTFE, kg/1000 uses	Process energy, MJ/1000 uses						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse ePTFE, gtg	9.60	2.46	0	0	0	43.6	0	46.0
390LRfab, gtg	2.37	0.0160	0	0.266	0	1.04	0	1.32
cradle-to-gate data								
340PETwvnfab, ctg	7.52	337	77.2	440	107	35.6	-132	864
220PETknitfab, ctg	1.34	54.5	13.8	64.3	18.7	6.11	-23.5	134
110PETknitfab, ctg	0.672	30.2	6.89	32.2	9.34	3.05	-11.8	69.8
LR ePTFE fabric, ctg	0.189	1.69	0.220	3.99	3.42	0.847	-2.88	7.29
polyurethane, ctg	0.165	1.60	0.0559	3.08	2.23	0.489	-1.53	5.92
Total mass of ctg inputs	9.89							
Total mass of product, kg	9.60							
	Total ctgs	424	98.2	543	141	46.1	-172	1,081
	Total gtgs	2.48	0	0.266	0	44.6	0	47.4
	Total Process Energy, MJ/1000 kg surg drape reuse ePTFE	427	98.2	543	141	90.7	-172	1,129

Modules comprising the major components of surg drape reuse ePTFE, 07/11/2018	Mass architecture of surg drape reuse ePTFE, kg/1000 uses	Natural Resource energy (nre*), MJ/1000 uses						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse ePTFE, gtg	9.60	7.87	0	0	0	52.3	0	60.2
390LRfab, gtg	2.37	0.0513	0	0.383	0	1.25	0	1.68
cradle-to-gate data								
340PETwvnfab, ctg	7.52	1,077	111	632	124	42.7	-190	1,796
220PETknitfab, ctg	1.34	174	19.8	92.4	21.5	7.33	-33.8	282
110PETknitfab, ctg	0.672	96.6	9.90	46.2	10.7	3.66	-16.9	150
LR ePTFE fabric, ctg	0.189	5.41	0.316	5.74	3.93	1.02	-4.13	12.3
polyurethane, ctg	0.165	5.13	0.0804	4.42	2.57	0.587	-2.20	10.6
Total mass of ctg inputs	9.89							
Total mass of product	9.60							
	Total ctgs	1,358	141	781	162	55.3	-247	2,251
	Total gtgs	7.92	0	0.383	0	53.5	0	61.8
	Total Natural Resource Energy, MJ/1000 kg surg drape reuse ePTFE	1,366	141	781	162	109	-247	2,313

Table 2.9 Summary of cradle-to-gate life cycle inventory for 1,000 reusable surgical drape uses, drape manufacture and delivery, PU drape

Modules comprising the major components of surg drape reuse PU, 07/11/2018	Mass architecture of surg drape reuse PU, kg/1000 uses	Process energy, MJ/1000 uses						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse PU, gtg	9.60	2.46	0	0	0	43.6	0	46.0
420 LR PU fab, gtg	2.37	0.0675	0	0.249	0	1.04	0	1.36
cradle-to-gate data								
340PETwvnfab, ctg	7.52	337	77.2	440	107	35.6	-132	864
220PETknitfab, ctg	1.24	50.3	12.7	59.4	17.2	5.64	-21.7	124
110PETknitfab, ctg	0.620	27.9	6.36	29.7	8.62	2.82	-10.9	64.5
PU barrier membrane, ctg	0.350	2.86	0.408	7.82	6.89	1.05	-6.56	12.5
polyurethane, ctg	0.158	1.53	0.0536	2.95	2.14	0.469	-1.47	5.68
Total mass of ctg inputs	9.89							
Total mass of product, kg	9.60							
	Total ctgs	419	96.8	539	142	45.6	-173	1,071
	Total gtgs	2.53	0	0.249	0	44.6	0	47.4
	Total Process Energy, MJ/1000 kg surg drape reuse PU	422	96.8	540	142	90.2	-173	1,118

Modules comprising the major components of surg drape reuse PU, 07/11/2018	Mass architecture of surg drape reuse PU, kg/1000 uses	Natural Resource energy (nre*), MJ/1000 uses						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse PU, gtg	9.60	7.87	0	0	0	52.3	0	60.2
420 LR PU fab, gtg	2.37	0.216	0	0.358	0	1.25	0	1.83
cradle-to-gate data								
340PETwvnfab, ctg	7.52	1,077	111	632	124	42.7	-190	1,796
220PETknitfab, ctg	1.24	161	18.3	85.4	19.8	6.77	-31.2	260
110PETknitfab, ctg	0.620	89.2	9.14	42.7	9.92	3.39	-15.6	139
PU barrier membrane, ctg	0.350	9.16	0.587	11.2	7.92	1.26	-9.43	20.7
polyurethane, ctg	0.158	4.91	0.0770	4.24	2.46	0.562	-2.11	10.1
Total mass of ctg inputs	9.89							
Total mass of product	9.60							
	Total ctgs	1,341	139	775	164	54.7	-248	2,226
	Total gtgs	8.09	0	0.358	0	53.5	0	62.0
	Total Natural Resource Energy, MJ/1000 kg surg drape reuse PU	1,349	139	776	164	108	-248	2,288

Figure 2.2 Cradle-to-gate process energy and natural resource energy per 1,000 kg of each major constituent of reusable surgical top drapes, ePTFE drape

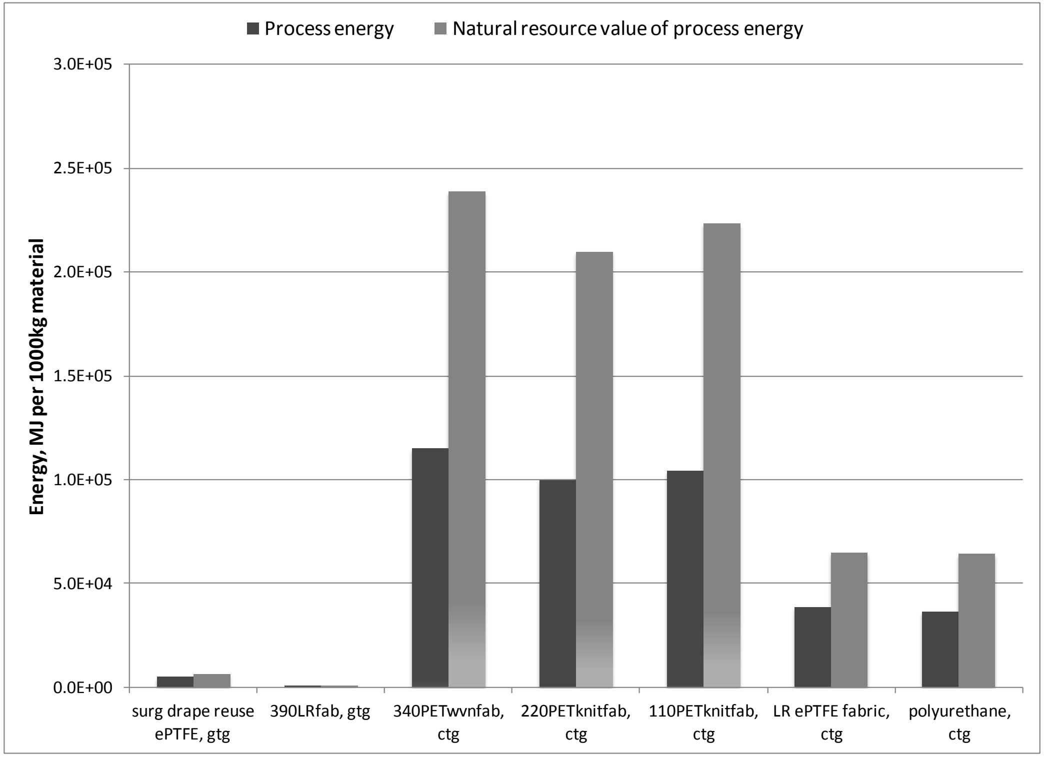


Figure 2.3 Cradle-to-gate process energy and natural resource energy per 1,000 kg of each major constituent of reusable surgical top drapes, PU drape

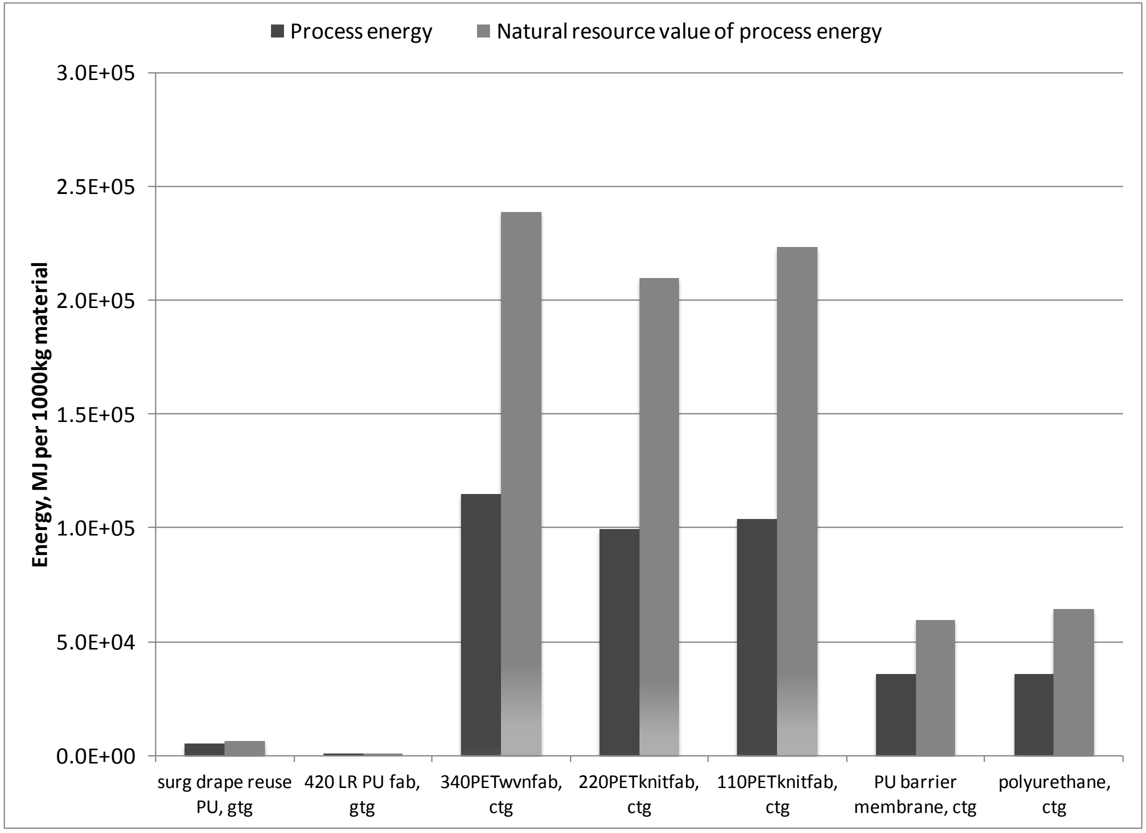


Figure 2.4 Cradle-to-gate process energy (total = 1,129 MJ) and natural resource energy (total = 2,313 MJ) per 1,000 reusable surgical drape uses, drape manufacturing, ePTFE drape

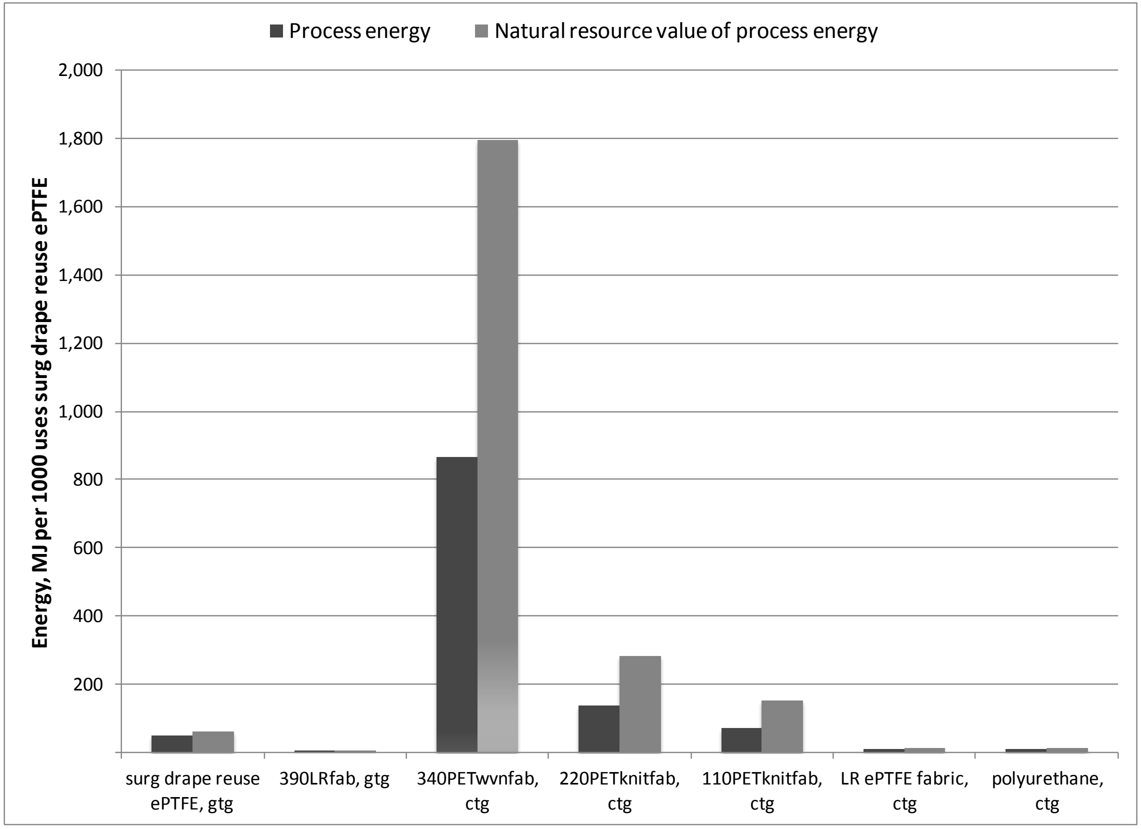
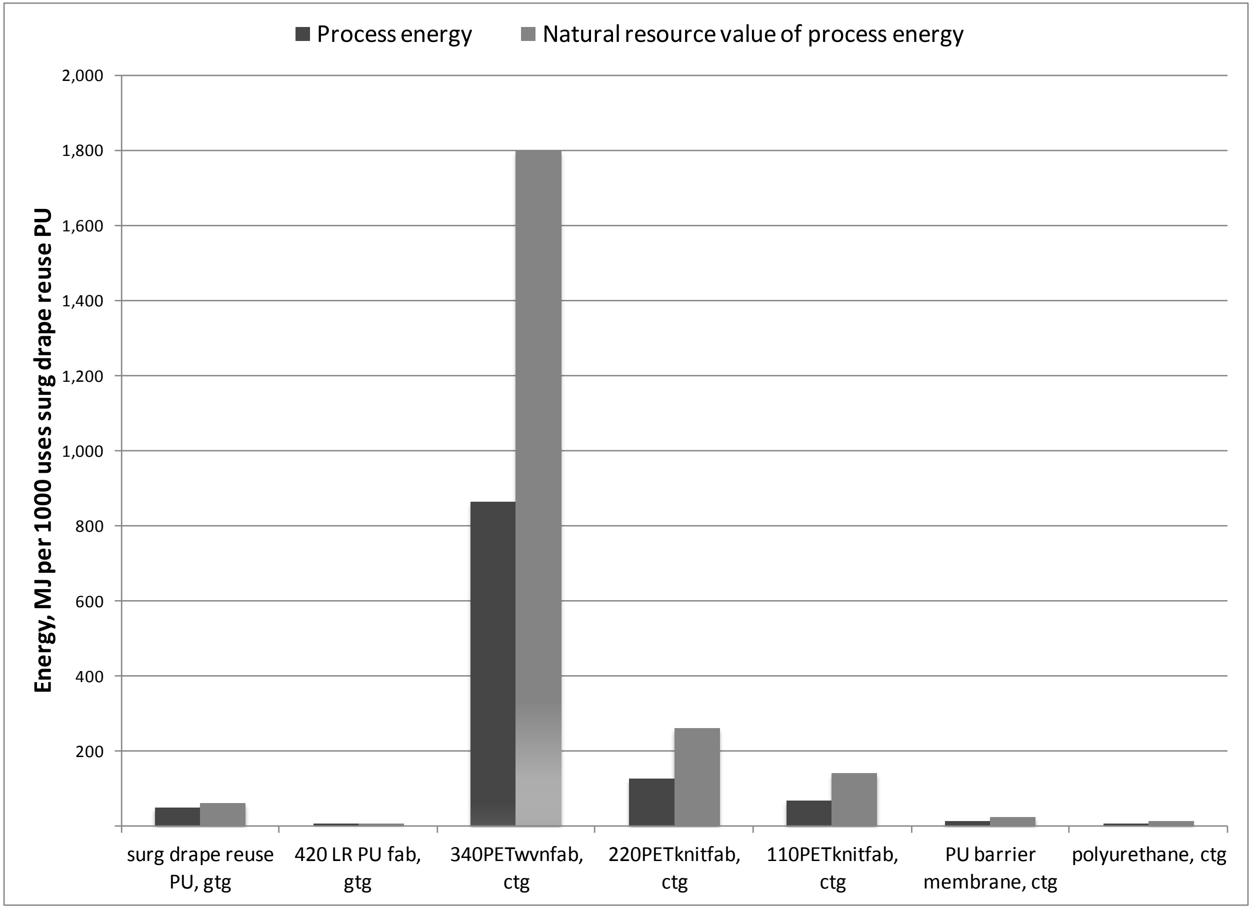


Figure 2.5 Cradle-to-gate process energy (total = 1,118 MJ) and natural resource energy (total = 2,288 MJ) per 1,000 reusable surgical drape uses, drape manufacturing, PU drape



Disposable Surgical Drapes

In a parallel fashion, the critical and non-critical zone fabrics in the single use (disposable) surgical top drapes were evaluated with respect to life cycle inventories. Most of these drapes involve a single nonwoven fabric and for the critical zones barrier films are added, Table 2.1. Similarly, the non-critical areas are various nonwoven fabrics. In general the disposable drapes are a nonwoven SMS PP fabric with barrier PP or PU films added to the critical zones for greater protection. In this report, the critical zone was material was evaluated as PP fabric. A sensitivity analysis showed that the selection between PP and PU barriers had a negligible impact on the environmental impacts and indicators studied.

The cradle-to-gate LCI of 1,000 kg SMS PP fabric is shown in Table 2.10. The top row is the nonwoven fabric plant. Following are the cradle-to-gate LCIs for PP fibers and b-copper phthalocyanine (a blue pigment), thus completing the supply chain back to natural resources from earth. The process energy and natural resource energy for SMS PP fabric (MJ/1,000 kg SMS PP fabric) were 30,500 and 54,000, respectively.

The cradle-to-gate LCI of 1,000 kg PP barrier film is shown in Table 2.11. The top row is the polypropylene film plant. Following is the cradle-to-gate LCI for polypropylene pellets, completing the supply chain back to natural resources from earth. The process energy and natural resource energy for PP barrier film (MJ/1,000 kg PP film) were 25,300 and 51,500, respectively.

Table 2.10 Summary of cradle-to-gate life cycle inventory for 1,000 kg SMS PP fabric

Modules comprising the major components of PP SMS Fabric, 05/03/2018	Mass architecture of PP SMS Fabric, kg/1000 kg PP SMS Fabric	Process energy, MJ/1000 kg PP SMS Fabric						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
PP SMS Fabric, gtg	1,000	1,487	5,975	51.9	0	440	0	7,954
390LRfab, gtg	2.37	0.0160	0	0.266	0	1.04	0	1.32
cradle-to-gate data								
polypropylene fiber from pell, ctg	1,014	6,813	0	2,666	1.42E+04	1,798	-3,769	2.17E+04
b-Copper phthalocyanine, ctg	10.2	133	70.9	395	286	41.5	-227	698
110PETknitfab, ctg	0.672	30.2	6.89	32.2	9.34	3.05	-11.8	69.8
LR ePTFE fabric, ctg	0.189	1.69	0.220	3.99	3.42	0.847	-2.88	7.29
polyurethane, ctg	0.165	1.60	0.0559	3.08	2.23	0.489	-1.53	5.92
Total mass of ctg inputs	1,025							
Total mass of product, kg	1,000							
	Total ctgs	6,979	78.1	3,100	1.45E+04	1,844	-4,012	2.25E+04
	Total gtgs	1,487	5,975	52.2	0	441	0	7,955
	Total Process Energy, MJ/1000 kg PP SMS Fabric	8,466	6,053	3,152	1.45E+04	2,285	-4,012	3.05E+04

Modules comprising the major components of PP SMS Fabric, 05/03/2018	Mass architecture of PP SMS Fabric, kg/1000 kg PP SMS Fabric	Natural Resource energy (nre*), MJ/1000 kg PP SMS Fabric						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
PP SMS Fabric, gtg	1,000	4,759	8,588	74.6	0	528	0	1.40E+04
390LRfab, gtg	2.37	0.0513	0	0.383	0	1.25	0	1.68
cradle-to-gate data								
polypropylene fiber from pell, ctg	1,014	2.18E+04	0	3,833	1.63E+04	2,158	-5,418	3.87E+04
b-Copper phthalocyanine, ctg	10.2	424	102	567	328	49.8	-327	1,145
110PETknitfab, ctg	0.672	96.6	9.90	46.2	10.7	3.66	-16.9	150
LR ePTFE fabric, ctg	0.189	5.41	0.316	5.74	3.93	1.02	-4.13	12.3
polyurethane, ctg	0.165	5.13	0.0804	4.42	2.57	0.587	-2.20	10.6
Total mass of ctg inputs	1,025							
Total mass of product	1,000							
	Total ctgs	2.23E+04	112	4,456	1.67E+04	2,213	-5,768	4.00E+04
	Total gtgs	4,759	8,588	75.0	0	529	0	1.40E+04
	Total Natural Resource Energy, MJ/1000 kg PP SMS Fabric	2.71E+04	8,701	4,531	1.67E+04	2,742	-5,768	5.40E+04

Table 2.11 Summary of cradle-to-gate life cycle inventory for 1,000 kg PP barrier film

Modules comprising the major components of PP52micron, 05/03/2018	Mass architecture of PP52micron, kg/1000 kg PP52micron	Process energy, MJ/1000 kg PP52micron						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
PP52micron, gtg	1,000	913	0	0	0	440	0	1,353
cradle-to-gate data								
polypropylene fiber from prop, ctg	1000	1.01E+04	0	2,629	1.40E+04	894	-3,640	2.40E+04
Total mass of ctg inputs	1000							
Total mass of product, kg	1,000							
	Total ctgs	1.01E+04	0	2,629	1.40E+04	894	-3,640	2.40E+04
	Total gtgs	913	0	0	0	440	0	1,353
	Total Process Energy, MJ/1000 kg PP52micron	1.10E+04	0	2,629	1.40E+04	1,334	-3,640	2.53E+04

Modules comprising the major components of PP52micron, 05/03/2018	Mass architecture of PP52micron, kg/1000 kg PP52micron	Natural Resource energy (nre*), MJ/1000 kg PP52micron						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
PP52micron, gtg	1,000	2,920	0	0	0	528	0	3,448
cradle-to-gate data								
polypropylene fiber from prop, ctg	1000	3.23E+04	0	3,780	1.61E+04	1,072	-5,233	4.80E+04
Total mass of ctg inputs	1000							
Total mass of product	1,000							
	Total ctgs	3.23E+04	0	3,780	1.61E+04	1,072	-5,233	4.80E+04
	Total gtgs	2,920	0	0	0	528	0	3,448
	Total Natural Resource Energy, MJ/1000 kg PP52micron	3.52E+04	0	3,780	1.61E+04	1,600	-5,233	5.15E+04

The single use surgical top drape is prepared in a cut, sew, and trim plant by heat bonding the PP barrier film to the SMS PP nonwoven fabric, Table 2.12. The architecture mass of these fabrics is given for 1,000 drapes, Table 2.12. The disposable drape manufacturing (cut, sew, and trim plant) is the GTG row at the top of the Table. The CTG of the SMS PP fabric and PP film are listed separately.

