Aus der

Universitätsklinik für Urologie Tübingen

Comparative Analyses of the Environmental and Health Impact of Reusable and Single-use Flexible Ureterorenoscopes

Inaugural-Dissertation
zur Erlangung des Doktorgrades
der Medizin

der Medizinischen Fakultät
der Eberhard Karls Universität
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Thöne, Marlene

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I dedicate this thesis to Anna-Katharina Kothe.

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ABBREVIATIONS

°C	Degrees Celsius
ABS	Acrylonitrile butadiene styrene
Approx.	Approximately
AV	Abfallverbrennungsanlage (waste incineration plant)
CAS	Chemical Abstracts Service
CKD	Chronic kidney disease
CVC	Central venous catheter
DALYs	Disability adjusted life years
e.g.	exempli gratia: for example
EI	Environmental impact
EoL	End of life
esp.	especially
ESWL	Extracorporeal Shock Wave Lithotripsy
et al.	et alia (and others)
ETO	Ethylene oxide
Fr	French: Outer diameter of Catheter; 1Fr=1/3mm
fURS	flexible ureteroscope
fURS	flexible ureteroscopes
GaBi	Ganzheitliche Bilanz
GHG	Greenhouse gas/greenhouse gases
GLO	global
GmbH	Gesellschaft mit beschränkter Haftung (limited company)
GWP	Global Warming Potential
HDPE	High-density polyethylene
HI	Health Impact
i.e.	id est (that means)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
kg CO_2eq	kilogram CO_2 equivalents
KrWG	Kreislaufwirtschaftsgesetz
LAGA	Länder-Arbeitsgemeinschaft Abfall
LCA	Life Cycle Assessment
LDPE	Low-density polyethylene
MABS	Methylmethacrylat acrylonitrile butadiene styrene
MDs	Medical devices
OR	Operation room
PE	Polyethylene
PNL	Percutaneous nephrolithotomy
PP	Polypropylene
PPE	Personal Protective Equipment
RDG-E	Reinigungs- und Desinfektionsgeräte für Endoskope (cleaning and disinfection equipment for endoscopes)
RIRS	Retrograde Intrarenal Surgery

ru	reusable
su	Single-use
tkm	tonne-kilometre
U	Unit process
UKT	Universitätsklinik Tübingen: University Hospital Tübingen
URS	Ureterorenoscopy
UTI	Urinary tract infection
vs.	versus

I INTRODUCTION

I.1 ENVIRONMENT AND HEALTH

I.1.1 GENERAL INFORMATION AND SCIENTIFIC BASIS

Human health depends on a functioning environment (Whitmee et al., 2015). Both the environment and human health are threatened by climate change. This linkage is called *Planetary Health* (Prescott et al., 2022). For example, extreme heat can cause or deteriorate different diseases. Kidney stones, for instance, are more likely to form when the body is dehydrated: When solubility is low due to lack of water (perspiration), precipitation is more likely (Romero et al., 2010).

I.1.2 THE CLIMATE IMPACT OF HEALTH CARE

The environment is damaged by human actions due to use of resources, pollution and waste (Sherman et al., 2020). Ongoing technical development of medical material can also impact ecosystems (Sousa et al., 2020). Globally, the health care sector is responsible for around 4% of greenhouse gas emissions (Karliner et al., 2019).

The production and disposal of materials for daily clinical use account for approx. 19% of the emissions of the healthcare system and therefore play an important role in climate protection in the healthcare sector (Tennison et al., 2021). 5% of German raw material consumption is attributable to the healthcare sector (Karliner et al., 2019).

I.1.3 GREENHOUSE GAS EMISSIONS AND CARBON FOOTPRINT

Alexander von Humboldt described human-influenced climate change as early as 1800, warning about destructive deforestation and the consequences for soil conditions, water levels, and the climate (Wulf, 2016).

In 2008, The Lancet created the first commission to describe climate change as the greatest threat to human health in the current century (Costello et al., 2008). The Lancet Countdown report of the year 2021 specifically mentions health threats like heatwave exposure, reduction in work capacity, increasing exposure to wildfires, transmission of infectious diseases, sea level rise, declining crop yield and quality and areas affected by drought (Romero et al., 2010).