Table 2.12 Summary of cradle-to-gate life cycle inventory for 1,000 disposable surgical drape uses, drape manufacture and delivery

Modules comprising the major components of surg drape disp PP, 07/11/2018	Mass architecture of surg drape disp PP, kg/1000 kg surg drape disp PP	Process energy, MJ/1000 uses surg drape disp PP						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape disp PP, gtg	245	138	0	0	0	1,925	0	2,063
cradle-to-gate data								
PP SMS Fabric, ctg	228	1,926	1,381	711	3,311	521	-913	6,937
PP52micron, ctg	23.7	261	0	62.2	332	31.6	-86.1	600
	252							
	245							
	Total ctgs	2,187	1,381	773	3,643	552	-999	7,536
	Total gtgs	138	0	0	0	1,925	0	2,063
	Total Process Energy, MJ/1000 kg surg drape disp PP	2,324	1,381	773	3,643	2,478	-999	9,600

Modules comprising the major components of surg drape disp PP, 07/11/2018	Mass architecture of surg drape disp PP, kg/1000 kg surg drape disp PP	Natural Resource energy (nre*), MJ/1000 uses surg drape disp PP						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape disp PP, gtg	245	441	0	0	0	2,311	0	2,751
cradle-to-gate data								
PP SMS Fabric, ctg	228	6,163	1,985	1,022	3,808	625	-1,312	1.23E+04
PP52micron, ctg	23.7	834	0	89.4	381	37.9	-124	1,219
* See Tables below for assumptions for	252							
	245							
	Total ctgs	6,997	1,985	1,111	4,189	663	-1,436	1.35E+04
	Total gtgs	441	0	0	0	2,311	0	2,751
	Total Natural Resource Energy, MJ/1000 kg surg drape disp PP	7,438	1,985	1,111	4,189	2,973	-1,436	1.63E+04

In Figure 2.6, these separate fabrics or films are shown on an energy intensity basis, MJ/1,000 kg of material. Figure 2.7 shows the total cradle-to-gate LCI energy for the disposable drape manufacture, accounting for the amount of each material used per 1000 uses. From Figure 2.7, it is clear that the cradle-to-gate energy required to manufacture and deliver disposable surgical drapes is the most influenced by the SMS PP fabric supply chain. Additionally, from Table 2.12, over 90% of the process energy associated with the cut-and-trim gate-to-gate operation is due to transport of the fabrics and drapes. Transport is discussed in further detail in Chapter 8.

Figure 2.6 Cradle-to-gate process energy and natural resource energy per 1,000 kg of each major constituent of disposable surgical drapes

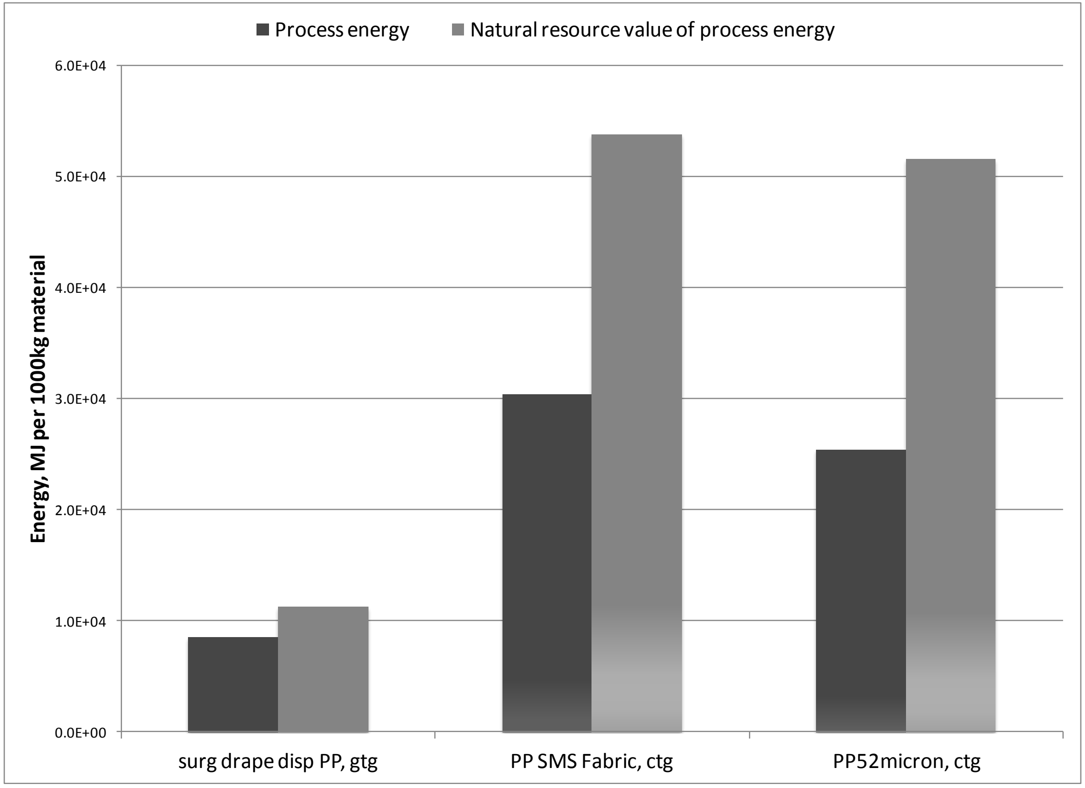
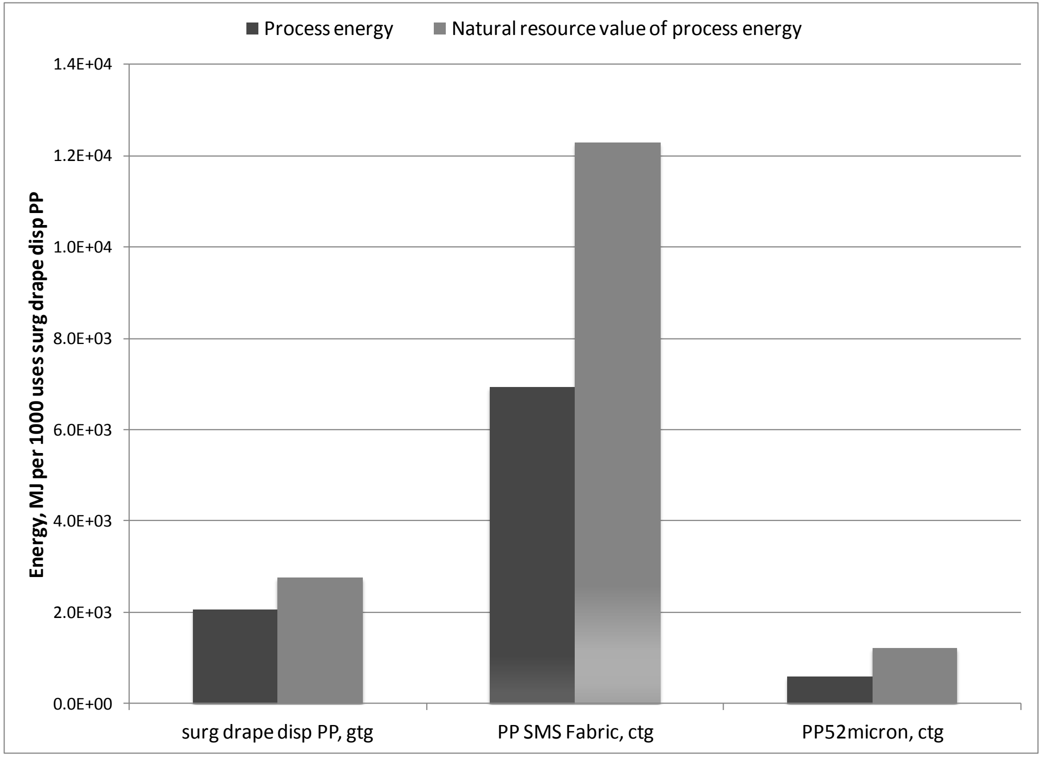


Figure 2.7 Cradle-to-gate process energy (total = 9,600 MJ) and natural resource energy (total = 16,260 MJ) per 1,000 disposable surgical drape uses, drape manufacturing



Summary

The drape manufacture and delivery CTG (including fabric supply chain) was the single most energy intensive process for disposable surgical drapes, accounting for 86% of the cradle-to-end-of-life (CTEOL) net NRE, Table 2.13. For reusable drapes, the drape manufacture and delivery CTG accounted for only 20% of the CTEOL net NRE, as the laundry and sterilization processes accounted for about 54% of the net NRE, Table 2.13 and Table 6.11. Thus, improvements in drape and fabric supply chain manufacturing efficiency would lead to a greater energy benefit for disposable drapes over reusable drapes. For example, a 10% energy reduction for the drape manufacturing, supply chain manufacturing, and delivery processes would lead to a 9% CTEOL energy reduction for disposable drapes, but only a 3% reduction for reusable drapes.

Note that reusable surgical drapes weighed about twice as much as disposable surgical drapes. On a per drape basis, the manufacture and delivery of a single reusable drape consumed about 9 times more energy than a single disposable drape. However, on a 1,000 uses basis, the reusable drapes were about 86% less energy intensive than the disposable drapes, because only one reusable drape was manufactured for every 60 disposable drapes manufactured.

Table 2.13 is a comparison of the natural resource energy (NRE) for the drape and supply chain manufacture and delivery of reusable and disposable surgical drapes.

Table 2.13 Summary of NRE for surgical drape manufacture and delivery (including complete supply chain), reusable and disposable

	NRE	
	MJ/1,000 drape uses	% of CTEOL NRE
Reusable surgical drape system	2,301	20%
Disposable surgical drape system	16,260	87%

Chapter 3 DRAPE PACKAGING MANUFACTURING CRADLE-TO-GATE

Background

Reusable and disposable surgical drapes require packaging to deliver to health care facilities. This packaging is subdivided into:

1. Primary packaging – The bags, wraps, and labels that allow a surgical drape to be opened in sterile conditions and handled according to accepted surgical practices. Such surgeries range from out-patient surgeries to low invasive laparoscopic surgeries to eight-plus hour surgeries. Regardless of the type of surgery, the representative packaging is generally:
   a. A disposable polymeric and/or paper bag that maintains sterile conditions
   b. A paper label with manufacturing and other information, which is normally disposable.
2. Secondary packaging – The bags and containers used to ship and handle the drapes that already have primary packaging. The representative secondary packaging includes:
   a. A cardboard box used to contain the primary-wrapped drapes.
   b. An aluminum cart used to transport reusable drapes to and from the laundry process. The cart was assumed to be reused infinite times. The life cycle results were not sensitive to the number of times the cart is reused. Therefore, a different reuse rate would not have a significant impact on the results of the study.
3. Tertiary packaging – The pallets and plastic wrap used to transport multiple drapes that already have primary and secondary packaging. The representative tertiary packaging for new drapes included wood pallets and linear low density polyethylene (LLDPE) shrink wrap. Wood pallets were considered to be recycled. Thus, manufacturing of the pallets was not considered. However, the energy required to transport the pallets was considered. The representative tertiary packaging for reused drapes included a high density polyethylene (HDPE) cover placed on the aluminum cart.

Primary, secondary and tertiary (PST) packaging for disposable and reusable surgical drapes consists of a series of basic materials formed into bags, wraps, containers, and inserts. In this life cycle study, these containers and inserts were measured from practice. The representative PST packaging materials for a single surgical top drape are given in Table 3.1.

It is recognized that variations in packaging materials occur across the broad range of supply companies. The packaging materials analyzed herein are generally representative and thus allow an understanding of the life cycle issues of surgical drape packaging. Each of the materials in Table 3.1 was evaluated with a cradle-to-gate (CTG) life cycle inventory (LCI) from natural resources (oil or trees) to final material and expressed first on a per kg of final material basis.

Table 3.1 Packaging description for a surgical top drape from manufacturer or converter to drape supply firm

Drape system	**Packaging system**	**Packaging use**	**Packaging material**
Disposable	Primary	Bag for maintaining sterile conditions	HDPE and paper
	Secondary	Shipping box	Boxboard which is recycled after use
	Tertiary	Protective wrap	LLDPE
		Pallet	Wood which is recycled before and after use
Reusable, new	Primary	Bag for maintaining sterile conditions	HDPE and paper
	Secondary	Shipping box	Boxboard which is recycled after use
	Tertiary	Protective wrap	LLDPE
		Pallet	Wood which is recycled before and after use
Reusable, reused	Primary	Bag for maintaining sterile conditions	HDPE and paper
	Secondary	Shipping cart	Reusable aluminum tote
	Tertiary	Polymeric tote cover	HDPE cover

HDPE = high density polyethylene; LLDPE = linear low density polyethylene

Methodology

The LCI results for packaging manufacture and delivery are presented in two ways to allow better understanding and transparency:

1. On a uniform basis of 1,000 kg of the packaging material, MJ/1,000 kg.
2. On the basis of the amount used for 1,000 surgical drape uses.

In addition, the mass of packaging to landfill or incineration was analyzed and included in the life cycle study.

The PST packaging was analyzed for drapes as delivered to the health care facility. For disposable drapes, the packaging delivered is the same as the packaging applied by the drape manufacturer. For reusable drapes, the packaging applied by the drape manufacturer is different than the packaging applied by the laundry operator, Table 3.1.

Surgical top drapes are often sent to a health care facility as part of a surgical pack. The pack includes additional items used in surgical procedures such as gowns, towels, covers, and bowls. The scope of this study only included surgical drapes and tapes. Thus, the drapes were examined as the only item in the pack. Packaging for surgical tapes is examined in Chapter 5.

Results

Reusable Surgical Drapes

The mass of PST packaging for new reusable surgical top drapes is given in Table 3.2 on a kg/ surgical top drape basis. New reusable surgical drapes are individually wrapped in a plastic/paper bag. Multiple drapes are placed in a cardboard box. Multiple cardboard boxes are placed on a pallet and wrapped. Each pallet has a mass of 18 kg and holds 408 drapes. Therefore, the pallet mass transported per drape is 18,000/408 = 44.1 g/drape. The pallets were considered to be reused infinite times before disposal and thus required no manufacturing material or energy. The total PST packaging manufactured for each new reusable surgical drape was 58.5 g (103 g transported). This packaging was used to transport drapes to the laundry facility.

The mass of PST packaging for reused reusable drapes from the laundry facility is given in Table 3.3. Reused drapes are individually wrapped in a plastic/paper bag. The wrapped drapes are placed in a reusable aluminum cart which is covered with a plastic sheet. Each aluminum cart has a mass of 72 kg and holds 200 drapes. Therefore, the aluminum cart mass transported per drape is 72,000 g / 200 drapes = 360 g/drape. The carts were considered to be reused infinite times before disposal and thus required no manufacturing material or energy. The total PST packaging manufactured for each reused reusable surgical drape was 58.0 g (418 g transported).

Because new drapes were laundered and repackaged, the reused reusable drapes packaging and transport was also used for drapes on the first use. At a reuse rate of 60 cycles, each surgical drape is packaged one time by the manufacturer and 60 times at the laundry facility. The total mass of PST packaging manufactured for 1,000 reusable surgical drape uses is about 59.0 kg, (420 kg transported), Table 3.4. The mass in Table 3.4 is calculated by adding Table 3.2 times 16.7 new drapes / 1000 uses to Table 3.3. For example, a new reusable drape had 8.4 g primary packaging and each laundered reusable gown had 42.75 g packaging. Thus, on a per use basis, each reusable drape use required 8.4 * 16.7/1000 + 42.75 = 42.89 g primary packaging (Table 3.4). Assuming the boxboard is recycled, 58.1 kg PST packaging is likely to be landfilled or incinerated for 1,000 reusable surgical drape uses.

The cradle-to-gate LCIs for the manufacturing of the PST packaging for 1,000 reusable surgical drape uses are given in Table 3.5 and Table 3.6 for new and reused drapes, respectively. The total process energy and natural resource energy (MJ/1,000 drape uses) for the packaging of 1,000 reusable surgical drapes was 1,095 and 1,801, respectively.

Each packaging component requires energy to manufacture and in Figure 3.1 the full cradle-to-gate energy (MJ) per 1,000 kg of each of the materials used in PST packaging for reusable drapes is shown. For the PST packaging used for reusable surgical drapes, the Figure shows that corrugated boxboard has the lowest energy intensity and that HDPE, LDPE, and paper bags and sheets have similar energy intensities about twice that of the corrugated boxboard (MJ/1,000 kg material). Figure 3.2 shows that the HDPE outer bag was the most influential component on a MJ/1,000 drape uses basis.

Table 3.2 Packaging for new reusable surgical drapes, manufacture and transport

Packaging	Material	Description	Use Rate, drapes / item	Mass manufactured, g / drape	Mass transported, g / drape
Primary	HDPE bag	8.4 g bag	1 drape / bag	8.4	8.4
Secondary	Corrugated boxboard	0.6 kg box	12 drapes / box	50.0	50.0
Tertiary	LDPE sheet	2,304 sq. in. LDPE pallet wrap, 80 gauge	408 drapes / pallet	0.0686	0.0686
	Pallet (transport calculations only)	18 kg	408 drapes / pallet	0	44.1
Total				**58.5**	**103**

HDPE = high density polyethylene; LDPE = low density polyethylene

Table 3.3 Packaging for reused reusable surgical drapes, manufacture and transport

Packaging	Material	Description	Use Rate, drapes / item	Mass manufactured, g / drape	Mass transported, g / drape
Primary	HDPE bag	42.75 g wrap	1 drape / wrap	42.75	42.75
	Insert paper	14.25 g paper	1 drape / paper	14.25	14.25
Secondary	Reusable aluminum cart (transport calculations only)	72 kg cart	200 drapes / cart	0	360
Tertiary	HDPE cover	200 g cover	200 drapes / cover	1.00	1.00
Total				**58.0**	**418**

HDPE = high density polyethylene

Table 3.4 Packaging for new and reused reusable surgical drapes, weighted average, manufacture and transport

Packaging	**Material**	**Mass manufactured, g / drape**	**Mass transported, g / drape**
Primary	HDPE bag	42.89	42.89
	Insert paper	14.25	14.25
Secondary	Corrugated boxboard	0.8333	0.8333
	Reusable aluminum cart	0	360
Tertiary	LDPE sheet	0.0011433	0.0011433
	Pallet	0	0.735
	HDPE cover	1.00	1.00
Total		**59.0**	**420**

Table 3.5 Summary of cradle-to-gate life cycle inventory for packaging of 1,000 uses reusable surgical drapes, packaging for new drapes from manufacturer

Modules comprising the major components of surg drape reuse pack new, 05/03/2018	Mass architecture of surg drape reuse pack new, kg/1000 kg surg drape reuse pack new	Process energy, MJ/1000 kg surg drape reuse pack new						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse pack new, gtg	0.974	0	0	0	0	0	0	0
cradle-to-gate data								
corrugated box, ctg	0.833	0	0	0	8.25	0	0	8.25
outerbagHDPE, ctg	0.140	0.643	0	0.467	1.97	0.191	-0.577	2.69
LDPEsheet, ctg	1.14E-03	6.62E-03	0	2.93E-03	0.0161	1.53E-03	-5.79E-03	0.0213
Total mass of ctg inputs	0.974							
Total mass of product, kg	0.974							
	Total ctgs	0.650	0	0.469	10.2	0.192	-0.583	11.0
	Total gtgs	0	0	0	0	0	0	0
	Total Process Energy, MJ/1000 kg surg drape reuse pack new	0.650	0	0.469	10.2	0.192	-0.583	11.0

Modules comprising the major components of surg drape reuse pack new, 05/03/2018	Mass architecture of surg drape reuse pack new, kg/1000 kg surg drape reuse pack new	Natural Resource energy (nre*), MJ/1000 kg surg drape reuse pack new						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse pack new, gtg	0.974	0	0	0	0	0	0	0
cradle-to-gate data								
corrugated box, ctg	0.833	0	0	0	9.49	0	0	9.49
outerbagHDPE, ctg	0.140	2.06	0	0.671	2.26	0.229	-0.829	4.39
LDPEsheet, ctg	1.14E-03	0.0212	0	4.21E-03	0.0185	1.84E-03	-8.32E-03	0.0374
Total mass of ctg inputs	0.974							
Total mass of product	0.974							
	Total ctgs	2.08	0	0.675	11.8	0.231	-0.838	13.9
	Total gtgs	0	0	0	0	0	0	0
	Total Natural Resource Energy, MJ/1000 kg surg drape reuse pack new	2.08	0	0.675	11.8	0.231	-0.838	13.9

Table 3.6 Summary of cradle-to-gate life cycle inventory for packaging of 1,000 uses reusable surgical drapes, packaging for reused drapes from laundry

Modules comprising the major components of surg drape reuse pack reuse, 05/03/2018	Mass architecture of surg drape reuse pack reuse, kg/1000 kg surg drape reuse pack reuse	Process energy, MJ/1000 kg surg drape reuse pack reuse						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse pack reuse, gtg	58.0	0	0	0	0	0	0	0
cradle-to-gate data								
outerbagHDPE, ctg	43.7	201	0	146	615	59.7	-180	841
insertpaper, ctg	14.3	46.7	0	136	47.5	12.5	0	243
Total mass of ctg inputs	58.0							
Total mass of product, kg	58.0							

Total ctgs	248	0	282	662	72.2	-180	1,084
Total gtgs	0	0	0	0	0	0	0
Total Process Energy, MJ/1000 kg surg drape reuse pack reuse	248	0	282	662	72.2	-180	1,084