Mean global temperature is steadily increasing (1.2°C ± 0.1°C higher than at the beginning of the industrial age, reference period 1850-1900) (Schulz & Simon, 2021).

The emission of greenhouse gases is the cause of the increase of the global average temperature (Schulz & Simon, 2021). The atmospheric concentration of carbon dioxide (CO_2) reached values of 300 parts per million (ppm) for the first time around 1900. In 2019, the level was 411 ppm. If other greenhouse gases are included, the level is 500 ppm CO_2 equivalents (Montzka, 2020) which, according to the Intergovernmental Panel on Climate Change, is above the value that would be necessary in order to avoid a warming of 2°C since the beginning of the industrial age (IPCC, 2021).

The carbon footprint has been defined as "*a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product*" by Wiedmann and Minx (2008).

I.1.3.1 MEDICAL WASTE

German hospitals are considered the fifth largest producer of waste in Germany (Lenzen-Schulte, 2019).

On the basis of the German waste management system (*Länder-Arbeitsgemeinschaft* Abfall, LAGA), medical waste must be disposed of in a way that neither health nor the environment is endangered. The LAGA suggests a waste hierarchy (Figure 1) that implies the following steps: 1. Prevention ("Abfallvermeidung"), 2. Reprocessing ("Wiederverwendung"), 3. Recycling („Aufbereitung“), 4. Other recovery („Sonstige Verwertung“), 5. Disposal („Abfallbeseitung“) (Bund/Länder-Arbeitsgemeinschaft Abfall, 2015).

Figure 1: Waste hierarchy. From Thöne, 2023 with kind permission of Dr. med. Julia Tabatabai, Heidelberger Klinische Standards, Medizinische Fakultät, Universität Heidelberg on March 28, 2023.

Part of the hospital waste is generated by the use of disposable products. Commonly, medical instruments and care products are either reprocessed for reuse (reusable products) or thrown away after use (single-use products).

I.1.3.1.1 Recycling

Recycling (re, Latin: back, again; ký́klos, Greek: circle) means the conversion of products into raw material for reuse. It is part of the waste hierarchy and aims at reducing resource demand and greenhouse gas emissions. In Germany, recycling has been established over the last decades. However, there are still challenges to fully implement recycling structures into everyday life. Even more challenging might be the introduction of recycling strategies for hospitals and other healthcare establishments. However, new ideas and pilot projects may be developed in the future.

I.1.4 PLANETARY HEALTH AND UROLOGY

I.1.4.1 THE CONCEPT OF PLANETARY HEALTH

Planetary Health is a concept that describes the interrelation between humans and the planet. The term was introduced in initial committees and articles on climate change and health in the early 2000s and has since become established.

While human health depends on the functioning of the planet’s ecosystems, human actions have an impact on these ecosystems.

The interaction between climate change and health should be considered by health professionals (Gabrysch, 2018).

I.1.4.2 CLIMATE EFFECTS ON HEALTH

Extreme heat is one of the effects of climate change on the human body. Pathophysiologically, heat stroke causes the body to heat up to >40°C, which cannot be compensated by sweating. As part of thermoregulation, vasodilation occurs, the heart rate increases reactively to maintain cardiac output, and a hypovolemic shock may result. Cardiac diseases, for example in the elderly, accordingly, favor the occurrence of heatstroke. Children are also particularly affected by heat (Martiello & Giacchi, 2010). Urologic diseases such as transitional cell cancer can be caused by environmental carcinogens (e.g. arsenic) and may be linked to damaged ecological systems (Letasiova et al., 2012). Another organ that is affected by climate change is the kidney.

I.2 KIDNEY DISEASES AND CLIMATE IMPACT

I.2.1 THE KIDNEY

As a central organ of blood volume and pressure and osmoregulation, the kidney plays a special role in the body's fluid balance. Its high metabolic workload leads to increased sensitivity to external influences. Thus, the kidney is one of the organs most affected by climate change.

I.2.2 KIDNEY DISEASES LINKED TO HEAT

Acute kidney failure can result from heat stroke. The Chicago heat wave of 1995, for example, caused acute kidney failure in over half of the heat stroke victims (Dematte et al., 1998). Increasing evidence is emerging for the presence of an association between recurrent heat episode-related acute renal failure and chronic kidney disease (CKD) (Johnson et al., 2019).

Although it has mechanisms that protect the body from heat stress, the kidney is one of the most vulnerable targets within the body when exposed to heat. For example, studies have shown that hospital admissions due to kidney diseases become more frequent with increasing heat. These included acute kidney failure, chronic kidney disease (CKD), electrolyte shifts, urinary tract infections and kidney stones (Johnson et al., 2019). If global warming continues, a sharp increase in kidney stone disease can be expected in particularly affected regions (Kuhlmann & Jabs, 2021).

Furthermore, the increased body temperature causes proteins that normally function optimally at a certain temperature (e.g. enzymes) to change their structure and form aggregates (=denaturation). This leads to the possible malfunctioning of the cells. The general overload of the body's own processes by the externally increased heat supply ultimately leads to an exaggerated immune response via resulting cell damage, which can cause microcirculatory reactions and induce multi-organ failure (Epstein & Yanovich, 2019).

The development of the term "CINAC-Chronic Interstitial Nephritis in Agricultural Communities" covers the disease patterns formerly known as "Global Warming Nephropathy" and "Mesoamerican Nephropathy" (Wilke et al., 2019). This is the development of CKD due to the combination of heat and physical labor, with exposure to environmental toxins also favoring disease development. In the case of young field workers who have no access to adequate therapy (dialysis), the disease initially leads to an incapacity to work culminating in premature death due to the disease. This also shows the social aspect of kidney disease caused by climate change.

However, the most prevalent kidney disease associated with climate change is probably urolithiasis. Heat and sunlight exposure are significant risk factors for lithogenesis and renal colic (Fakheri & Goldfarb, 2011). Fakheri and Goldfarb assumed the high prevalence rate of this condition to increase by 10% in the course of 50 years. They also point out the economic burden resulting from this (Fakheri & Goldfarb, 2011); however, this will not be the focus of this study.

I.2.3 UROLITHIASIS

Kidney stones (urinary stones) are concretions forming in the kidneys or urinary tract when crystalizing blood components exceed their solubility product (nephrolithiasis, ureterolithiasis or, independent of location: urolithiasis). They can consist of calcium oxalate (around 75% of renal calculi), uric acid or struvite (both about 10%) or other substances (cystine, calcium phosphate, xanthine) (Leusmann, 1991).