Modules comprising the major components of surg drape reuse pack reuse, 05/03/2018	Mass architecture of surg drape reuse pack reuse, kg/1000 kg surg drape reuse pack reuse	Natural Resource energy (nre*), MJ/1000 kg surg drape reuse pack reuse						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse pack reuse, gtg	58.0	0	0	0	0	0	0	0
cradle-to-gate data								
outerbagHDPE, ctg	43.7	643	0	210	707	71.6	-259	1,372
insertpaper, ctg	14.3	149	0	196	54.6	15.0	0	415
Total mass of ctg inputs	58.0							
Total mass of product	58.0							

Total ctgs	792	0	406	762	86.6	-259	1,787
Total gtgs	0	0	0	0	0	0	0
Total Natural Resource Energy, MJ/1000 kg surg drape reuse pack reuse	792	0	406	762	86.6	-259	1,787

Figure 3.1 Process energy and natural resource energy per 1,000 kg of each major constituent of packaging for reusable surgical drape

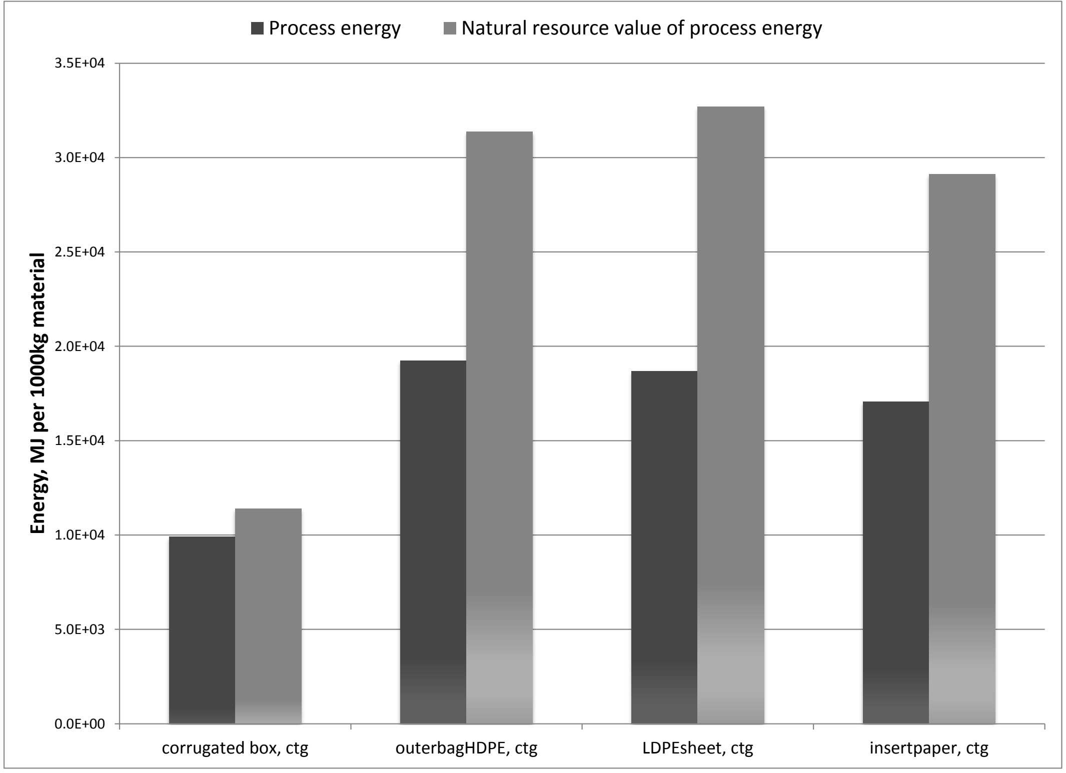
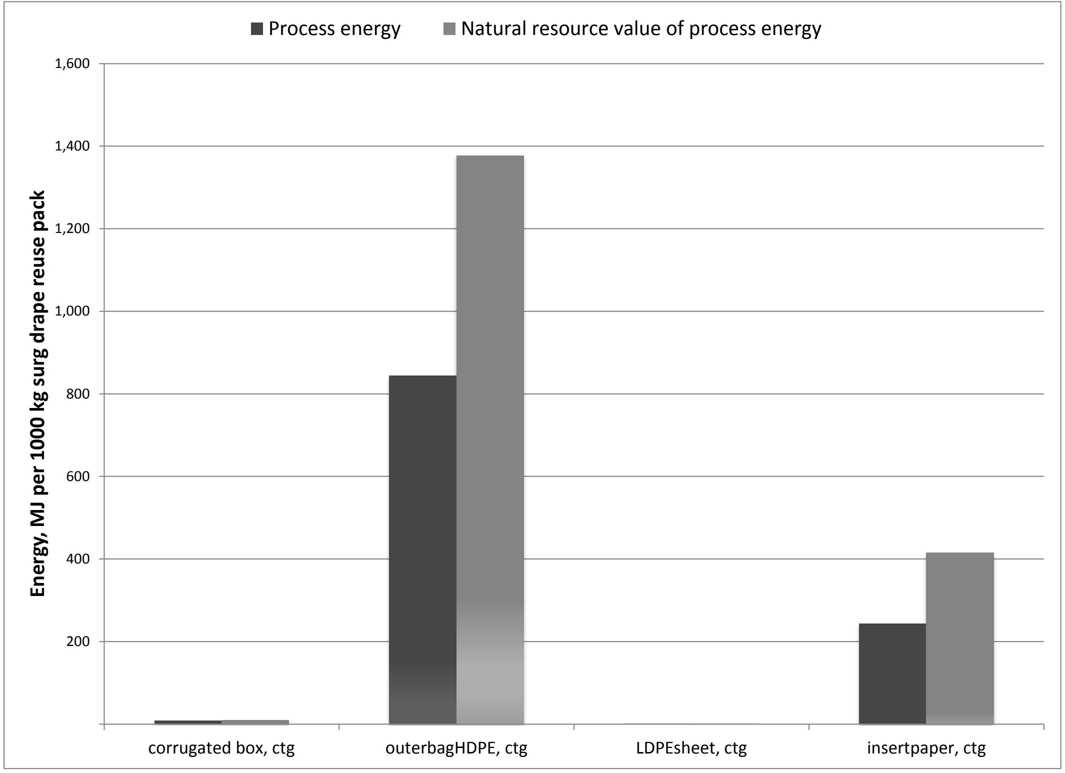


Figure 3.2 Process energy (total = 1,095 MJ/1,000 reusable surgical drape uses) and NRE (total = 1,801 MJ/1,000 reusable surgical drape uses) for packaging reusable surgical drapes



Disposable Surgical Drapes

The mass of PST packaging for new disposable drapes from the manufacturer is given in Table 3.7 on a g/drape basis. The drapes are individually wrapped in a plastic/paper bag. Multiple drapes are placed in a cardboard box. Multiple cardboard boxes are placed on a pallet and wrapped. Each pallet has a mass of 18 kg and holds 1,440 drapes. Therefore, the pallet mass transported per drape is 18,000/1,440 = 12.5 g/drape. The pallets were considered to be reused infinite times before disposal and thus required no manufacturing material or energy. The total PST packaging manufactured for each disposable surgical drape was 88.3 g (101 g transported). Assuming the boxboard is recycled, 57.0 kg PST packaging is likely to be landfilled or incinerated for 1,000 disposable surgical drape uses.

The 57.0 kg packaging likely to be landfilled per 1,000 uses disposable surgical top drapes was about 19 wt % of the total of packaging plus drape weight going to the landfill. If one estimates that the disposable drape accumulates the same weight of contaminants after surgery as the same reusable item (about 1.55 kg soiled drape/kg clean drape), then the packaging wt % going to the landfill can be calculated. Using these values, the disposable packaging for disposable surgical top drapes is about 13 wt % of the soiled drape plus packaging sent to landfill. The 10 wt % range is much lower than the 40-60% attributed to packaging from surgical gowns reported by Mittermayer, 2005. Since Mittermayer did not describe the data for the higher estimates, the reader should utilize the transparency in this report to evaluate the packaging landfill impacts.

The cradle-to-gate LCI for the manufacturing of the PST packaging for 1,000 disposable surgical drapes is given in Table 3.8. The total process energy and natural resource energy

(MJ/1,000 drape uses) for the packaging of 1,000 disposable surgical drapes were 1,375 and 2,112, respectively.

Each packaging component requires energy to manufacture and in Figure 3.3 the full cradle-to-gate energy (MJ) per 1,000 kg of each of the materials used in PST packaging for disposable drapes is shown. For the PST packaging used for disposable surgical drapes, Figure 3.3shows that corrugated boxboard had the lowest energy intensity and that HDPE, LDPE, and paper bags and sheets have similar energy intensities about twice that of the corrugated boxboard (MJ/1,000 kg material). Figure 3.4 shows that the HDPE outer bag was the most influential component on a MJ/1,000 drape uses basis.

Table 3.7 Packaging for disposable surgical drapes, manufacture and transport

Packaging	**Material**	**Description**	**Use Rate, drapes / item**	**Mass manufactured, g / drape**	**Mass transported, g / drape**
Primary	HDPE bag	42.75 g wrap	1 drape / wrap	42.8	42.8
	Insert paper	14.25 g paper	1 drape / paper	14.3	14.3
Secondary	Corrugated boxboard	1.0 kg box	32 drapes / box	31.3	31.3
Tertiary	LDPE sheet	2,304 sq. in. LDPE pallet wrap, 80 gauge	1,440 drapes / pallet	0.0194	0.0194
	Pallet (transport calculations only)	18 kg	1,440 drapes / pallet	0	12.5
Total				**88.3**	**101**

HDPE = high density polyethylene, LDPE = low density polyethylene

Table 3.8 Summary of cradle-to-gate life cycle inventory for packaging of 1,000 uses disposable surgical drapes, packaging for drapes from manufacturer

Modules comprising the major components of surg drape disp pack, 05/07/2018	Mass architecture of surg drape disp pack, kg/1000 kg surg drape disp pack	Process energy, MJ/1000 kg surg drape disp pack						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape disp pack, gtg	88.3	0	0	0	0	0	0	0
cradle-to-gate data								
outerbagHDPE, ctg	42.8	196	0	142	601	58.3	-176	822
corrugated box, ctg	31.3	0	0	0	309	0	0	309
insertpaper, ctg	14.3	46.7	0	136	47.5	12.5	0	243
LDPEsheet, ctg	0.0194	0.112	0	0.0497	0.272	0.0260	-0.0982	0.362
Total mass of ctg inputs	88.3							
Total mass of product, kg	88.3							

		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
	Total ctgs	243	0	279	958	70.9	-176	1,375
	Total gtgs	0	0	0	0	0	0	0
	Total Process Energy, MJ/1000 kg surg drape disp pack	243	0	279	958	70.9	-176	1,375

Modules comprising the major components of surg drape disp pack, 05/07/2018	Mass architecture of surg drape disp pack, kg/1000 kg surg drape disp pack	Natural Resource energy (nre*), MJ/1000 kg surg drape disp pack						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape disp pack, gtg	88.3	0	0	0	0	0	0	0
cradle-to-gate data								
outerbagHDPE, ctg	42.8	628	0	205	691	70.0	-253	1,341
corrugated box, ctg	31.3	0	0	0	356	0	0	356
insertpaper, ctg	14.3	149	0	196	54.6	15.0	0	415
LDPEsheet, ctg	0.0194	0.359	0	0.0715	0.313	0.0312	-0.141	0.634
Total mass of ctg inputs	88.3							
Total mass of product	88.3							

		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
	Total ctgs	778	0	401	1,102	85.0	-253	2,112
	Total gtgs	0	0	0	0	0	0	0
	Total Natural Resource Energy, MJ/1000 kg surg drape disp pack	778	0	401	1,102	85.0	-253	2,112

Figure 3.3 Process energy and natural resource energy per 1,000 kg of each major constituent of packaging for disposable surgical drapes

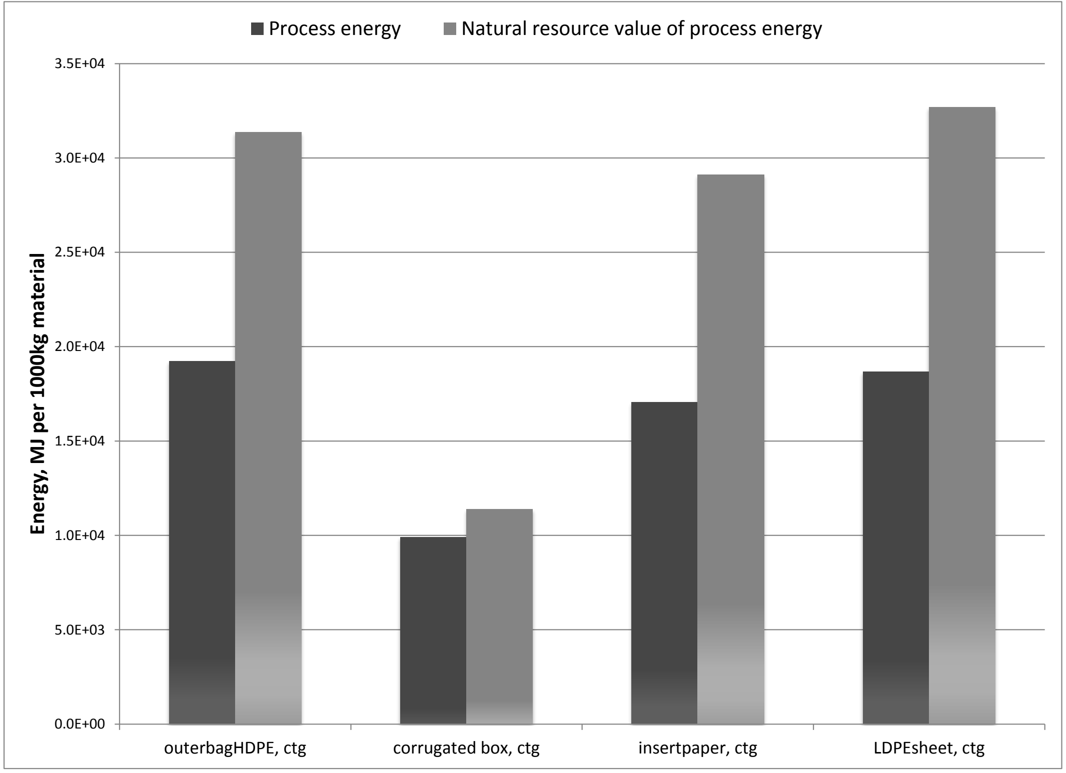
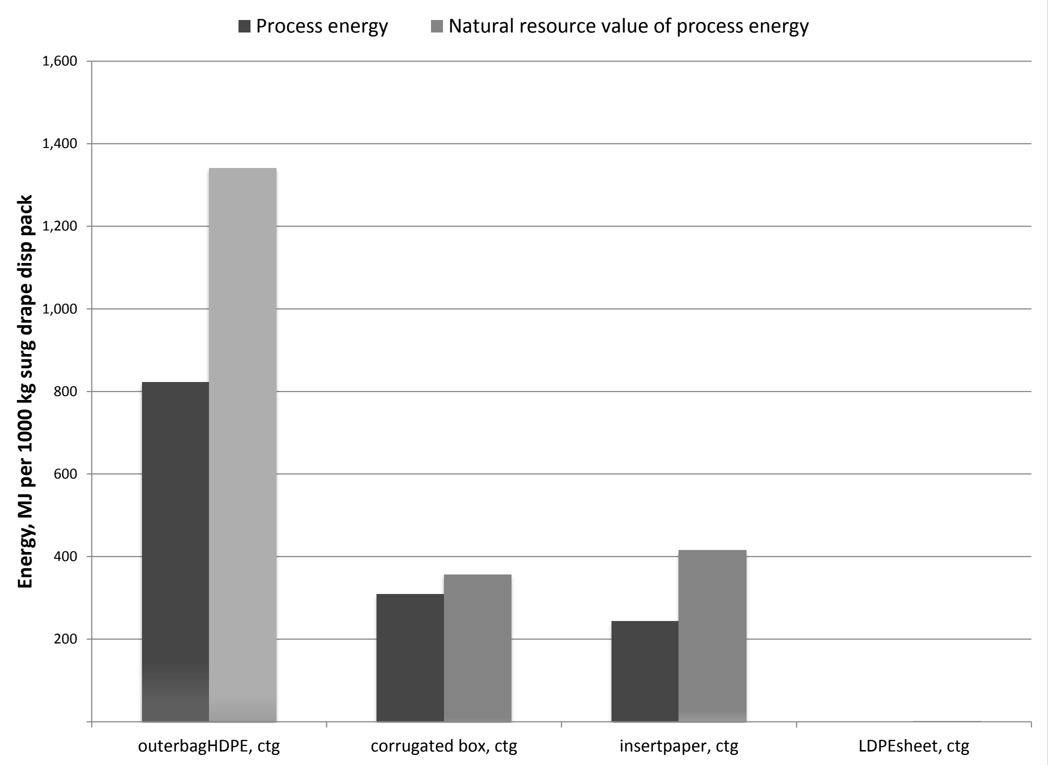


Figure 3.4 Process energy (total = 1,375 MJ/1,000 drape uses) and NRE (total = 2,112 MJ/1,000 drape uses) for packaging disposable surgical drapes



The transparency of the life cycle inventory results presented in the Tables and Figures in this Chapter can be used to seek improvements in surgical drape packaging. The relative differences and the influence of the materials with higher energy intensities are similar if the detailed analysis for improvement had been done for packaging of other health care garments, such as gloves, gowns, or towels.

Summary

Table 3.9 is a comparison of the natural resource energy (NRE) for packaging for reusable and disposable surgical drapes.

Table 3.9 Summary of NRE for packaging manufacturing, reusable and disposable surgical drapes

	NRE	
	MJ/1,000 drape uses	% of CTEOL NRE
Reusable surgical drape system	1,801	16%
Disposable surgical drape system	2,112	12%

References

1. Mittermayer H (2005) *Reusable surgical fabrics*, state of the art 2003, CliniCum, Special Issue, Sept. 11p., 2005.

Chapter 4 SURGICAL TAPE MANUFACTURING CRADLE-TO-GATE

Background

Double-sided medical-grade tapes are used to attach surgical drapes to patients in the operating room. A diagram of a typical surgical tape is shown in Figure 4.1. Pressure sensitive adhesives (PSAs) are coated on each side of a carrier fabric. The strip of carrier with adhesives is rolled around a core using a release liner. Multiple rolls are packaged and shipped in a box.

Figure 4.1 Diagram of double coated tape as used in surgical tapes

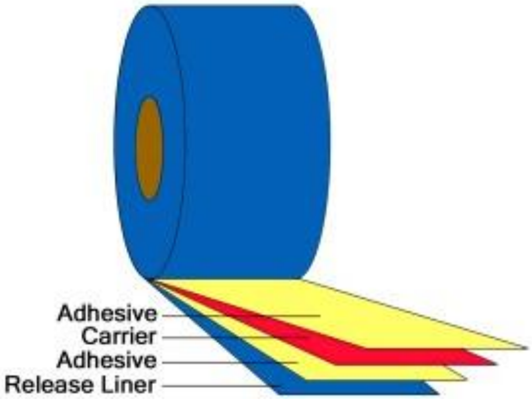


Image source: https://www.novafilmsusa.com/adhesives-101/pressure-sensitive-tape-guide

A wide variety of surgical tapes are available on the market. The typical materials used to manufacture surgical tapes are shown in Table 4.1. The objective of the life cycle study was to provide transparent life cycle information for medical-grade tapes used with surgical drapes.

Table 4.1 Materials commonly used to produce medical-grade surgical tapes

Tape component	Example materials
Skin side adhesive	Pressure sensitive adhesives: block copolymers of acrylics, urethanes, polyolefins, polyester, etc.
Drape side adhesive	
Carrier fabric	Paper or polyester (PET)
Release liner	Paper or plastic coated with a thin layer of silicone
Core	Paper or plastic
Packaging	Paper and/or plastic boxes, inserts, films, bags, etc.

Methodology

The LCI results for tapes and components are analyzed in two ways to allow better understanding and transparency:

1. On a uniform basis of 1,000 kg of the tape or material, MJ/1,000 kg.
2. On the basis of the amount used for one roll of tape.
3. On the basis of the amount of tape used with 1,000 uses of 4 m^2 surgical top drapes.

The results are discussed under separate sections below for tape used with reusable and disposable drapes. Note that sterilization of surgical tapes is covered in Chapter 6.

The surgical tape manufacturing cradle-to-gate analysis included the complete supply chain, from natural resources in earth to delivery of the tape to a distributor or hospital. This analysis included the tape assembly plant where tapes are manufactured from input materials. The tape manufacturing gate-to-gate (GTG) life cycle inventories (LCIs) were developed separately for tapes used with reusable and disposable drapes.

A wide variety of surgical tapes are available on the market. In this life cycle study, two tapes were examined:

1. MED TS 190 surgical tape – Used with reusable drapes. Includes a tissue carrier fabric allowing the tape to dissolve in the laundry step.
2. S070 surgical tape – Used with disposable drapes. Includes a polyester carrier fabric.

Surgical tape is typically applied to surgical drapes before the drapes arrive at the hospital. The amount of tape used with each drape depends on a number of factors, including the type and size of the drape. For a 4 m^2 surgical top drape, approximately 50-70 cm of tape (5 cm width) is used with each drape. In this study, 60 cm of tape is shown as representative. The transparency of the life cycle data allow individual firms to easily modify the life cycle results for any amount of tape used.

Results

Surgical Tapes Used with Reusable Surgical Drapes

The main components of tapes used with reusable surgical top drapes are a butyl acrylate-based adhesive, a paper/silicone release liner, a tissue carrier fabric, and a polystyrene core. The composition of one roll of surgical tape (5 cm x 100 m) is given in Table 4.2. Thus, the cradle-to-gate LCI for surgical tape used with reusable surgical drapes was based on the cradle-to-gate LCIs of the adhesive, release liner, carrier fabric, and core.

*Table 4.2 Mass composition of one roll of surgical tape (5 cm * 100 m)*

Component	**Material**	**Fabric weight**	**Total mass per roll (fabric weight * 5 m^2)**
Adhesive	Butyl acrylate-based PSA	45 g/m^2 skin side 45 g/m^2 drape side 90 g/m^2 total	225 g skin side 225 g drape side 450 g total
Carrier fabric	Tissue paper	13.2 g/m^2	66 g
Release liner	Kraft paper/silicone	90 g/m^2	450 g
Core	Polystyrene	N/A	43 g
Total	**--**	**--**	**1,009 g**

The cradle-to-gate results for the manufacture and delivery of surgical tape used with 1,000 uses of reusable top drapes are shown in Table 4.3. Approximately 60 cm of tape (5 cm width) is used with each drape use. Thus, 1.009 kg/100 m * 0.60 m/use * 1,000 uses = 6.05 kg tape is used with each 1,000 drape uses. The tape manufacturing is the GTG row at the top of the Table, followed by the CTGs of the four major components of surgical tape.

Table 4.3 Summary of cradle-to-gate life cycle inventory of surgical tape used with 1,000 uses reusable surgical top drapes (6.05 kg tape)

Modules comprising the major components of MED TS 190 tape, 05/10/2018	Mass architecture of MED TS 190 tape, kg/6.05 kg MED TS 190 tape	Process energy, MJ/6.05 kg MED TS 190 tape						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
MED TS 190 tape, gtg	6.05	10.6	0	0	0	3.21	0	13.8
cradle-to-gate data								
E09 adhesive, ctg	2.70	7.60	0.0291	120	38.1	5.74	-49.3	122
paper release liner, ctg	2.70	8.84	0	25.7	11.4	2.46	-0.872	47.5
cellulose tissue, ctg	0.396	0.586	0	0	2.90	0.174	0	3.66
Polystyrene, ctg	0.258	0.335	0.115	2.77	10.7	0.546	-8.52	5.90
Total mass of ctg inputs	6.05							
Total mass of product, kg	6.05							
	Total ctgs	17.4	0.144	148	63.1	8.92	-58.7	179
	Total gtgs	10.6	0	0	0	3.21	0	13.8
	Total Process Energy, MJ/6.05 kg MED TS 190 tape	27.9	0.144	148	63.1	12.1	-58.7	193

Modules comprising the major components of MED TS 190 tape, 05/10/2018	Mass architecture of MED TS 190 tape, kg/6.05 kg MED TS 190 tape	Natural Resource energy (nre*), MJ/6.05 kg MED TS 190 tape						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
MED TS 190 tape, gtg	6.05	33.8	0	0	0	3.85	0	37.6
cradle-to-gate data								
E09 adhesive, ctg	2.70	24.3	0.0419	172	43.8	6.89	-70.9	176
paper release liner, ctg	2.70	28.3	0	36.9	13.1	2.95	-1.25	80.0
cellulose tissue, ctg	0.396	1.88	0	0	3.34	0.209	0	5.42
Polystyrene, ctg	0.258	1.07	0.165	3.99	12.3	0.655	-12.3	5.88
Total mass of ctg inputs	6.05							
Total mass of product	6.05							
	Total ctgs	55.6	0.207	213	72.6	10.7	-84.4	267
	Total gtgs	33.8	0	0	0	3.85	0	37.6
	Total Natural Resource Energy, MJ/6.05 kg MED TS 190 tape	89.3	0.207	213	72.6	14.6	-84.4	305

In Figure 4.2, the tape component life cycle inventory energy intensities are portrayed graphically, MJ/1,000 kg of each material. In the comparison, the butyl-acrylate based E09 adhesive is more than twice as energy intensive as the polystyrene core, paper/silicone release liner, and cellulose tissue paper carrier fabric. The tape manufacture process has the lowest energy intensity on a per kg basis. Figure 4.3 shows the total cradle-to-gate LCI energy for the tape used with 1,000 reusable drape uses (6.05 kg tape use), accounting for the amount of each tape component used. In this case, the manufacturing energy required for the butyl acrylate-based adhesive and the paper/silicone release liner accounts for over 80% of the surgical tape life cycle energy. Thus, it is clear that the cradle-to-gate energy required to manufacture surgical tape used with reusable surgical drapes is the most influenced by the adhesive and release liner supply chains. On a 1,000 drape uses basis, the overall process energy and natural resource energy requirements for the cradle-to-gate manufacture and delivery of tape used with 1,000 reusable surgical drape uses (MJ/1,000 uses reusable drape) were 193 and 305, respectively.

Figure 4.2 Process energy and natural resource energy per 1,000 kg of each major constituent of surgical tape for reusable surgical drapes

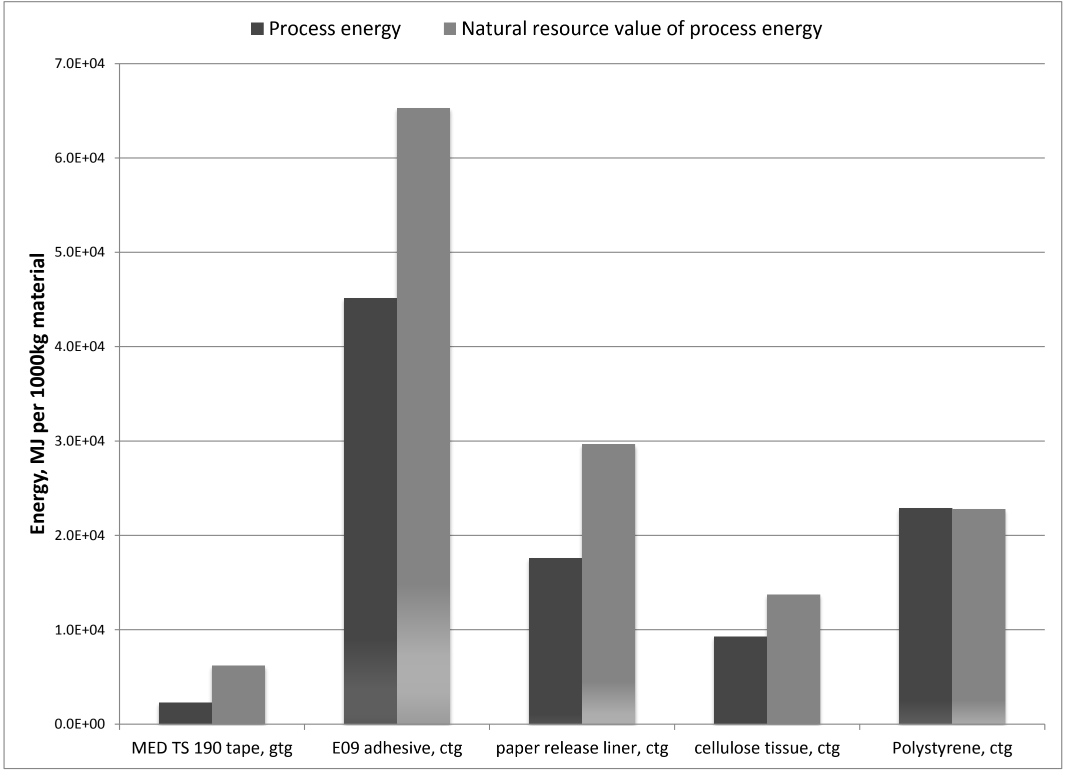
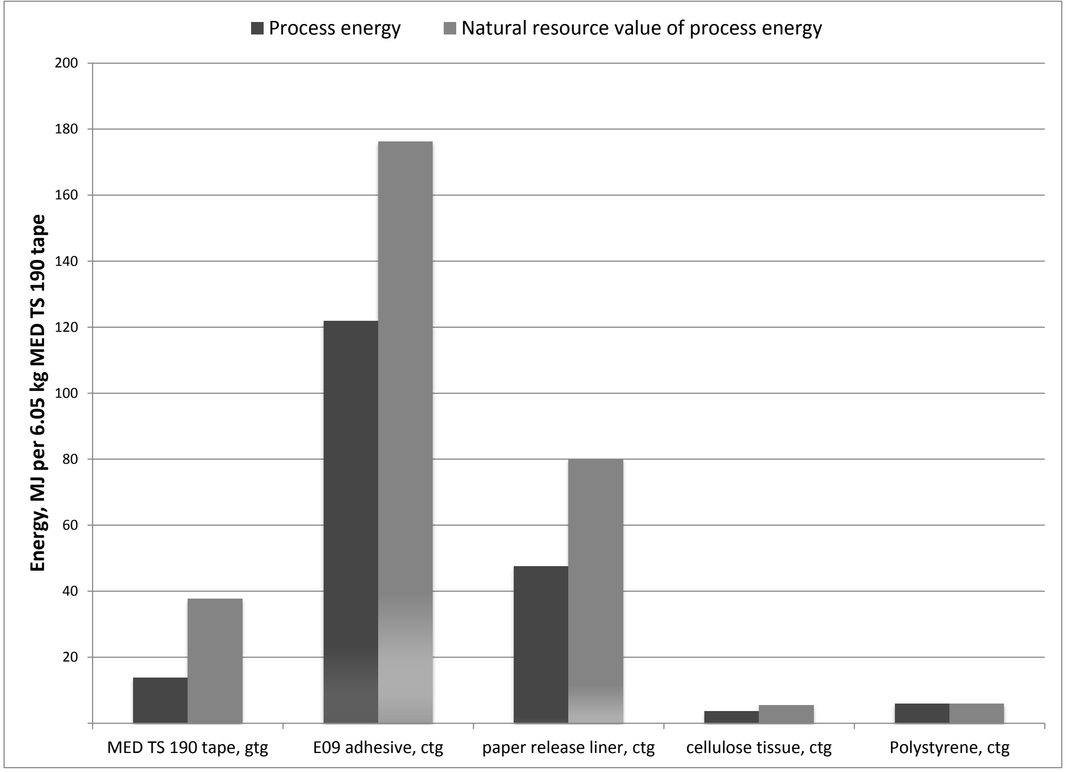


Figure 4.3 Process energy (total = 193 MJ/1,000 drape uses) and NRE (total = 305 MJ/1,000 drape uses) for surgical tape for reusable surgical drapes (1,000 drape uses = 6.05 kg tape)



Surgical Tapes Used with Disposable Surgical Drapes

The main components of tapes used with disposable surgical top drapes are a polyolefin-based adhesive, a paper/silicone release liner, a polyester carrier fabric, and a polystyrene core. The composition of one roll of surgical tape (5 cm x 200 m) is given in Table 4.2. Thus, the cradle-to-gate LCI for surgical tape used with disposable surgical drapes was based on the cradle-to-gate LCIs of the adhesive, release liner, carrier fabric, and core.

*Table 4.4 Mass composition of one roll of surgical tape (5 cm * 200 m)*

Component	**Material**	**Fabric weight**	**Total mass per roll (fabric weight * 10 m^2)**
Adhesive	Polyolefin-based PSA	32 g/m^2 skin side 32 g/m^2 drape side 64 g/m^2 total	320 g skin side 320 g drape side 640 g total
Carrier fabric	Polyester	17 g/m^2	170 g
Release liner	Kraft paper/silicone	90 g/m^2	900 g
Core	Polystyrene	N/A	43 g
Total	**--**	**--**	**1,753 g**

The cradle-to-gate results for the manufacture and delivery of surgical tape used with 1,000 uses of disposable top drapes are shown in Table 4.3. Approximately 60 cm of tape (5 cm width) is used with each drape use. Thus, 1.753 kg/200 m * 0.60 m/use * 1,000 uses = 5.26 kg tape is used with each 1,000 drape uses. The tape manufacturing is the GTG row at the top of the Table, followed by the CTGs of the four major components of surgical tape.

Table 4.5 Summary of cradle-to-gate life cycle inventory of surgical tape used with 1,000 uses disposable surgical top drapes (5.26 kg tape)

Modules comprising the major components of S070 tape, 07/10/2018	Mass architecture of S070 tape, kg/5.26 kg S070 tape	Process energy, MJ/5.26 kg S070 tape						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
S070 tape, gtg	5.26	3.87	0	0	0	9.90	0	13.8
cradle-to-gate data								
paper release liner, ctg	2.70	8.84	0	25.7	11.4	2.46	-0.872	47.5
TLH 2013 adhesive, ctg	1.92	2.94	0.334	15.7	39.3	3.34	-21.4	40.2
PET fiber, from TPA, ctg	0.510	3.67	4.79	9.50	4.21	1.65	-8.18	15.7
Polystyrene, ctg	0.129	0.167	0.0575	1.39	5.33	0.273	-4.26	2.95
Total mass of ctg inputs	5.26							
Total mass of product, kg	5.26							
	Total ctgs	15.6	5.18	52.3	60.3	7.73	-34.7	106
	Total gtgs	3.87	0	0	0	9.90	0	13.8
	Total Process Energy, MJ/5.26 kg S070 tape	19.5	5.18	52.3	60.3	17.6	-34.7	120

Modules comprising the major components of S070 tape, 07/10/2018	Mass architecture of S070 tape, kg/5.26 kg S070 tape	Natural Resource energy (nre*), MJ/5.26 kg S070 tape						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
S070 tape, gtg	5.26	12.4	0	0	0	11.9	0	24.3
cradle-to-gate data								
paper release liner, ctg	2.70	28.3	0	36.9	13.1	2.95	-1.25	80.0
TLH 2013 adhesive, ctg	1.92	9.41	0.480	22.6	45.2	4.01	-30.8	50.9
PET fiber, from TPA, ctg	0.510	11.8	6.89	13.7	4.85	1.98	-11.8	27.4
Polystyrene, ctg	0.129	0.535	0.0826	1.99	6.13	0.328	-6.13	2.94
Total mass of ctg inputs	5.26							
Total mass of product	5.26							
	Total ctgs	50.0	7.45	75.1	69.3	9.27	-49.9	161
	Total gtgs	12.4	0	0	0	11.9	0	24.3
	Total Natural Resource Energy, MJ/5.26 kg S070 tape	62.4	7.45	75.1	69.3	21.2	-49.9	186

In Figure 4.4, the tape component life cycle inventory energy intensities are portrayed graphically, MJ/1,000 kg of each material. In the comparison, the polyester carrier fabric is the most energy-intensive, followed by the polystyrene core, TLH 2013 adhesive, and the paper/silicone release liner. The tape manufacture process has the lowest energy intensity on a per kg basis. Figure 4.5 shows the total cradle-to-gate LCI energy for the tape used with 1,000 disposable drape uses (5.26 kg tape use), accounting for the amount of each tape component used. In this case, the manufacturing energy required for the HMPSA and the paper/silicone release liner accounts for over 70% of the surgical tape life cycle energy. Thus, it is clear that the cradle-to-gate energy required to manufacture surgical tape used with disposable surgical drapes is the most influenced by the adhesive and release liner supply chains. On a 1,000 drape uses basis, the overall process energy and natural resource energy requirements for the cradle-to-gate manufacture and delivery of tape used with 1,000 disposable surgical drape uses (MJ/1,000 uses disposable drape) were 113 and 177, respectively.

Figure 4.4 Process energy and natural resource energy per 1,000 kg of each major constituent of surgical tape for disposable surgical drapes

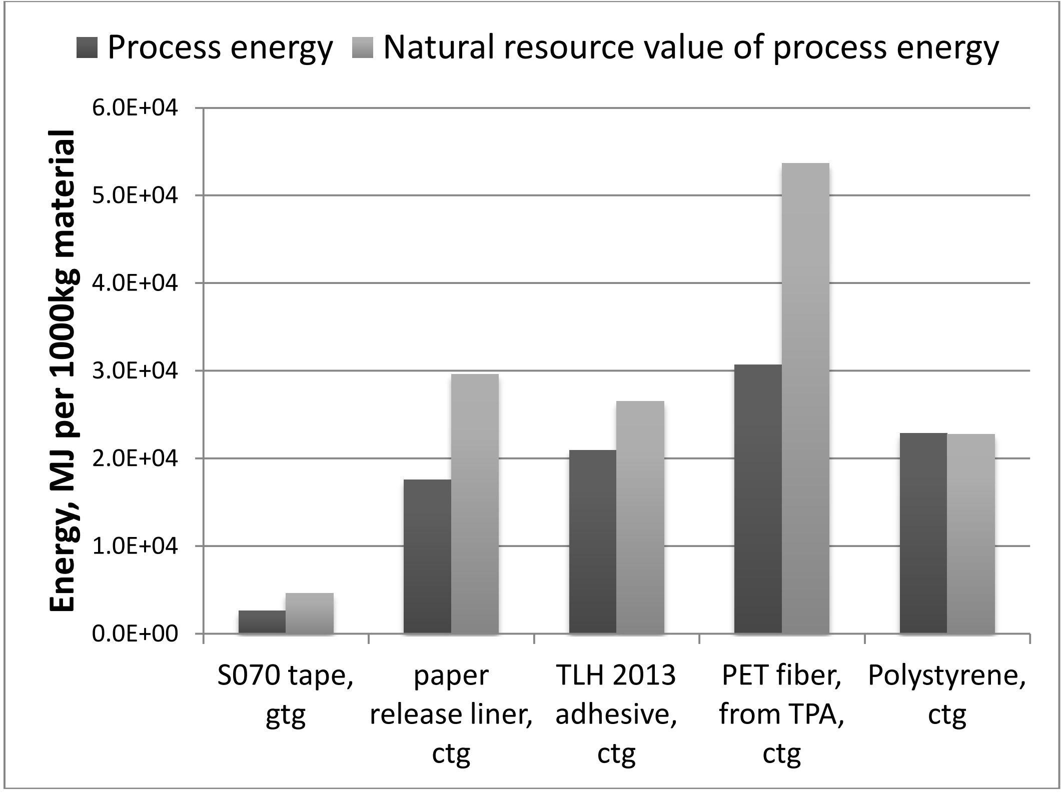
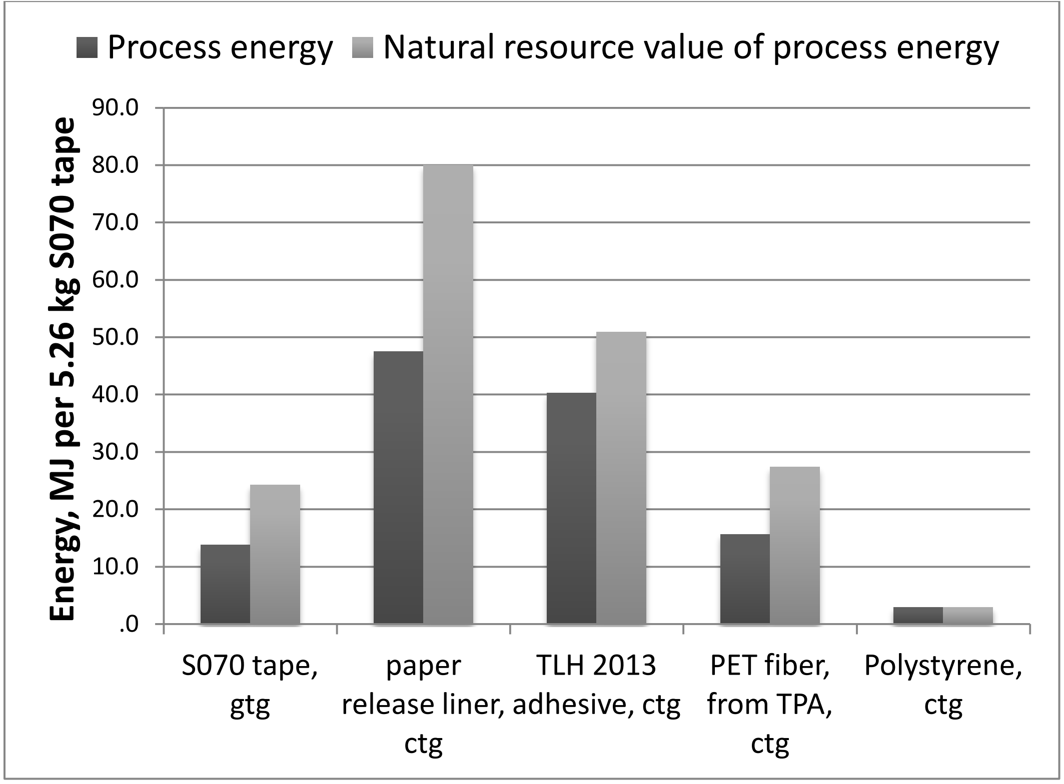


Figure 4.5 Process energy (total = 120 MJ/1,000 drape uses) and NRE (total = 186 MJ/1,000 drape uses) for surgical tape for disposable surgical drapes (1,000 drape uses = 5.26 kg tape)



Summary

The surgical tape manufacture and delivery CTG (including tape supply chain) accounted for less than 3% of the cradle-to-end-of-life (CTEOL) net NRE for reusable and disposable drape systems, Table 4.6.

Table 4.6 is a comparison of the natural resource energy (NRE) for the surgical tape and supply chain manufacture and delivery for tapes used with reusable and disposable surgical drape systems.

Table 4.6 Summary of NRE for surgical tape manufacture and delivery (including complete supply chain), tapes used with reusable and disposable drape systems

	NRE	
	MJ/1,000 drape uses	% of CTEOL NRE
Reusable surgical drape system	305	2.6%
Disposable surgical drape system	186	1.0%

Chapter 5 TAPE PACKAGING MANUFACTURE CRADLE-TO-GATE

Background

Tapes used with reusable and disposable surgical drape systems require packaging to deliver to health care facilities. This packaging is subdivided into:

1. Primary packaging – Surgical tapes are not individually packaged. Thus, there is no primary packaging for surgical tapes.
2. Secondary packaging – The bags and containers used to ship and handle multiple rolls of surgical tape. The representative secondary packaging includes:
    a. A cardboard box used to contain the multiple rolls of tape.
    b. Cardboard plates, cardboard cores, and siliconized paper rings used to secure the rolls of tape within the box.
    c. A plastic bag used to contain multiple rolls of tape within the box.
    d. Tape used to close the box.
3. Tertiary packaging – The pallets and plastic wrap used to transport multiple boxes of tapes. The representative tertiary packaging for surgical tapes included wood pallets and linear low density polyethylene (LLDPE) shrink wrap. Wood pallets were considered to be recycled. Thus, manufacturing of the pallets was not considered. However, the energy required to transport the pallets was considered.

Primary, secondary and tertiary (PST) packaging for surgical tapes used with disposable and reusable surgical drapes consists of a series of basic materials formed into bags, wraps, containers, and inserts. In this life cycle study, these containers and inserts were measured from practice. The representative PST packaging materials for surgical tapes are given in Table 5.1.

It is recognized that variations in packaging materials occur across the broad range of supply companies. The packaging materials analyzed herein are generally representative and thus allow an understanding of the life cycle issues of surgical tape packaging. Each of the materials in Table 5.1 was evaluated with a cradle-to-gate (CTG) life cycle inventory (LCI) from natural resources (oil or trees) to final material and expressed first on a per kg of final material basis.

Table 5.1 Packaging description for surgical tape from manufacturer or converter to drape supply firm

Drape system	**Packaging system**	**Packaging use**	**Packaging material**
Disposable	Primary	--	--
	Secondary	Carton box	Boxboard which is recycled after use
		Carton cores	Boxboard which is recycled after use
		Carton plates	Boxboard which is recycled after use
		Siliconized paper rings	Paper/silicone
		Plastic bag	Polyethylene
		Tape	Polypropylene
	Tertiary	Protective wrap	LLDPE
		Pallet	Wood which is recycled before and after use
Reusable	Primary	--	--
	Secondary	Carton box	Boxboard which is recycled after use
		Carton cores	Boxboard which is recycled after use
		Carton plates	Boxboard which is recycled after use
		Siliconized paper rings	Paper/silicone
		Plastic bag	Polyethylene
		Tape	Polypropylene
	Tertiary	Protective wrap	LLDPE
		Pallet	Wood which is recycled before and after use

LLDPE = linear low density polyethylene

Methodology

The LCI results for surgical tape packaging manufacture and delivery are presented in three ways to allow better understanding and transparency:

1. On a uniform basis of 1,000 kg of the packaging material, MJ/1,000 kg.
2. On the basis of the amount used for one roll of tape.
3. On the basis of the amount used for 1,000 surgical drape uses.