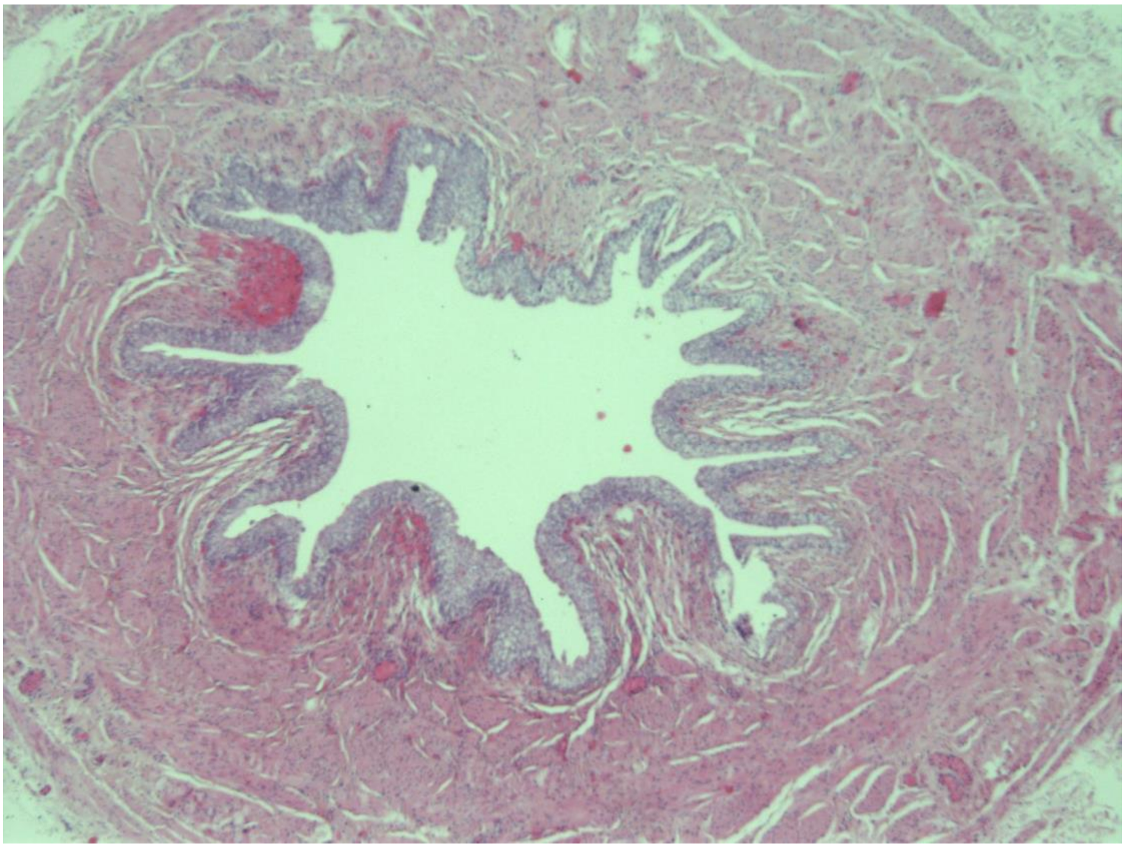


Figure 2: Ureter, cross-section. With kind permission of Dr. med. Jürgen Knolle, Institute of Pathology Halle-Dölau on March 27, 2023.

I.2.3.1 EPIDEMIOLOGY

The prevalence and incidence of nephrolithiasis is increasing worldwide, undulating with food (esp. starchy food) availability, for instance (Romero et al., 2010). In the USA, approximately 10% of the population suffer from kidney stone disease (Glazer et al., 2022). The prevalence of kidney stones peaks at the age of 30-60 years (Prince & Scardino, 1960) and is more likely for persons with a kidney stone history (Glazer et al., 2022).

Patients are predominantly male (Prince & Scardino, 1960, Romero et al., 2010). Geographical and "*racial*" criteria also affect kidney stone formation (Stamatelou et al., 2003, Dallas et al., 2017, Glazer et al., 2022). Other, partly modifiable risk factors for urolithiasis are diabetes, obesity and the metabolic syndrome (Goldfarb & Hirsch, 2015).

Even before the turn of the millennium, studies hypothesized a link between sunlight and hypercalciuria (Parry & Lister, 1975) and a higher prevalence of urolithiasis in the hot summer months (Prince & Scardino, 1960):

"*The seasonal variation is quite striking, and the incidence curve follows with remarkable closeness the temperature curve throughout the year"*.