In addition, the mass of packaging to landfill or incineration was analyzed and included in the life cycle study.

Results

Surgical Tapes Used with Reusable Drapes

The mass of PST packaging for surgical tapes used with reusable drapes is given in Table 5.2 on a g/tape roll basis. Note that one roll of MED TS 190 surgical tape measures 100 m x 5 cm and weighs 1.009 kg. Surgical tapes are not individually wrapped. Multiple rolls of tape are wrapped in a plastic bag and packaged using corrugated boxboard cores, plates, and boxes. Siliconized paper rings are also used for packing and the boxes are taped closed. Multiple boxes are placed on a pallet and wrapped. Each pallet has a mass of 25 kg and holds 240 rolls of tape. Therefore, the pallet mass transported per tape roll is 25,000/240 = 104 g/tape roll. The pallets were considered to be reused infinite times before disposal and thus required no manufacturing material or energy. The total PST packaging manufactured for each tape roll was 101 g (205 g transported).

The cradle-to-gate LCI for the manufacturing of the PST packaging for surgical tapes used with 1,000 reusable drape uses is given in Table 5.3. Note that 60 cm (by 5 cm) of tape are used with each drape use. Thus, 0.60 m/100 m * 1.009 kg * 1,000 uses = 6.05 kg surgical tape are used with 1,000 uses of reusable drapes. The total process energy and natural resource energy (MJ/1,000 drape uses) for the tape packaging used with 1,000 reusable drape uses was 6.35 and 7.66, respectively.

Each packaging component requires energy to manufacture and in Figure 5.1 the full cradle-to-gate energy (MJ) per 1,000 kg of each of the materials used in PST packaging for surgical tapes used with reusable drapes is shown. For the PST packaging used for surgical tapes for reusable drapes, Figure 5.1 shows that corrugated boxboard has the lowest energy intensity and that HDPE, LDPE, siliconized paper rings, and polypropylene cores have similar energy intensities about twice that of the corrugated boxboard (MJ/1,000 kg material). Figure 5.2 shows that the corrugated boxboard was the most influential component on a MJ/1,000 drape uses basis.

Table 5.2 Packaging for surgical tapes used with reusable drapes, manufacture and transport (one tape roll = 100 m x 5 cm = 1.009 kg)

Packaging	**Material**	**Description**	**Use Rate, rolls / item**	**Mass manufactured, g / roll**	**Mass transported, g / roll**
Primary	--	--	--	--	--
Secondary	Corrugated boxboard	1.902 kg boxboard	20 rolls / box	95.1	95.1
	Siliconized paper ring	50 g rings	20 rolls / box	2.50	2.50
	HDPE bag	69 g bag	20 rolls / box	3.45	3.45
	Tape	5 g tape	20 rolls / box	0.250	0.250
Tertiary	LDPE sheet	0.96 m^2 LDPE pallet wrap, 80 gauge	240 rolls / pallet	0.0896	0.0896
	Pallet (for transport calculations only)	25 kg	240 rolls / pallet	0	104
Total				**101**	**205**

HDPE = high density polyethylene; LDPE = low density polyethylene

Table 5.3 Summary of cradle-to-gate life cycle inventory for surgical tape packaging used with 1,000 uses reusable surgical drapes, packaging for surgical tapes from manufacturer

Modules comprising the major components of MED TS 190 pack, 05/15/2018	Mass architecture of MED TS 190 pack, kg/0.608 kg MED TS 190 pack	Process energy, MJ/0.608 kg MED TS 190 pack						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
MED TS 190 pack, gtg	0.608	0	0	0	0	0	0	0
cradle-to-gate data								
corrugated box, ctg	0.571	0	0	0	5.65	0	0	5.65
outerbagHDPE, ctg	0.0207	0.0951	0	0.0690	0.291	0.0282	-0.0853	0.398
siliconized paper ring, ctg	0.0150	0.0491	0	0.143	0.0635	0.0137	-4.84E-03	0.264
polypropylene fiber from pell, ctg	1.50E-03	0.0101	0	3.95E-03	0.0210	2.66E-03	-5.58E-03	0.0321
LDPEsheet, ctg	5.38E-04	3.11E-03	0	1.38E-03	7.55E-03	7.20E-04	-2.72E-03	0.0100
Total mass of ctg inputs	0.608							
Total mass of product, kg	0.608							
	Total ctgs	0.157	0	0.217	6.03	0.0453	-0.0984	6.35
	Total gtgs	0	0	0	0	0	0	0
	Total Process Energy, MJ/0.608 kg MED TS 190 pack	0.157	0	0.217	6.03	0.0453	-0.0984	6.35

Modules comprising the major components of MED TS 190 pack, 05/15/2018	Mass architecture of MED TS 190 pack, kg/0.608 kg MED TS 190 pack	Natural Resource energy (nre*), MJ/0.608 kg MED TS 190 pack						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
MED TS 190 pack, gtg	0.608	0	0	0	0	0	0	0
cradle-to-gate data								
corrugated box, ctg	0.571	0	0	0	6.50	0	0	6.50
outerbagHDPE, ctg	0.0207	0.304	0	0.0992	0.335	0.0339	-0.123	0.649
siliconized paper ring, ctg	0.0150	0.157	0	0.205	0.0730	0.0164	-6.96E-03	0.444
polypropylene fiber from pell, ctg	1.50E-03	0.0323	0	5.67E-03	0.0242	3.19E-03	-8.02E-03	0.0573
LDPEsheet, ctg	5.38E-04	9.96E-03	0	1.98E-03	8.68E-03	8.64E-04	-3.91E-03	0.0176
Total mass of ctg inputs	0.608							
Total mass of product	0.608							
	Total ctgs	0.504	0	0.312	6.94	0.0543	-0.142	7.66
	Total gtgs	0	0	0	0	0	0	0
	Total Natural Resource Energy, MJ/0.608 kg MED TS 190 pack	0.504	0	0.312	6.94	0.0543	-0.142	7.66

Figure 5.1 Process energy and natural resource energy per 1,000 kg of each major constituent of surgical tape packaging used with reusable surgical drapes

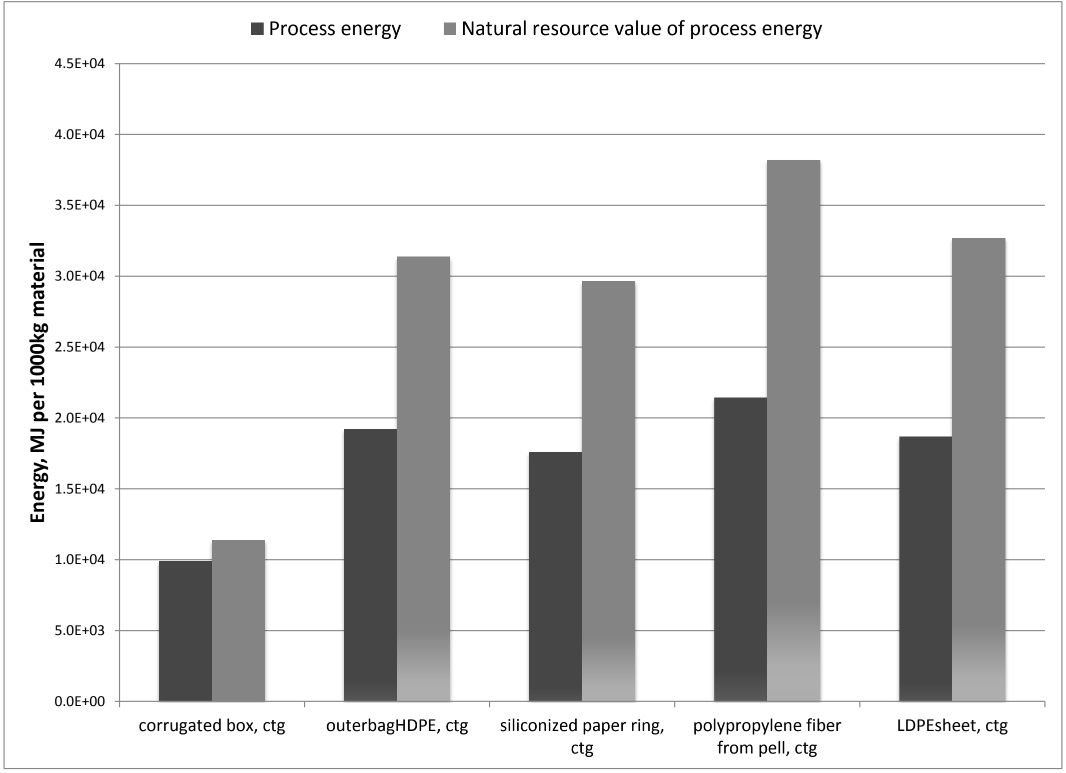
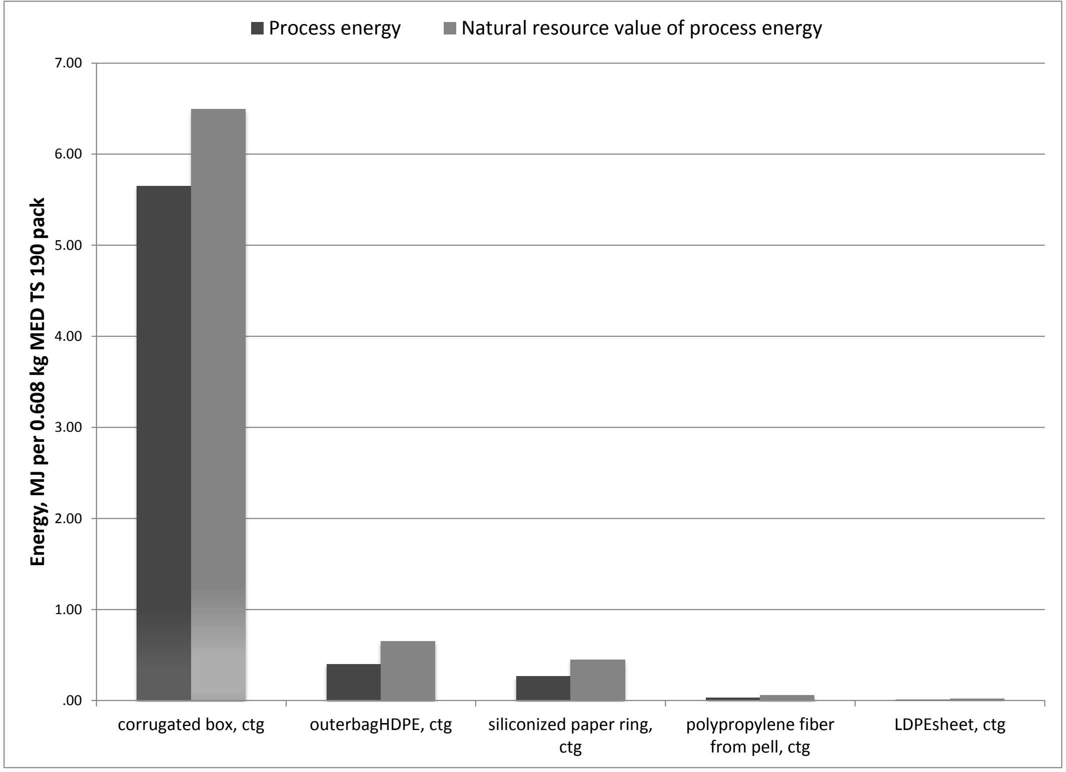


Figure 5.2 Process energy (total = 6.35 MJ/1,000 drape uses) and NRE (total = 7.66 MJ/1,000 drape uses) for surgical tape packaging used with reusable surgical drapes



Surgical Tapes Used with Disposable Drapes

The mass of PST packaging for surgical tapes used with disposable drapes is given in Table 5.4 on a g/tape roll basis. Note that one roll of S070 surgical tape measures 200 m x 5 cm and weighs 1.753 kg. Surgical tapes are not individually wrapped. Multiple rolls of tape are wrapped in a plastic bag and packaged using corrugated boxboard cores, plates, and boxes. Siliconized paper rings are also used for packing and the boxes are taped closed. Multiple boxes are placed on a pallet and wrapped. Each pallet has a mass of 25 kg and holds 192 rolls of tape. Therefore, the pallet mass transported per tape roll is 25,000/192 = 130 g/tape roll. The pallets were considered to be reused infinite times before disposal and thus required no manufacturing material or energy. The total PST packaging manufactured for each tape roll was 118 g (248 g transported).

The cradle-to-gate LCI for the manufacturing of the PST packaging for surgical tapes used with 1,000 disposable drape uses is given in Table 5.5. Note that 60 cm (by 5 cm) of tape are used with each drape use. Thus, 0.60 m/200 m * 1.753 kg * 1,000 uses = 5.26 kg surgical tape are used with 1,000 uses of disposable drapes. The total process energy and natural resource energy (MJ/1,000 drape uses) for the tape packaging used with 1,000 disposable drape uses was 3.69 and 4.45, respectively.

Each packaging component requires energy to manufacture and in Figure 5.3 the full cradle-to-gate energy (MJ) per 1,000 kg of each of the materials used in PST packaging for surgical tapes used with disposable drapes is shown. For the PST packaging used for surgical tapes for disposable drapes, Figure 5.3 shows that corrugated boxboard has the lowest energy intensity and that HDPE, LDPE, siliconized paper rings, and polypropylene cores have similar energy intensities about twice that of the corrugated boxboard (MJ/1,000 kg material). Figure 5.4 shows that the corrugated boxboard was the most influential component on a MJ/1,000 drape uses basis.

Table 5.4 Packaging for surgical tapes used with disposable drapes, manufacture and transport (one tape roll = 200 m x 5 cm = 1.753 kg)

Packaging	**Material**	**Description**	**Use Rate, rolls / item**	**Mass manufactured, g / roll**	**Mass transported, g / roll**
Primary	--	--	--	--	--
Secondary	Corrugated boxboard	1.769 kg boxboard	16 rolls / box	111	111
	Siliconized paper ring	40 g rings	16 rolls / box	2.50	2.50
	HDPE bag	69 g bag	16 rolls / box	4.31	4.31
	Tape	5 g tape	16 rolls / box	0.313	0.313
Tertiary	LDPE sheet	0.96 m^2 LDPE pallet wrap, 80 gauge	192 rolls / pallet	0.113	0.113
	Pallet (for transport calculations only)	25 kg	192 rolls / pallet	0	130
Total				**118**	**248**

HDPE = high density polyethylene, LDPE = low density polyethylene

Table 5.5 Summary of cradle-to-gate life cycle inventory for surgical tape packaging used with 1,000 uses disposable surgical drapes, packaging for tape from manufacturer

Modules comprising the major components of S070 pack, 05/15/2018	Mass architecture of S070 pack, kg/0.353 kg S070 pack	Process energy, MJ/0.353 kg S070 pack						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
S070 pack, gtg	0.353	0	0	0	0	0	0	0
cradle-to-gate data								
corrugated box, ctg	0.332	0	0	0	3.28	0	0	3.28
outerbagHDPE, ctg	0.0129	0.0594	0	0.0431	0.182	0.0176	-0.0533	0.249
siliconized paper ring, ctg	7.50E-03	0.0246	0	0.0713	0.0317	6.83E-03	-2.42E-03	0.132
polypropylene fiber from pell, ctg	9.37E-04	6.30E-03	0	2.47E-03	0.0131	1.66E-03	-3.49E-03	0.0201
LDPEsheet, ctg	3.38E-04	1.95E-03	0	8.65E-04	4.74E-03	4.52E-04	-1.71E-03	6.30E-03
Total mass of ctg inputs	0.353							
Total mass of product, kg	0.353							
	Total ctgs	0.0922	0	0.118	3.52	0.0266	-0.0609	3.69
	Total gtgs	0	0	0	0	0	0	0
	Total Process Energy, MJ/0.353 kg S070 pack	0.0922	0	0.118	3.52	0.0266	-0.0609	3.69

Modules comprising the major components of S070 pack, 05/15/2018	Mass architecture of S070 pack, kg/0.353 kg S070 pack	Natural Resource energy (nre*), MJ/0.353 kg S070 pack						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
S070 pack, gtg	0.353	0	0	0	0	0	0	0
cradle-to-gate data								
corrugated box, ctg	0.332	0	0	0	3.78	0	0	3.78
outerbagHDPE, ctg	0.0129	0.190	0	0.0620	0.209	0.0212	-0.0766	0.406
siliconized paper ring, ctg	7.50E-03	0.0786	0	0.102	0.0365	8.20E-03	-3.48E-03	0.222
polypropylene fiber from pell, ctg	9.37E-04	0.0202	0	3.55E-03	0.0151	2.00E-03	-5.01E-03	0.0358
LDPEsheet, ctg	3.38E-04	6.25E-03	0	1.24E-03	5.45E-03	5.42E-04	-2.46E-03	0.0110
Total mass of ctg inputs	0.353							
Total mass of product	0.353							
	Total ctgs	0.295	0	0.169	4.04	0.0319	-0.0876	4.45
	Total gtgs	0	0	0	0	0	0	0
	Total Natural Resource Energy, MJ/0.353 kg S070 pack	0.295	0	0.169	4.04	0.0319	-0.0876	4.45

Figure 5.3 Process energy and natural resource energy per 1,000 kg of each major constituent of packaging for surgical tape packaging used with disposable surgical drapes

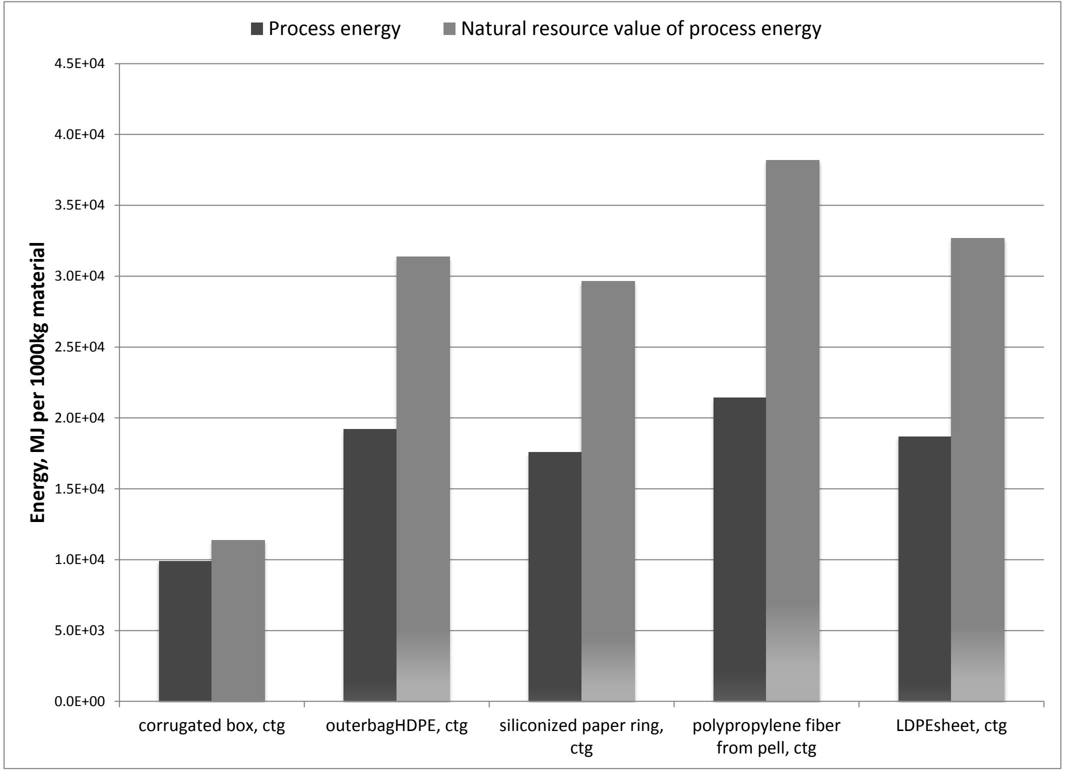
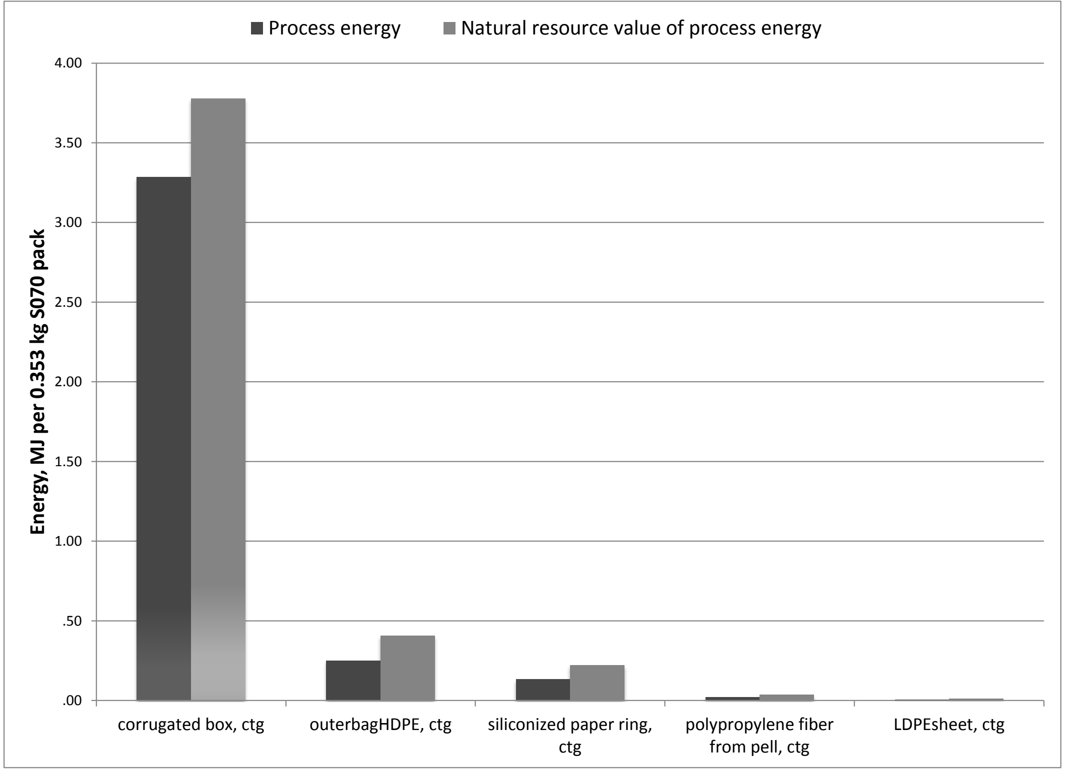


Figure 5.4 Process energy (total =3.69 MJ/1,000 drape uses) and NRE (total = 4.45 MJ/1,000 drape uses) for surgical tape packaging used with disposable surgical drapes



The transparency of the life cycle inventory results presented in the Tables and Figures in this Chapter can be used to seek improvements in surgical tape packaging. The relative differences and the influence of the materials with higher energy intensities are similar if the detailed analysis for improvement had been done for packaging of other health care garments, such as gloves, gowns, or towels.

Summary

Table 3.9 is a comparison of the natural resource energy (NRE) for packaging for surgical tapes used with reusable and disposable surgical drapes.

Table 5.6 Summary of NRE for surgical tape packaging manufacturing, reusable and disposable surgical drape systems

	NRE	
	MJ/1,000 drape uses	% of CTEOL NRE
Reusable surgical drape system	7.66	0.068%
Disposable surgical drape system	4.45	0.024%

Chapter 6 USE PHASE

Background and Methodology

The use of surgical drapes and tapes in health care facilities constituted a life cycle segment in this study. The use phase described in this Chapter includes the sterilization of disposable and reusable drapes and associated tapes as well as the laundry plus inspection and repair (small fraction of drapes) for reusable drapes.

Laundry

Each reusable surgical drape is laundered prior to each use. The laundry process for reusable drapes in this life cycle study included:

1. The utilization of water.
    a. metered water use
    b. evaporated water (blue water use)
    c. recovered water (from soil on used drapes)
2. The creation and treatment of wastewater containing the surgical waste measured from the laundry of soiled drapes.
3. The consumption of energy (electricity and natural gas) in the wash, rinse, and dry steps.

The typical laundry process for reusable surgical textiles is a combination of washing and drying using electricity and natural gas energy inputs. The laundry gate-to-gate LCI was evaluated with field data, Table 6.1 and Table 6.2. The laundry data was based on 1,000 kg drape weight; therefore, the data per 1,000 drape uses is dependent on the weight of the drape.

Table 6.1 Metered water consumption for washing and rinsing in medical laundry facilities

Cycle	**Industry Range**	**Used in this LCI**
	kg metered water/1,000 kg textiles	
Wash	1,300-4,000	2,310
Rinse	5,200-16,000	8,690
Total	3,500-20,000*	11,000

Note: About 33% of the water used in laundry is hot water at 65-75 °C, while 67% is cold water at 25-40 °C.
* Chainge consortium questionnaires showed 4,000 to 15,000 kg metered water / 1000 kg textiles.

Industrial laundry processes use 6,500-20,000 kg metered water/1,000 kg textiles, Table 6.1. The high portion of this range is thought to be unreasonable for current laundry operations. The vast majority of this metered water is returned to the municipality at acceptable levels for human exposure via a wastewater treatment plant, which is included in the boundary of these analyses. Therefore, only the evaporative losses, considered part of the blue water balance, are included as a water impact, see Chapter 1. The evaporative losses were measured in the field as the weight difference between wet textiles before drying and dry textiles after drying. This water is often referred to as water retention into the dryer, and is defined as kg water per kg of dried drape. The quantity typically depends on the material and knit or weave type being laundered as well as the type of mechanical drying (spin or press). Gowns and drapes from hospital operating room use often have higher than typical water retention, particularly drapes and gowns with critical zones. These zones trap water and make it difficult to extract in press or spin cycles. Quality equipment achieves about 50% (40-60%) water retention (Adcock, 2018). The two predominant methods of dewatering are pressing and spinning (centrifuge). The pressing tends to be less efficient for drapes due to the possibility of damaging the trilaminate with pressure. The press typically achieves a water retention of 50%, and the centrifugal dewatering method achieves a lower water retention with a minimum of 30% (Riedo, 2018). Data were collected from four completed surveys of laundry operators during this study. The water retention ranged from 40 to 60%, and the average was 49%. The reported water retention (49%) was consistent with expert judgment (Adcock and Riedo) and was used in this study. After drying, the drapes have about 5% residual moisture (as is). Thus, 0.44 kg water was evaporated per kg of dried drapes.

Soiled drapes (as received at the laundry) contain a mix of tissue, blood, sweat, and other liquids retained in the drapes. Collectively, these materials are referred to as soil. Data on drape and surgical gown weights (as received and dried) were obtained from an earlier study with SRI Surgical (now Synergy Health) (Environmental Clarity, 2011). The soiled drapes and gowns weighted 1.55 kg for each kg of dried drapes/gowns. Thus, the soil weight was 0.55 kg / kg dried drape. The total solids (TS) fraction of the wastewater was measured, and the TS content was 0.05 kg / kg dried drape. To calculate the water content in the soil that was recovered in the laundry and sent to the wastewater treatment plant, the difference between the measured soil weight and total solids was used. This results in 0.5 kg water/ kg drape (dry weight). Thus, the ‘soil’ content was 90% water. When disposable drapes are used, the water content in the soil would be sent to an incinerator or landfill, and would not be recovered. Therefore, this recovered water represents a water savings when reusable drapes are compared with disposable drapes.

Metered water consumption, evaporative losses, and recovered water from soil are shown for reusable surgical drapes in Table 6.3. The net blue water consumed in the laundry is the water evaporated minus the water that comes into the laundry on the drapes. Thus, the net blue water use is 253 kg – 288 kg = -35 kg water / kg laundered. There is a large uncertainty in this number. However, these data show that the water evaporated in the dryer is about equal to and offset by the water (moisture level) on the returned surgical drapes and gowns.

The energy use data for laundering drapes were provided by four European laundries. The average energy use of these data were 700 MJ electricity and 5,500 MJ gas per 1000 kg dry weight laundered. These were consistent with a larger body of data including other studies done by Environmental Clarity. The ranges of energy use and the energy judged representative for laundering surgical drapes and gowns was 1000 MJ electricity and 5,800 MJ gas per 1000 kg dry weight laundered (Table 6.2). The split between energy for the washer and dryer is often not specified in the dataset. According to Al Adcock (2018), about 75% of the washer water is heated. Using efficiencies of 50-85% in the washer, the washer uses 1,400 to 2,300 MJ/kg laundered. The theoretical energy required to heat and evaporate water is 2,800 MJ/kg evaporated. Thus, the dryer efficiency was estimated to be 28-36%.

Table 6.2 Utility consumption in industrial laundry facilities

Property	**Industry Range**	**Used in this LCI**
	Process Energy, MJ/1,000 kg textiles laundered	
Total natural gas	3,200-7,700	5,750
Total electricity	540-2,200	1,000
Total energy	4,000-10,000	6,750

Note: The industry ranges in Table 6.2 are based on utility data from over 20 health care and cleanroom laundry facilities in North America and Europe.

Table 6.3 Laundry water consumption

Drape	**Weight, g**	**Metered water input, kg / 1,000 drape uses**	**Evaporated water, kg / 1,000 drape uses**	**Recovered water from soil content, kg / 1,000 drape uses**	**Net blue water, kg water / 1,000 uses**
Reusable surgical drape	576	6,342	253	288	-35

Wastewater Treatment

Following the laundry process, wastewater proceeds to a municipal wastewater treatment plant, taken as an aerobic process. In this life cycle study, the first step was to quantify the waste from health care use. This waste characterization was measured by chemical oxygen demand (COD) in the wastewater.

The wastewater treatment plant LCI used the chemical oxygen demand (COD) load as the link to the energy use and effluents from this process. This was based on the microbial treatment mechanisms and the analysis of Jimenez-Gonzalez and Overcash (2001). The life cycle profile for the wastewater treatment plant per 1,000 kg COD and per 1,000 drape uses is given in Table 6.4. It is recognized that this assessment was an average across the various types of laundered health care items and is thus representative. Much greater resources would be needed to assign the health care wastes to particular items.

Table 6.4 Wastewater treatment plant life cycle inventory results for 1,000 kg COD input (Jimenez-Gonzalez and Overcash, 2001) and for 1,000 drape uses

Inputs	**Values for 1,000 kg COD**	**Values for 1,000 reusable drape uses**
Chemical oxygen demand (COD), kg	1,000	3.30
Water to accompany bio solids output, kg	7,000	23.1
Oxygen from air, kg	870	2.87
Electricity, MJ	3,960	13.1
Outputs		
Carbon dioxide, kg	1,196	3.95
Bio solids (dry), kg	350	1.16
Water with bio solids, kg	7,000	23.1
COD in effluent (86 % treatment efficiency), kg	140	0.462

Laundry Summary

The laundry process CTG for 1,000 kg surgical drapes is given in Table 6.5. Soiled textiles from surgical procedures are put into the laundry process. Measurement over one week at a surgical laundry facility (about 100,000 lb. soiled textiles/week) determined that about 0.55 kg surgical waste (fluid, tissue, blood)/kg clean reusable textiles are removed by the laundry process. This is the same amount of surgical waste per 1,000 drapes that is delivered to the landfill or incinerator in the case of disposable drapes. The full cradle-to-gate energy values and the breakdown as process energy and NRE are given. The total process energy and NRE for laundering 1,000 kg surgical drapes (MJ/1,000 kg drapes) were 6,786 and 9,925 MJ, respectively. Table 6.6 gives laundry process energy and NRE for 1,000 drape uses for reusable drapes.

The water used and wastewater treated also require energy and in Table 6.5 the CTG energy for each component is shown. Figure 6.1 shows that the laundry process (washing and drying) was much higher in energy intensity than the incoming water and outgoing wastewater treatment processes. Therefore, the exact amount of soil on the drapes (as COD) was not critical to the life cycle study.

The cleaned and dried drapes are carefully inspected and tested before sending to health care facilities. Visual inspection with light identifies physical damage which is then repaired. The testing identifies drapes with inadequate barrier performance, and so the failed items (a small number) are removed from service. Most reusable drape laundry plants use a tracking system to identify when drapes reach the design life (for example, 60 cycles) and need to be replaced. About 2% of drapes are not adequately clean after one laundry cycle and are rewashed. Following the inspection process, drapes are folded and packaged, see Chapter 3.

Since the wastewater after the wastewater treatment plant is returned to regulated levels as acceptable for human exposure and was included as a part of the reusable drape LCI, only the evaporative losses of water and added water from the soil that is on the drapes as received by the laundry were included as a blue water impact. This evaporative loss was measured by four laundry operators in Europe, and several in the US. Some of these were specific to surgical drapes and gowns. Additionally, two experts in the field were consulted. The evaporated water was judged to be about 0.44 kg water / kg as is drape. . Thus, the water consumption for 1,000 reusable surgical drape uses (each with laundry/sterilization) was 576kg*0.44 kg/kg=253 kg evaporative water loss/1,000 surgical top drape uses. The water content in the soil on the drapes as received was estimated by a study on surgical gowns and drapes done in the United States. The water content was 0.5 kg/kg laundered drape. Thus, the water recovered in the laundry was 576kg*0.5 kg/kg = 288 kg water recovered. The net water loss was -35 kg / kg drape (a net gain of water).

Table 6.5 Summary of cradle-to-gate life cycle inventory for laundry of 1,000 kg surgical drapes-

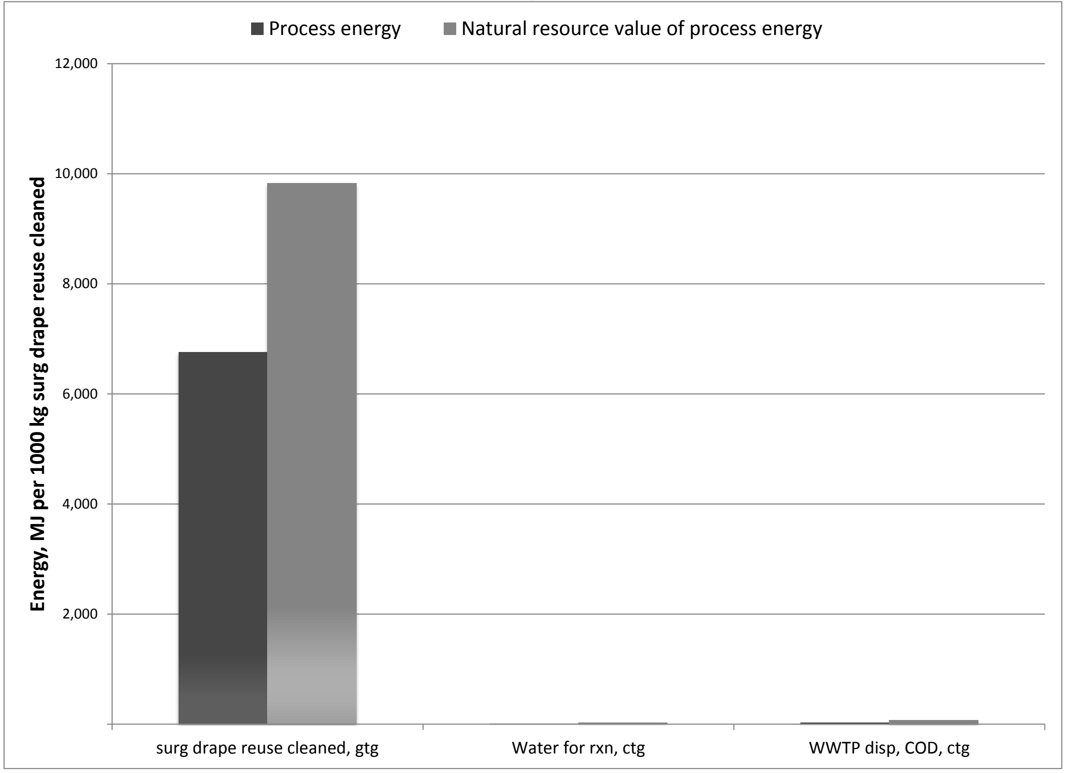
Modules comprising the major components of surg drape reuse cleaned, 05/07/2018	Mass architecture of surg drape reuse cleaned, kg/1000 kg surg drape reuse cleaned	Process energy, MJ/1000 kg surg drape reuse cleaned						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse cleaned, gtg	1,000	1,003	0	0	5,751	0	0	6,754
cradle-to-gate data								
Water for rxn, ctg	1.10E+04	8.86	0	0	0	0	0	8.86
WWTP disp, COD, ctg	5.74	22.7	0	0	0	0	0	22.7
Total mass of ctg inputs	1.10E+04							
Total mass of product, kg	1,000							
	Total ctgs	31.6	0	0	0	0	0	31.6
	Total gtgs	1,003	0	0	5,751	0	0	6,754
	Total Process Energy, MJ/1000 kg surg drape reuse cleaned	1,035	0	0	5,751	0	0	6,786

Modules comprising the major components of surg drape reuse cleaned, 05/07/2018	Mass architecture of surg drape reuse cleaned, kg/1000 kg surg drape reuse cleaned	Natural Resource energy (nre*), MJ/1000 kg surg drape reuse cleaned						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg drape reuse cleaned, gtg	1,000	3,211	0	0	6,614	0	0	9,824
cradle-to-gate data								
Water for rxn, ctg	1.10E+04	28.4	0	0	0	0	0	28.4
WWTP disp, COD, ctg	5.74	72.7	0	0	0	0	0	72.7
Total mass of ctg inputs	1.10E+04							
Total mass of product	1,000							
	Total ctgs	101	0	0	0	0	0	101
	Total gtgs	3,211	0	0	6,614	0	0	9,824
	Total Natural Resource Energy, MJ/1000 kg surg drape reuse cleaned	3,312	0	0	6,614	0	0	9,925

Table 6.6 Laundry process energy and NRE (MJ/1,000 surgical drape uses)

Drape	**Fabric**	**Weight, kg**	**Process energy, MJ / 1,000 drape uses**	**NRE, MJ / 1,000 drape uses**
Reusable	PET/ePTFE/PU	576	3,909	5,717

Figure 6.1 Process energy (total = 6,786 MJ/1,000 kg surgical drape laundry) and NRE (total = 9,925 MJ/1,000 kg surgical drape laundry)



Steam Sterilization

Each reusable surgical top drape is sterilized prior to each use. The associated surgical tape used with the surgical drapes is also sterilized. The typical sterilization process for reusable surgical drapes and associated tapes is steam sterilization. Steam sterilization is the practice of killing harmful organisms from an item with the use of moist heat (Kirk Othmer, 2000). The most common methods of steam sterilization are gravity-displacement cycles and dynamic air-removal cycles. In gravity-displacement cycles, saturated steam enters the sterilization chamber and displaces ambient air. In dynamic-air systems, ambient air is first removed with a vacuum, followed by saturated steam pulses in the chamber. Gravity-displacement systems operate at temperatures of 121-135 °C with exposure times of 10-30 minutes. Dynamic-air systems tend to be more efficient and operate at 132-135 °C for 3-4 minutes. Drying times are on the order of 5-15 minutes. Detailed standards for steam sterilization are available from the American National Standards Institute and the Canadian Standards Association (ANSI, 2017; CSA, 2014).

In this life cycle study, a representative dynamic-air removal steam sterilization cycle was used. A 3.568 m^3 chamber with a 286 kg capacity was shown. The steam temperature used was 132.5 °C with a dwell time of 4 minutes and a drying time of 25 minutes. The life cycle characterization of conventional dynamic-air steam sterilization is given in Table 6.7 for 1,000 kg item sterilized. The energy results for 1,000 reusable surgical drape uses, including sterilization of both drapes and tapes, are given in Table 6.8.

Table 6.7 Summary of cradle-to-gate life cycle inventory for dynamic-air steam sterilization of 1,000 kg reusable surgical drapes and tapes

Modules comprising the major components of surg gown reuse ster, 05/07/2018	Mass architecture of surg gown reuse ster, kg/1000 kg surg gown reuse ster	Process energy, MJ/1000 kg surg gown reuse ster						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg gown reuse ster, gtg	1,000	62.8	0	38.0	394	0	0	495
cradle-to-gate data								
Water for rxn, ctg	153	0.123	0	0	0	0	0	0.123
Total mass of ctg inputs	153							
Total mass of product, kg	1,000							
	Total ctgs	0.123	0	0	0	0	0	0.123
	Total gtgs	62.8	0	38.0	394	0	0	495
	Total Process Energy, MJ/1000 kg surg gown reuse ster	63.0	0	38.0	394	0	0	495

Modules comprising the major components of surg gown reuse ster, 05/07/2018	Mass architecture of surg gown reuse ster, kg/1000 kg surg gown reuse ster	Natural Resource energy (nre*), MJ/1000 kg surg gown reuse ster						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
surg gown reuse ster, gtg	1,000	201	0	54.6	453	0	0	709
cradle-to-gate data								
Water for rxn, ctg	153	0.395	0	0	0	0	0	0.395
Total mass of ctg inputs	153							
Total mass of product	1,000							
	Total ctgs	0.395	0	0	0	0	0	0.395
	Total gtgs	201	0	54.6	453	0	0	709
	Total Natural Resource Energy, MJ/1000 kg surg gown reuse ster	201	0	54.6	453	0	0	709

Table 6.8 Steam sterilization process energy for reusable drapes and NRE (MJ/1,000 surgical drape uses)

Item	**Material**	**Weight, kg**	**Process energy, MJ / 1,000 drape uses**	**NRE, MJ / 1,000 drape uses**
Reusable drape	PET/ePTFE/PU	576	285	408
Surgical tape	Paper/adhesive	6.05	2.99	4.29
Total	**--**	**582**	**288**	**413**

Ethylene Oxide Sterilization

Each disposable surgical top drape is sterilized prior to each use. The associated surgical tape used with the surgical drapes is also sterilized. The typical sterilization process for disposable surgical drapes and associated tapes is ethylene oxide (EtO) sterilization. Ethylene oxide is commonly used to sterilize items that are sensitive to temperatures greater than 60 °C, such as plastics, optics, and electronics.

In this life cycle study, a representative EtO sterilization process was used. A 50 m^3 chamber with a 3,396 kg capacity was shown. The life cycle characterization of conventional EtO sterilization is given in Table 6.9 for 1,000 kg item sterilized. The energy results for 1,000 disposable surgical drape uses, including sterilization of both drapes and tapes, are given in Table 6.10.

Table 6.9 Summary of cradle-to-gate life cycle inventory for ethylene oxide sterilization of 1,000 kg disposable surgical drapes and tapes

Modules comprising the major components of sterilization, EtO, textiles, 05/07/2018	Mass architecture of sterilization, EtO, textiles, kg/1000 kg sterilization, EtO, textiles	Process energy, MJ/1000 kg sterilization, EtO, textiles						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
sterilization, EtO, textiles, gtg	1,000	11.1	0	7.83	0	0	0	18.9
cradle-to-gate data								
Ethylene oxide, ctg	7.89	28.8	0	15.0	80.5	6.08	-61.6	68.7
Total mass of ctg inputs	7.89							
Total mass of product, kg	1,000							
	Total ctgs	28.8	0	15.0	80.5	6.08	-61.6	68.7
	Total gtgs	11.1	0	7.83	0	0	0	18.9
	Total Process Energy, MJ/1000 kg sterilization, EtO, textiles	39.9	0	22.8	80.5	6.08	-61.6	87.6

Modules comprising the major components of sterilization, EtO, textiles, 05/07/2018	Mass architecture of sterilization, EtO, textiles, kg/1000 kg sterilization, EtO, textiles	Natural Resource energy (nre*), MJ/1000 kg sterilization, EtO, textiles						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
sterilization, EtO, textiles, gtg	1,000	35.5	0	11.3	0	0	0	46.7
cradle-to-gate data								
Ethylene oxide, ctg	7.89	92.2	0	21.5	92.5	7.29	-88.6	125
Total mass of ctg inputs	7.89							
Total mass of product	1,000							
	Total ctgs	92.2	0	21.5	92.5	7.29	-88.6	125
	Total gtgs	35.5	0	11.3	0	0	0	46.7
	Total Natural Resource Energy, MJ/1000 kg sterilization, EtO, textiles	128	0	32.8	92.5	7.29	-88.6	172

Table 6.10 Ethylene oxide sterilization process energy and NRE (MJ/1,000 surgical drape uses)

Item	**Fabric**	**Weight, kg**	**Process energy, MJ / 1,000 drape uses**	**NRE, MJ / 1,000 drape uses**
Disposable drape	Polypropylene	245	21.5	42.1
Surgical tape	Paper/adhesive	5.26	0.461	0.905
Total	**--**	**250**	**22.0**	**43.0**

Summary

A major difference in the life cycle of reusable and disposable surgical drapes is that reusable drapes are laundered between uses. The life cycle inventory of the laundry process has been quantified herein.

Reusable and disposable surgical drapes and associated tapes are sterilized before use. However, different sterilization technologies are used. Steam sterilization is used for reusable drapes and associated tapes while ethylene oxide sterilization is used for disposable drapes and associated tapes. The life cycle inventories of both sterilization processes have been quantified herein.