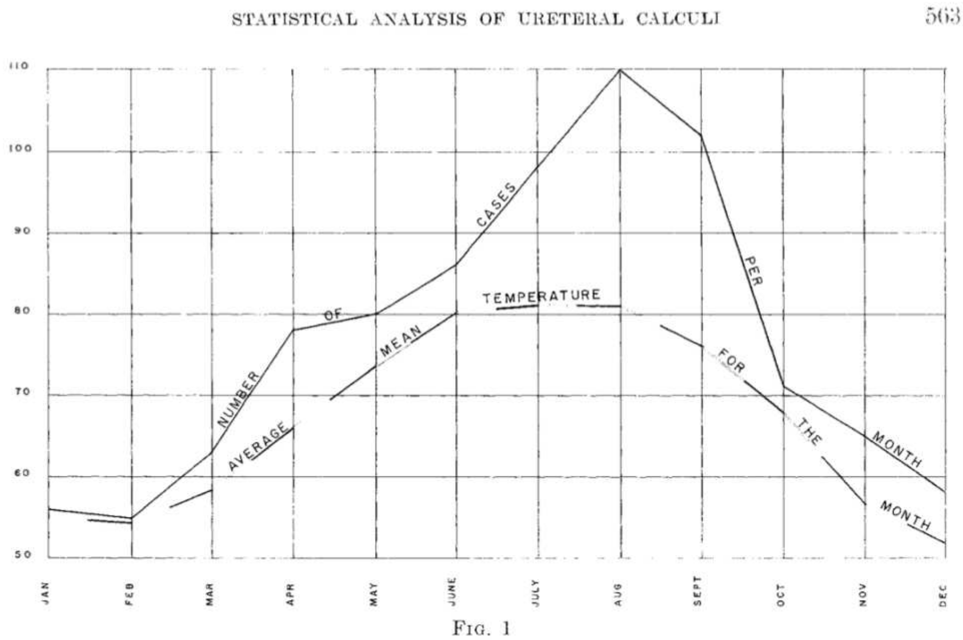


Figure 3: Ureteral calculi and temperature (from Prince & Scardino, 1960. License granted on March 27, 2023 by Wolters Kluwer Health, Inc., License number: 5517000394082)

More recent studies suggest global warming to be implicated in the formation of kidney stones (Romero et al., 2010, Fakheri & Goldfarb, 2011, Goldfarb & Hirsch, 2015, Chu et al., 2022):

"(…) a body of literature suggests a role of heat and climate as significant risk factors for lithogenesis" (Fakheri & Goldfarb, 2011).

Stamatelou and Goldfarb stated in the beginning of 2023 that the "*Climate*" was "*undeniably involved in the development of kidney stones*" (Stamatelou & Goldfarb, 2023).

I.2.3.2 DIAGNOSIS AND PROGNOSIS

Ureteral calculi are diagnosed by sonography (first choice); CT is considered the gold standard. Stone analysis can be performed by infrared spectrometry, X-ray diffraction analysis and polarization microscope. The prognosis of kidney stone disease is quite favourable (Glazer et al., 2022).

I.2.3.3 Therapy

There are conservative and interventional treatment options for urolithiasis. Uroliths in themselves do not necessarily require therapy. However, when urinary stones become symptomatic (=urinary stone disease), they can cause severe colic. Initial pain therapy (e.g. metamizole), which is often indicated along with fluid intake, may also promote stone passage (Seitz et al., 2019). Large or obstructing stones may require interventional therapy, most commonly ureterorenoscopy. Less frequently applied techniques are extracorporeal shock wave lithotripsy (ESWL) and percutaneous nephrolithotomy (PNL, first choice for stones >20mm). Metaphylaxis (post-treatment) is recommended in some cases as urinary stones may reoccur.

I.2.4 Ureteroscopy

Ureterorenoscopy (or: ureteroscopy; URS) represents a common therapeutic intervention for kidney stones (Deininger et al., 2018) and is also used for diagnostic purposes. Post intervention, the insertion of a temporary double J-catheter that serves to drain the urine while the ureteral mucosa is swollen is frequent.

Flexible ureteroscopes (fURS) are medical devices commonly used in urology to diagnose and treat kidney stones (Wason et al., 2022). They have been called an "*endoscopic key to the upper urinary tract*" by Wason et al. (2022). Ureteroscopy is also used for *detection* and treatment of strictures and urothelial carcinoma (e.g. via laser ablation or vaporization).

Figure 4: Reusable fURS. Picture taken by Marlene Thöne at Universitätsklinikum Tübingen (UKT).

Figure 5: Single-use fURS. Picture taken by Marlene Thöne at Universitätsklinikum Tübingen (UKT).

I.2.4.1 DESIGN OF THE INSTRUMENT

After the introduction of the rigid ureteroscopes by Karl Storz in 1980, Olympus expanded the field during the 1980s by converting a pediatric bronchoscope into a deflectable flexible ureteroscope. In 1989, the semirigid ureteroscope was introduced to the market. This allowed flexion of the device with intact visualization function (Wason et al., 2022).

Meanwhile, miniature devices such as cameras and stone baskets are standard in modern ureterorenoscopy and flexibility ranges up to 275 degrees.

In more detail, flexible ureteroscopes consist of a handle and a flexible tube (6 to 9 Fr, sheath: 9 to 16 Fr). The tube contains the working channels for irrigation and instrument insertion (wire baskets, electrocautery, biopsy forceps). Ureteroscopy with lithotripsy (stone disintegration) requires special instruments such as laser fibers or ultrasound, electrohydraulic and pneumatic probes (Wason et al., 2022).