The laundry process is the single most energy intensive process in the reusable surgical drape system life cycle, accounting for about 51% of the net process cradle-to-end-of-life NRE. This is in contrast to disposable drapes, which did not have a laundry step and so the drape manufacture accounted for about 86% of the NRE, Table 2.13. Thus, improvements in laundry efficiency would lead to the greatest benefit for reusable drape systems. For example, a 10%

energy reduction for the laundry process would lead to a 5% CTEOL energy reduction for reusable drape systems, but no reduction for disposable drape systems.

The sterilization of surgical drapes and tapes is a critical process for health and safety, but was only a small contribution to the environmental life cycle. The NRE for sterilization contributed less than 4% of the total CTEOL NRE for reusable drape systems and less than 1% for disposable drape systems.

Table 6.11 is a comparison of the natural resource energy (NRE) for the use phase of reusable and disposable surgical drapes. The use phase includes laundry and sterilization for reusable drapes, sterilization for disposable drapes, and sterilization for tapes used with both reusable and disposable drapes.

Table 6.11 Summary of NRE for use phase, reusable and disposable surgical drapes, includes laundry and sterilization processes

	NRE	
	MJ/1,000 drape uses	% of CTEOL NRE
Reusable surgical drape system	6,130	54%
Disposable surgical drape system	43.0	0.23%

References

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2. Canadian Standards Association (CSA) (2014) Standard Z314.3-14 *Effective sterilization in health care settings by the steam process*
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Chapter 7 END-OF-LIFE PHASE

Background and Methodology

Reusable and disposable surgical drape systems have substantially different end-of-life (EOL) pathways that are captured in this life cycle study. The drapes are synthetic polymers and ultimately (whether single or multiple use) will be landfilled or incinerated for energy production. These textiles are essentially inert in the landfill environment. However, the reusable products deliver the surgical waste (fluids, tissue, and blood) and associated surgical tapes to an aerobic treatment system (the wastewater treatment plant following each laundry step, see Chapter 6), while disposable products deliver the surgical waste and tapes to an anaerobic landfill. This difference was accounted for in the life cycle analysis.

Reusable textiles are sometimes “downgraded” for use in non-surgical processes at the end of the 60 surgical cycles. After reuse, the textiles are ultimately landfilled or incinerated for energy production. In this life cycle study, the surgical drapes were assumed to be downgraded. The boundary was such that the collection and reuse activities were assigned to the reuse product. Thus the benefit from not using virgin materials for the downgraded product is assigned to the downgraded product. The benefit of not landfilling was assigned to the surgical drape. However, landfilling was included to determine the environmental impact in the case that the drapes are not reused. Thus, landfilling of the drapes was shown.

Results

Landfill

The EOL boundary for reusable and disposable surgical drapes includes the general practice of landfilling after health care use. The disposable drapes also deliver surgical waste, including biological waste and surgical tape, to the landfill. The reusable drapes deliver this waste, including tape, to the laundry system. The tape shown for use with reusable drapes in this life cycle study is formulated to disintegrate in the laundry. Thus, the burden for tapes used with reusable drapes shifts from the landfill to the wastewater treatment plant, which is included in the study.

The landfill life cycle inventory included collection, transportation, and processing of the drapes from the health care or laundry facility to the landfill. Collections were based on a post-consumer waste landfill transport model. Surgical drapes and tapes are synthetic polymers and thus do not degrade in the landfill. However, each surgical drape carries a small amount of biological waste from human use in health care facilities. This biological waste is degradable, and the amount present was quantified as total organic carbon (TOC). The landfill life cycle inventory used TOC to link biological waste input to energy and emissions from the landfill. The TOC is readily degraded in the anaerobic landfill environment. The amount of TOC on surgical drapes from health care use contamination was estimated based on wastewater chemical oxygen demand (COD) values from reusable textile laundry facilities. The COD in the laundry wastewater was 3.30 kg COD/1,000 drapes and accounted for the COD of the biological waste on the drapes and tapes and the COD of the organic chemicals (detergents) used in the laundry process. The COD related to the organic chemicals used in the laundry process (C_{12}-C_{16} linear ethyoxylated alcohol detergents and acetic acid) was calculated as 0.085 kg COD based on the combustion reactions of the chemicals. Therefore, the COD related to biological waste on the reusable drapes and tapes was 3.30-0.085 = 3.215 kg COD. Finally, the COD was converted to total organic carbon (TOC) based on a conversion factor of 0.2 kg TOC/kg COD developed in a previous surgical textile study. Therefore, the biological waste on the drapes was 3.215*0.2 = 0.643 kg TOC/1,000 surgical drapes. The biological waste was assumed to be the same (on a per drape basis) for reusable and disposable drape systems, as both drapes are used in health care environments. Therefore, for surgical drapes, 0.643 kg biological waste as TOC was delivered to the landfill per 1,000 drapes. For reusable drapes, only 16.7 drapes were disposed for every 1,000 uses (0.643 kg TOC/60 drapes = 0.0107 kg TOC). For disposable drapes, 1,000 drapes were disposed for every 1,000 uses (0.643 kg TOC).

The landfill LCI utilized several assumptions for the wastes found on surgical textiles placed in landfills, as related to U.S. practices:

1. Organic carbon in a landfill degrades to 55 wt % methane and 45 wt % carbon dioxide gasses (Manfredi et al., 2009; Chanton, et al., 2009).
2. The fraction of organic carbon that degrades is taken from Eleazer et al., 2000; Barlaz et al., 2009; and Manfredi et al., 2009 for a 100 year degradation cycle. For readily degradable waste this is 88 wt %.
3. The organic carbon is a fraction of the total wet weight of the solid waste being landfilled and for degradable biological waste like protein, this is 56 wt % (Wang, et. al, 1997). That is, for each kg of organic carbon, there is 1.78 kg of biological waste mass landfilled.
4. On a basis of mass of waste landfilled in the U.S., 60 wt % goes into landfills with gas capture (Thornloe, 2009).
5. The time average landfill gas collection efficiency is 65 wt % (Manfredi et. al., 2009; Chanton, et. al., 2009). Thus, on a national basis for biological waste, 39 wt % of the methane generated is captured (65% of 60 wt %).
6. The uncollected methane fraction of the gas degrades in soil layers while escaping to the atmosphere resulting in a 50% loss of the uncollected fraction (Chanton, et. al., 2009).
7. The uncollected and collected carbon dioxide fraction of landfill gas derived from the biological wastes is taken as biogenic since humans consume plants and animals (that consume plants) grown while capturing carbon dioxide. Thus, this carbon dioxide is assigned a zero impact value.
8. Some organic carbon is sequestered in the landfill (essentially permanently) and that is taken as 12 wt % of the input organic carbon to landfill (Barlaz, et. al., 2009).
9. The collected landfill gas experiences a 3 wt % loss in the collection system.
10. The balance of the collected gas (65 wt % - 3 wt % = 62 wt %) ends up in the U.S. as 50% for combustion with electricity generation and 50% as flared. Both of these outcomes lead to carbon dioxide emissions and as in #7 above are assumed to be biogenic origin and hence a zero impact value. Non-biogenic carbon is not zero impact.
11. The methane lost to the atmosphere is multiplied by 24 to obtain the carbon dioxide equivalent loss (Bogner, et. al., 2007).
12. The drapes and tapes are landfilled as plastic waste and are essentially not degradable, but incur the operating energy of placement in the landfill, based on the mass of the drapes and tapes.

The assumptions and flow of 1,000 kg of biogenic carbon to the landfill are shown in Figure 7.1. The energy for landfilling of biological waste was associated with three components of the life cycle assessment:

The methane that escapes to the atmosphere was converted into carbon dioxide equivalents using a factor of 24. Then, from analysis of multiple energy processes involving combustion, the approximate factor of 0.0608 kg CO_2eq/MJ natural resource energy combusted was used to obtain the energy fuel equivalent (MJ) to this lost methane. On the basis of 1,000 kg of biological waste landfilled and the results from Figure 7.1, the methane emissions are equivalent to 44,700 MJ of fuel combustion, Table 7.1. The overall mass of biological waste (0.643 kg degradable organic carbon as TOC per 1,000 landfilled drapes) was used to estimate the mass of waste associated with a fixed amount of organic carbon generated in health care practices. This biological waste incurs process energy from the landfill practices, Table 7.1 (Manfredi, et. al., 2009). The methane captured and used for electricity production was an energy credit based on the fuel value and is shown in Table 7.1 (-2,120 MJ/1,000 kg wet biological waste landfilled).

For 1,000 kg wet biological waste, 169 MJ process energy was assessed for construction and operation of the landfill. The methane emitted to the atmosphere had a GWP CO_2eq equal to 44,700 MJ NRE. The utilization of the landfill gas for electricity generation was a credit (-2,120 MJ), Table 7.1.

The landfill LCI for 1,000 disposable surgical drapes (307 kg non-degradable plastic, drapes plus tapes plus packaging) is shown in Table 7.2. The landfill LCI for reusable surgical drapes is similar, but scaled from 307 kg plastic to 68.0 kg plastic (drapes plus packaging), Table 7.2. In addition to the non-degradable plastic, degradable biological health care waste is also landfilled. The landfill of degradable health care waste is determined as the calculated biological waste of 0.643 kg/1,000 surgical drapes. The landfill LCI for the biological waste is shown in Table 7.3 and is the same for both reusable and disposable drapes on a per drape basis.

The EOL boundary for the packaging for reusable and disposable surgical drapes included the common practice of recycling the corrugated boxboard. Landfill operations were included for the various amounts of plastics used as packaging for reusable and disposable surgical drapes.

The EOL boundary for surgical tapes used with disposable drapes included landfill operations. The EOL boundary for surgical tapes used with reusable drapes included wastewater treatment, as the tapes were considered to decompose in the laundry.

Figure 7.1 Life cycle inventory schematic of methane and carbon dioxide fate in landfill

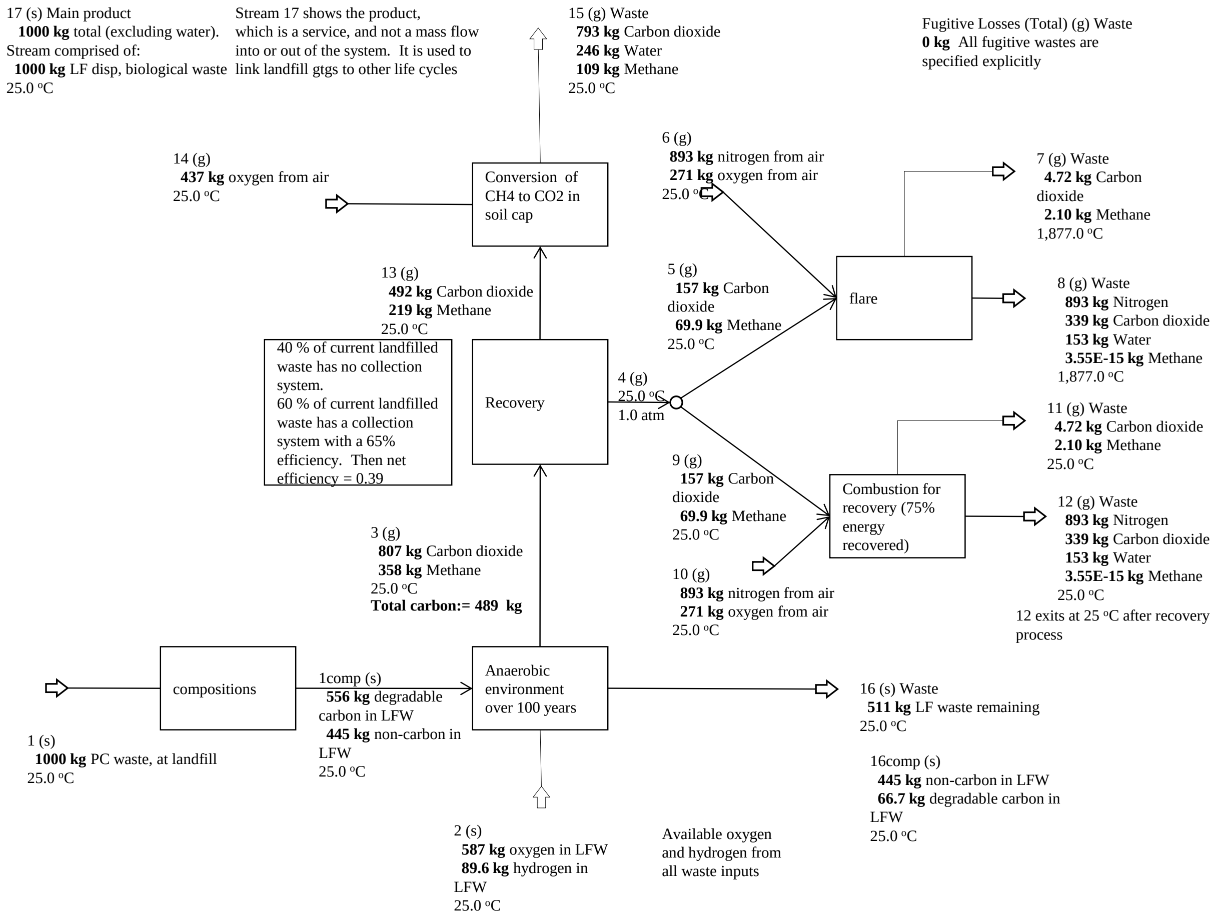

Table 7.1 Process energy per 1,000 kg of landfill input waste for infrastructure and operating a conventional landfill (Manfredi, et. al., 2009) and examples using 1,000 uses disposable and reusable surgical drapes and tapes and associated biological waste

Item	wet biological waste to landfill (88% degradable), MJ/1,000 kg	307 kg plastic (non-degradable waste) to landfill, MJ / 1,000 disposable drapes	68.0 kg plastic (non-degradable waste) to landfill, MJ / 1,000 reusable drapes	0.643 kg biological waste to landfill, MJ / 1,000 surgical drapes
Operating equipment, diesel	77			
Construction operating equipment, diesel	29			
Overhead electricity	43			
Liner, cradle-to-gate of material [a]	18			
Drainage material, cradle-to-gate [b]	2			
Total, diesel	108	33.2	7.34	0.0694
Total, electricity	48.4	14.9	3.29	0.0311
Total, natural gas	12.6	3.87	0.857	0.00810
Overall process energy input	169	51.9	11.5	0.109
Potential recovery for methane burned for energy [c]	-2,830	0	0	-1.82
Methane lost to atmosphere [d]	44,700 (114 kg CH_4)	0	0	28.7 (0.073 kg CH_4)

[a] Energy estimated to be 40% electricity and 60% natural gas, corrected NRE to process energy

[b] Energy estimated to be diesel, corrected NRE to process energy

[c] 75% efficiency based on HHV in energy recovery system

[d] Expressed as an equivalent fuel combusted to give the same carbon dioxide equivalent emission (kg CH_4 * 24 kg CO_2eq / kg CH_4 * 16.45 MJ fuel / kg CO_2eq)

Note: This Table includes energy requirements for landfill operation. Transport to the landfill is not included in the table, but is included in the overall life cycle and is shown in and Table 7.2 and Table 7.3 as “PC waste, at landfill, ctg.”

Table 7.2 Summary of cradle-to-gate life cycle inventory for landfill disposal of 1,000 kg plastic

Modules comprising the major components of LF disp, plastic, 05/07/2018	Mass architecture of LF disp, plastic, kg/1000 kg LF disp, plastic	Process energy, MJ/1000 kg LF disp, plastic						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
LF disp, plastic, gtg	1,000	48.4	0	0	121	0	0	169
cradle-to-gate data								
PC waste, at landfill, ctg	1,000	0.0700	0	0	214	0	0	214
Total mass of ctg inputs	1,000							
Total mass of product, kg	1,000							

Total ctgs	0.0700	0	0	214	0	0	214
Total gtgs	48.4	0	0	121	0	0	169
Total Process Energy, MJ/1000 kg LF disp, plastic	48.5	0	0	335	0	0	383

Modules comprising the major components of LF disp, plastic, 05/07/2018	Mass architecture of LF disp, plastic, kg/1000 kg LF disp, plastic	Natural Resource energy (nre*), MJ/1000 kg LF disp, plastic						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
LF disp, plastic, gtg	1,000	155	0	0	139	0	0	294
cradle-to-gate data								
PC waste, at landfill, ctg	1,000	0.224	0	0	246	0	0	246
Total mass of ctg inputs	1,000							
Total mass of product	1,000							

Total ctgs	0.224	0	0	246	0	0	246
Total gtgs	155	0	0	139	0	0	294
Total Natural Resource Energy, MJ/1000 kg LF disp, plastic	155	0	0	385	0	0	540

Note: This Table represents landfill collection and operation for 1,000 kg inert plastic. For disposable surgical drape systems, 245 kg drape, 57.0 kg packaging, and 5.26 kg tape are landfilled (307 kg total plastic) for a total of 118 MJ process energy and 166 MJ NRE. For reusable surgical drape systems, 58.1 kg packaging are landfilled. The drapes weigh 9.6 kg. Thus, 68.0 kg total plastic for the case where a secondary use is not done. The total energy was 22 MJ process and 31 MJ NRE with secondary use and a total of 26.0 MJ process energy and 36.7 MJ NRE without a secondary use.

Table 7.3 Summary of cradle-to-gate life cycle inventory for landfill disposal of 1,000 kg biological waste

Modules comprising the major components of LF disp, biological waste, 05/07/2018	Mass architecture of LF disp, biological waste, kg/1000 kg LF disp, biological waste	Process energy, MJ/1000 kg LF disp, biological waste						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
LF disp, biological waste, gtg	1,000	48.4	0	0	121	0	-2,831	-2,662
cradle-to-gate data								
PC waste, at landfill, ctg	1,000	0.0700	0	0	214	0	0	214
Total mass of ctg inputs	1,000							
Total mass of product, kg	1,000							
	Total ctgs	0.0700	0	0	214	0	0	214
	Total gtgs	48.4	0	0	121	0	-2,831	-2,662
	Total Process Energy, MJ/1000 kg LF disp, biological waste	48.5	0	0	335	0	-2,831	-2,448

Modules comprising the major components of LF disp, biological waste, 05/07/2018	Mass architecture of LF disp, biological waste, kg/1000 kg LF disp, biological waste	Natural Resource energy (nre*), MJ/1000 kg LF disp, biological waste						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
LF disp, biological waste, gtg	1,000	155	0	0	139	0	-4,069	-3,776
cradle-to-gate data								
PC waste, at landfill, ctg	1,000	0.224	0	0	246	0	0	246
Total mass of ctg inputs	1,000							
Total mass of product	1,000							
	Total ctgs	0.224	0	0	246	0	0	246
	Total gtgs	155	0	0	139	0	-4,069	-3,776
	Total Natural Resource Energy, MJ/1000 kg LF disp, biological waste	155	0	0	385	0	-4,069	-3,529

Note: This Table represents landfill collection and operation for 1,000 kg biological waste. For disposable surgical drape systems, 0.643 kg biological waste is landfilled for a total of -1.57 MJ process energy and -2.27 MJ NRE. For reusable surgical drape systems, 0.0107 kg biological waste is landfilled for a total of -0.0262 MJ process energy and -0.0378 MJ NRE.

Alternate EOL Pathways: Reuse and Recycling

An alternate EOL boundary for reusable surgical textiles includes the practice of reusing these textiles for other non-surgical purposes. In fact, surgical gowns and isolation gowns are often “downgraded” at end-of-life for use in other applications. The reuse activities result in an environmental benefit equal to the energy avoided by not manufacturing the garments being replaced. The credit associated with this benefit is attributed to the clinic or distributing company that collects and reuses the textiles. Therefore, in the case of reuse, the collection, reuse, and landfill activities and credits are outside of the boundary of this LCI. In the case of reuse, the only items landfilled are the plastic packaging. Reuse of reusable surgical drapes in other industries results in a reduction in solid waste generation of about 14%.

Recycling disposable surgical drapes at end-of-life could potentially lead to significant reductions in solid waste generation, as the drape itself accounts for about 80% of the solid waste generated at the health care facility. Recycling is also a possibility with reusable surgical drapes, as both drapes are primarily plastic materials. However, to achieve a complete environmental analysis regarding the potential benefits of recycling, additional evaluation of specific recycling processes would be needed.

Loss of Instruments

In addition to degradable wastes, it has been noted that surgical instruments are also lost with disposable systems from health care facilities to the landfill. This is measured from reusable textile systems where these instruments arrive at the laundry with surgical textiles and are recovered. The recovered instruments are cleaned, sterilized, and returned to the appropriate hospital, an important economic savings. The mass and number of instruments lost were based on studies from two industrial contacts. There are a surprising variety of lost instruments, but as a preliminary estimate these are assumed to be 304 stainless steel. For the stainless steel shape, a sponge stainless steel bowl was selected. For disposable drape systems, these instruments are assumed to be lost to the landfill and thus the manufacture of an equivalent mass of instruments was assigned to the end-of-life in the disposable LCI.

The amount of accumulated lost instruments was found to be 0.22 – 0.28 kg instruments/1,000 reusable surgical gowns in a previous study. The weight of lost instruments is assumed to be the same for 1,000 disposable surgical top drapes. The average weight of the lost instruments was about 0.27 kg per instrument. The cradle-to-gate LCI for the 304 stainless steel sponge basin is shown in Table 7.4, on a 1,000 kg basis. This was then used with the 0.22 – 0.28 kg lost stainless steel instruments/1,000 disposable drapes as a part of the overall LCI, see Chapter 1 on CTEOL of reusable and disposable drapes.

Table 7.4 Summary of cradle-to-gate life cycle inventory for production 1,000 kg stainless steel bowl

Modules comprising the major components of stainless steel bowl, 05/07/2018	Mass architecture of stainless steel bowl, kg/1000 kg stainless steel bowl	Process energy, MJ/1000 kg stainless steel bowl						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
stainless steel bowl, gtg	1,000	1,400	0	0	0	440	0	1,840
cradle-to-gate data								
304 stainless steel, ctg	1,273	2,701	167	551	3,620	1,818	-734	8,123
Total mass of ctg inputs	1,273							
Total mass of product, kg	1,000							
	Total ctgs	2,701	167	551	3,620	1,818	-734	8,123
	Total gtgs	1,400	0	0	0	440	0	1,840
	Total Process Energy, MJ/1000 kg stainless steel bowl	4,101	167	551	3,620	2,258	-734	9,963

Modules comprising the major components of stainless steel bowl, 05/07/2018	Mass architecture of stainless steel bowl, kg/1000 kg stainless steel bowl	Natural Resource energy (nre*), MJ/1000 kg stainless steel bowl						
		Electricity	Dow-therm	Steam	Non-transport direct use of Fuel	Transport Fuel	Heat potential recovery	Total Net Energy
gate-to-gate data								
stainless steel bowl, gtg	1,000	4,480	0	0	0	528	0	5,008
cradle-to-gate data								
304 stainless steel, ctg	1,273	8,643	240	792	4,163	2,182	-1,055	1.50E+04
Total mass of ctg inputs	1,273							
Total mass of product	1,000							
	Total ctgs	8,643	240	792	4,163	2,182	-1,055	1.50E+04
	Total gtgs	4,480	0	0	0	528	0	5,008
	Total Natural Resource Energy, MJ/1000 kg stainless steel bowl	1.31E+04	240	792	4,163	2,710	-1,055	2.00E+04

Note: This Table represents production of 1,000 kg stainless steel bowl to replace surgical instruments lost to the landfill. For disposable surgical drape systems, 0.220 kg surgical instruments are produced for a total of 2.19 MJ process energy and 4.40 MJ NRE.

Summary

The energy and emissions for landfill processes are dominated by transport to the landfill and operation of the landfill.

Table 7.5 is a comparison of the NRE for the end-of-life phase for reusable and disposable surgical drape systems.

Table 7.5 Summary of NRE for end-of-life phase, reusable and disposable surgical drape systems

	NRE	
	MJ/1,000 drape uses	% of CTEOL NRE
Reusable surgical drape system	31	0.26%
Disposable surgical drape system	168	0.94%

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Chapter 8 TRANSPORT

Background and Methodology

Different transportation scenarios were used for the reusable surgical drapes and associated tapes, disposable surgical drapes and associated tapes, and for the chemicals used in the supply chain of 1,000 drape uses. The cradle-to-end-of-life transport examined in the life cycle study included:

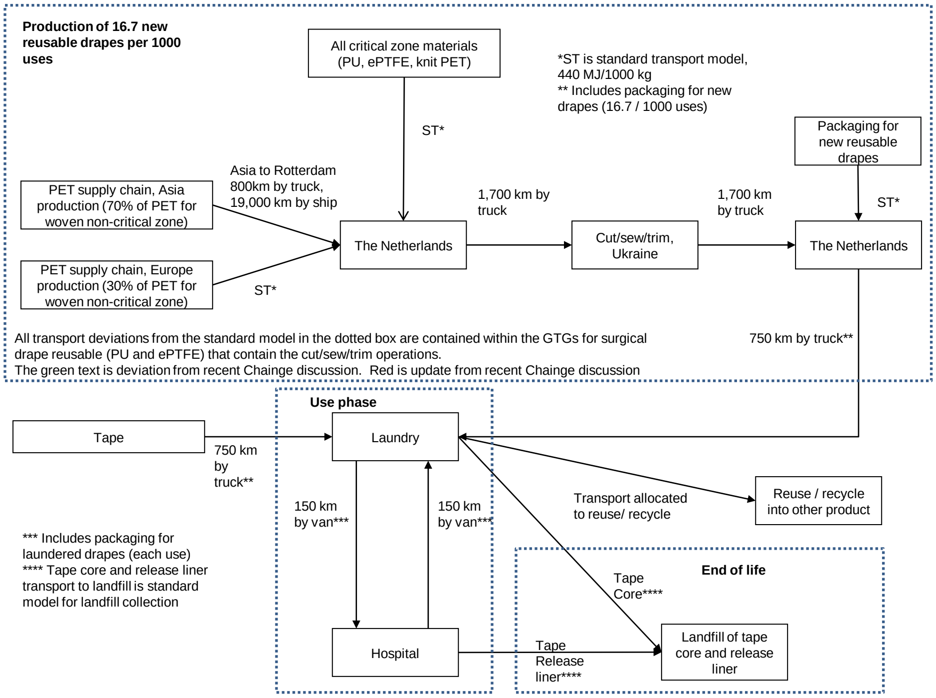
1. One-way transport of all materials used in the drape and tape supply chains from natural resources to the drape and tape manufacturing plants (cradle-to-gate).
2. One-way transport of drapes and tapes from the manufacturing plants to distribution centers (gate-to-gate).
3. Round-trip transport of reusable drapes from the distribution center to the laundry facility (gate-to-gate).
4. Most of the reusable drapes and associated tapes are sterilized at the laundry, and most disposable drapes and associated tapes are sterilized at the kit packing facility. Thus, no additional transport was used for sterilization in this study. The small amount of sterilization associated transport that is sometimes used in practice has negligible impact on the results.
5. One-way transport of disposable drapes and tapes from the health care facility to the landfill or point of reuse (gate-to-end-of-life). One-way transport of tape release liner and tape core from the tape used for reusable drape system.

Materials for reusable drapes were considered to be manufactured in both Asia and Europe. About 70% of the PET materials used in the non-critical zone were manufactured in Asia, and transported to Europe for drape manufacture. Disposable drapes were considered to be manufactured in China, and surgical tapes for both drapes were considered to be manufactured in Europe for purposes of transport calculations in this study.

The Environmental Clarity database uses default transport distances for most chemicals based on U.S. industrial chemical data. The transport scenario for supply chain chemicals and materials (#1 in the above list) is not expected to have a large impact on the final results. Thus, within the supply chains for surgical drape and tape manufacture, most gate-to-gate (GTG) life cycle inventories (LCIs) were assigned a default transport distance of 330 miles, as the U.S. average distance for shipping industrial chemicals (U.S. Dept. of Commerce, 1997). The 330 miles was 50% train, 30% truck, and 20% inland ship. These had energy uses (MJ/1,000 kg/km) of 0.25, 1.05, and 0.37 respectively. Together, the transport energy was 440 MJ/1,000 kg for these supply chain chemicals. Occasionally, other transport energy values were used, especially when it was well-known that a material is transported long distances. Examples include mineral ores that are typically mined in Africa and South America.

The energy consumption for final delivery of the drapes and tapes to distribution centers, laundry facilities, sterilization facilities, and landfills (#2 through #5 in the above list) was explicitly calculated based on detailed transportation scenarios shown in Figure 8.1 and Figure 8.2. The calculations are shown in detail in the Results section below.

Figure 8.1. Transport scenario for reusable drape system

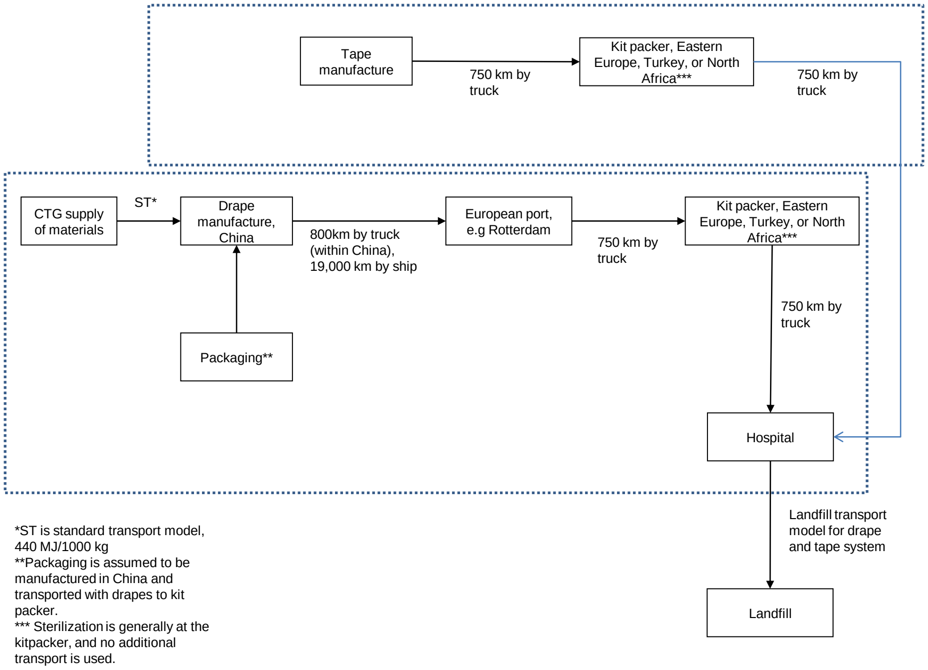


*ST is standard transport model, 440 MJ/1000 kg
** Includes packaging for new drapes (16.7 / 1000 uses)

All transport deviations from the standard model in the dotted box are contained within the GTGs for surgical drape reusable (PU and ePTFE) that contain the cut/sew/trim operations.
The green text is deviation from recent Chainge discussion. Red is update from recent Chainge discussion

*** Includes packaging for laundered drapes (each use)
**** Tape core and release liner transport to landfill is standard model for landfill collection

Figure 8.2. Transport scenario for disposable drape system



*ST is standard transport model, 440 MJ/1000 kg
**Packaging is assumed to be manufactured in China and transported with drapes to kit packer.
*** Sterilization is generally at the kitpacker, and no additional transport is used.

Results

Reusable Surgical Drape System

Reusable surgical drapes were proposed to have a portion the fabric or fibers produced in Asia. The remainder of the fabric supply chain and fabric was in Western Europe. The cut, sew, and trim operations were in Eastern Europe. Cut-sew-trim losses were 3% of the product weight. Thus, for each kg of completed drape, there were 1.03 kg materials transported to cut-sew-trim operations. The energy for each operation is summarized in Table 8.1 on a 1000 kg drape basis. Transport of materials manufactured in Asia required 800 km by truck and 19,000 km by ship to a Western European port. This was 70% of the non-critical zone, which was 76% of the drape weight. Thus, the mass was 1000kg*0.7*.76*1.03=547 kg/1000 kg drape. The rest of the non-critical zone material was 235 kg, and this received the standard transport energy of 0.44 MJ/kg. The critical zone materials were 24% of the total weight. Thus, these were 1000*.24*1.03=247 kg, and these also received the standard transport energy of 0.44 MJ/kg. All of the materials (1030kg) kg were transported 1700 km to cut-sew-trim operations, and the full drape weight (1000kg) was transported back to Western Europe. Finally, the drapes (1000 kg) and packaging (179kg) were transported 750 km to the laundry. These distances were used with 1.1 MJ/1,000 kg/km for truck and 0.16 MJ/1,000 kg/km for ship. The total transport energy for new drapes delivered to the laundry 4,992 MJ/1000 kg. Standard transport energies (440 MJ/1000 kg) are included in the input materials to the gtg. Thus, the additional energy added based on the stated transport model is 4,539 MJ/1000 kg. On a basis of 1000 drape uses, this is 9.6 kg drape / 1000 uses * 4.539 MJ/kg = 43.6 MJ/1000 uses. This excludes transport between gtgs in the supply chain of the fabrics and transport from laundry to the hospital.

Table 8.1 Transportation calculations for 1,000 kg new reusable surgical drape, manufacturing facility to distribution center. Transport in use phase is not included in this Table.

Location	**Type**	**Energy (MJ/mt·km)**	**Distance (km)**	**Weight (kg)**	**Energy (MJ/1,000 kg drapes)**
Non-woven PET produced in Asia transported to port in Asia	Truck	1.1	800	547	481
Non-woven PET produced in Asia transported to port in the Netherlands	Ship	0.016	19,000	547	166
Non-woven PET produced in Europe transported to the Netherlands	Standard			235	103
Critical zone materials transported to the Netherlands	Standard			247	109
All materials transported from the Netherlands to cut/sew/trim in Ukraine	Truck	1.1	1,700	1,030	1,926
Cut/sew/trim in Ukraine to the Netherlands (fabric)	Truck	1.1	1,700	1,000	1,870

The Netherlands to hospital (drapes and packaging)	Truck	1.1	750	1,179	337
Total					**4992**
Adjustment for transport counted in supply chain*				**1031**	**-453**
Adjusted total (additional transport for supply chain)					**4,539**

* The fabric inputs have the default transport of 440 MJ/1,000 kg in our database. To avoid double-counting, the already-assigned transport is subtracted from the total transport value calculated above. The amount subtracted is 440 MJ/1,000 kg fabric * 1,031 kg fabric/1,000 kg drape = 454 MJ/1,000 kg drapes.

Surgical tapes required for use with reusable surgical drapes were proposed to be transported 750 km from the manufacturing site in Western Europe to the laundry. Transport of packaging in the amount of 1.23 kg packaging per 6.05 kg tape was also included (see Chapter 5). Transport was by truck, and was 1.1 MJ/metric ton/ km. Thus, for reusable surgical drape systems, the tape transport from manufacturer to customer was 1.1 MJ/1,000 kg/km*750km * (6.05 + 1.23) kg = **6.0 MJ process energy / 1,000 uses reusable surgical drapes**. Note that this energy for transporting reusable drapes from the manufacturer to the customer was accounted for in the tape supply chain gate-to-gates (Chapter 4) and so is therefore not included in the summary for this Chapter.

In the use phase, reusable surgical drapes and associated packaging were transported from the laundry to the hospital and back to the laundry. Sterilization was typically done at the laundry facility. Therefore, no additional transport was included. The transport distance from hospital to laundry was estimated by the Chainge Consortium to be 150km each way.

Reusable surgical drapes are washed before each use (including the first use) and are re-packaged at the laundry center with 0.418 kg packaging / drape. For 1,000 reusable surgical drape uses, (0.576 + 0.418)*1,000 = 994 kg clean drape and packaging are shipped and (0.576*1.543 + 0.360)*1,000 = 1,249 kg soiled drape and packaging are returned (0.543 kg soil/kg drape). Thus, the average mass shipped is (994 + 1,249)/2 = 1,121.5 kg. Fuel consumption for the typical van truck used to transport surgical drapes is 2.56 MJ/1,000 kg/km. Therefore, diesel transport for laundry and sterilization is calculated as 2.56/1000*300*1,121.5 = **861 MJ / 1,000 reusable surgical drape uses**.

Surgical tapes used with reusable drapes are transported from the laundry to hospital and back. The whole tape and packaging are transported to the hospital (6.05 kg tape + 1.23 kg packaging = 7.28 kg). The tape minus the release liner, (6.05kg - 2.7 kg = 3.4 kg per 1000 uses, is transported back. Thus, the weighted average weight transported was (7.23+3.4)/2=5.3 kg. Transport of the tapes to and from is the hospital is calculated as 2.56 MJ/1000 kg/km * (5.3 kg) / 1,000 drape uses * 300 km = **4.10 MJ / 1,000 reusable surgical drape uses**.

The end-of-life for reusable surgical drape systems consisted of reuse in other industries. As a sensitivity analysis, transporting the drapes to a landfill was calculated in to show the impact of landfilling used drapes (see Chapter 7). The landfill transportation energy was based on information from municipal solid waste collections. The transport for this step was included in the landfill gate-to-gates and was **14.6 MJ process energy / 1,000 reusable surgical drape**

uses. This energy value is included in Chapter 7 and therefore is not included in the summary for this Chapter.

Disposable Surgical Drape System

Disposable surgical drapes were proposed to have the fabric, the fabric supply chain, and the cut, sew, and trim operations in China. Transportation of new drapes involved 800 km by truck in China, 19,000 km by ship from China to Western Europe, 750 km by truck to the kit packer, and 750 km by truck to hospitals. These distances were used with 1.1 MJ/1,000 kg/km for truck and 0.16 MJ/1,000 kg/km for ship. This transport distance was also used for the packaging. Thus, for the disposable surgical drapes and the associated primary, secondary, and tertiary packaging, the disposable drape transport was **1,926 MJ process energy / 1,000 disposable surgical drapes**. The calculations are shown in Table 8.2. Note that this energy for transporting disposable fabrics from the manufacturer to the customer was accounted for in the fabric supply chain gate-to-gates (Chapter 2) and is therefore not included in the summary for this Chapter.

Table 8.2 Transportation calculations for 1,000 disposable surgical drapes, manufacturing facility to distribution center

Location	**Type**	**Process Energy (MJ/1,000 kg/km)**	**Distance (km)**	**Weight (kg)***	**Process Energy (MJ/1,000 drapes)**
Plant to port in China (drapes and packaging)	Truck	1.1	800	346	304
Port in China to port in Netherlands (drapes and packaging)	Ship	0.16	19,000	346	1,052
Port to kit packer in Eastern Europe (drapes and packaging)	Truck	1.1	750	346	285
Kit packer to hospital (drapes and packaging)	Truck	1.1	750	346	285
Total					**1,926**

*Each disposable surgical drape weighed 0.245 kg (see Chapter 2). Packaging transported for each disposable surgical drape was 0.1008 kg (see Chapter 3). The basis of the life cycle analysis was 1,000 drapes. Therefore, the total shipping weight was (0.245 kg + 0.1008 kg) * 1,000 drapes = 346 kg.

Surgical tapes required for use with disposable surgical drapes were proposed to have the standard transport energy of 750 km to kit packer and 750 to hospital. Transport of packaging in the amount of 0.743 kg packaging per 5.26 kg tape was also included (see Chapter 5). Thus, for disposable surgical drape systems, the tape transport from manufacturer to customer was 1.1 MJ/1,000 kg/km*1500km * (5.26 + 0.743) kg = **9.9 MJ process energy / 1,000 uses disposable surgical drapes**. Note that this energy for transporting disposable drape tapes from the manufacturer to the customer was accounted for in the tape supply chain gate-to-gates (Chapter 4) and so is therefore not included in the summary for this Chapter.

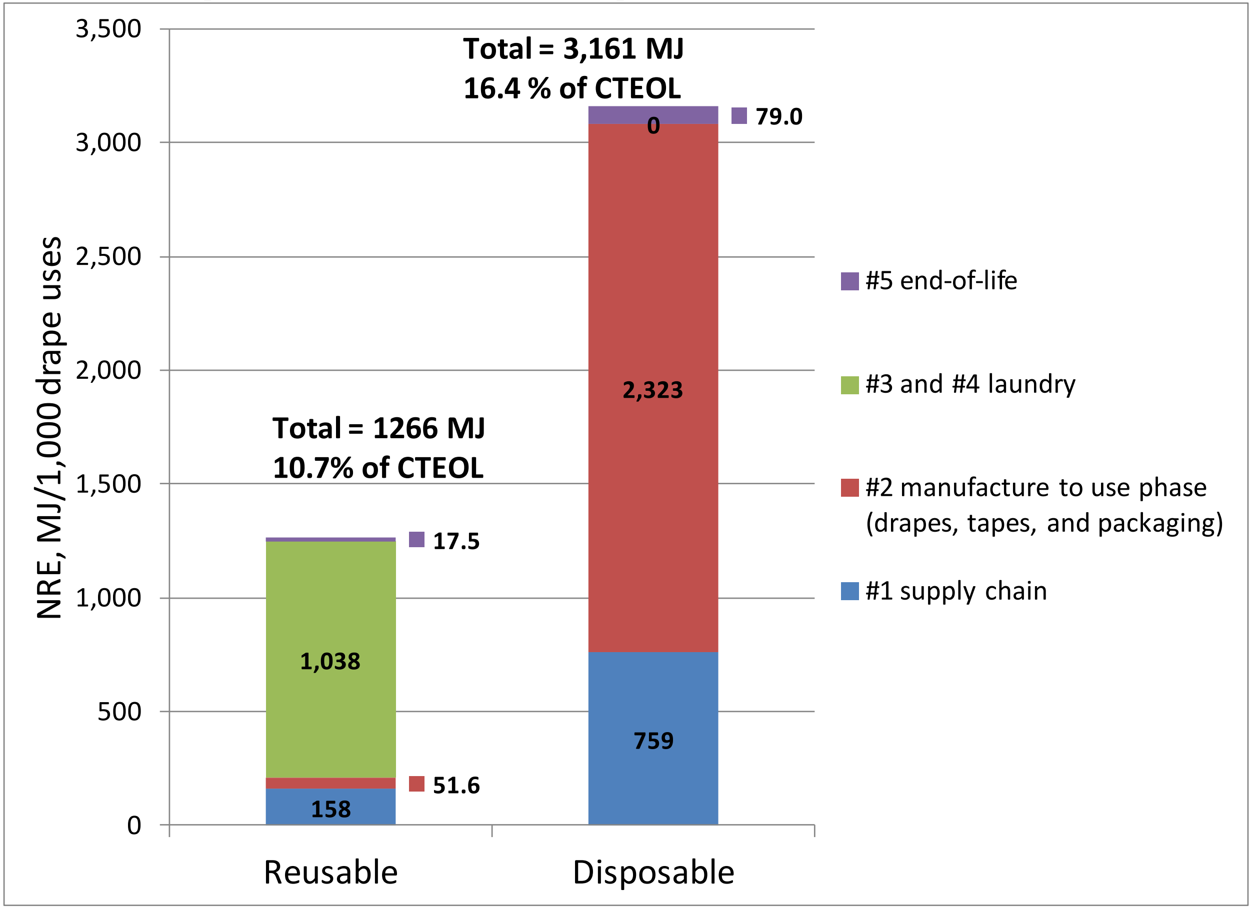
Disposable surgical drapes are not laundered before use, and sterilization generally takes place at the kit packer. Therefore, no additional transportation was used..

The end-of-life for disposable surgical drapes consisted of transporting the drapes to a landfill (see Chapter 7). The landfill transportation energy was based on information from municipal solid waste collections. The transport for this step was included in the landfill gate-to-gates and was **65.8 MJ process energy / 1,000 disposable surgical drapes**. This energy value was included in Chapter 7 and therefore is not included in the summary for this Chapter.

Summary

Reusable surgical drape systems consumed additional transport fuel for transportation of drapes to and from laundry operations when compared to disposable drapes, which are not laundered. However, when considering all transportation throughout the supply chain, reusable surgical drape systems consumed about 60% less transport fuel than disposable drape systems. The transport differences are particularly apparent in the supply chain and manufacturing stages, because 1,000 reusable drape uses consumed over 78% less material (drape, tape, and packaging materials) than 1,000 disposable drape uses. Thus, less material was transported in the early supply chain stages. Diesel transport NRE consumption for reusable and disposable surgical drape systems is summarized in Figure 8.3. Overall, NRE from transport was a relatively low factor in the CTEOL analysis. Transportation energy accounted for 10.7% of CTEOL NRE consumption for reusable drape systems and 16.4% for disposable drape systems.

Figure 8.3 Diesel transport NRE consumption for transportation of surgical drape systems, MJ diesel/1,000 drape uses (reusable = 970 MJ; disposable = 2,745 MJ)



Note: The values in Figure 8.3 are natural resource energies (NRE). For diesel transport, a scale up factor of 1.2 is used to convert process energy to NRE, Table 1.3.

Table 8.3 is a comparison of the NRE for the use-phase transport (items #3 and #4 on page 102 and Figure 8.3) for reusable and disposable surgical drape systems. Items #1, #2 and #5 on page 102 and Figure 8.3 were included in other sections of the report, and are therefore excluded from this summary Table.

Table 8.3 Summary of NRE for use-phase transport, reusable and disposable surgical drape systems

	NRE	
	MJ/1,000 drape uses	% of CTEOL NRE
Reusable surgical drape system	1,038	8.9%
Disposable surgical drape system	0	0%

References

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