Flexible ureteroscopes are equipped with a digital camera for image transmission and a deflectable tip which provides access to the (most tortuous) lower pole of the kidney. As described above, there are semi-rigid ureteroscopes (deflection <10 degrees) as well; however, in our study, we focus on the flexible instruments as they are usually used in the University Hospital of Tübingen (Universitätsklinikum Tübingen, UKT).

I.2.5 Reusable vs. single-use

Currently, reusable (ru) and single-use (su) flexible ureteroscopes are on the market. At the UKT, reusable fURS are more commonly used. However, "*Single-use flexible ureteroscopes are already widely adopted within urology practices (…)*" (Rindorf et al., 2021).

Earlier studies have compared the costs and clinical efficiency of reusable vs. single-use devices (Deininger et. al, 2018, Mager et al., 2018, Dragos et al., 2019, Ventimiglia et al., 2020). According to the authors of earlier studies, reusable and single-use fURS are functionally equivalent:

„*Overall success rate as main outcome parameter and stone-free rate, operation time and radiation exposure as additional outcome parameters demonstrated no significant difference between reusable and single-use flexible ureterorenoscopes*" (Mager et al., 2018).

Another doctoral thesis performed at the same center (UKT) as the present one evaluated features like deflection of the tip, irrigation flow and illumination level of two single-use and one reusable fURS and also did not draw a definitive conclusion on the clinical performance of a certain device (Haberstock, 2020). Other studies focused on the size of reusable flexible ureteroscopes (Nagele et al., 2006) or optical characteristics of single-use flexible ureteroscopes (Patil et al., 2023), for instance.

I.2.6 Planetary Health and ureteroscopes

Generally, it is assumed that technological progress results in higher environmental pollution than traditional approaches (Drew et al., 2021).

Environmental aspects of urologic endoscopes have been considered only in a rather limited way in scientific research (Rindorf et al., 2021).

I.2.6.1 The role of Urology

Urology aims at preserving or improving the health of patients. Surgical treatment and other therapy options have constantly improved in the last few years. Misrai et al., however, mention that the "*human benefits*" that urologic care aims at "*do not necessarily translate into environmental benefits*" (Misrai et al., 2020). Health professionals working in the urologic field are called upon repeatedly to take its carbon footprint into account (Eardley, 2022).

The first considerations on the environmental impact (EI) of medical instruments have been made in other disciplines. However, as a special surgical subject, urology plays a pioneering role in medicine due to the dynamic development of technical innovations in the minimally invasive and endoscopic field by integrating new developments (Rausch, 2021). An accurate evaluation of the carbon footprint of surgical procedures in urology is necessary (Misrai et al., 2020).

I.2.6.2 Impact of flexible ureteroscopes

Single-use variants of these devices have been used more frequently in the last years but "*environmental issues related to the use of su-fURS (...) remain to be inquired and addressed*" (Ventimiglia et al., 2020).

There is one report from Australia considering the carbon footprint of reusable and single-use fURS concluding that the environmental impact of the two respective devices is comparable (Davis et al., 2018); however, in Australia, energy input is mainly coal-based (https://de.wikipedia.org/wiki/Kohlebergbau_in_Australien. Accessed February 17, 2023). Thus, the results are not transferable to European/German fURS. Single-use *cystoscopes* have been investigated by Irish researchers (Hogan et al., 2022), who conclude there was a benefit in su cystoscopes regarding environmental issues, as well as by Koo et al. in the USA, who found out the opposite: "*The environmental impact of reusable flexible cystoscopes is markedly less than [su]cystoscopes over the life cycle of the devices (...)*" (Koo et al, 2021).

Generally, the reusable version of a medical instrument is considered to have a lower EI than its single-use equivalent (Sousa et al., 2020). One way or the other, *"(...) further studies should be conducted to estimate the environmental impact of disposable equipment and use of (...) chemicals when reprocessing reusable cystoscopes"* (Rindorf et al., 2021).

I.2.6.3 Considerations on hygiene and costs

When environmental considerations are made in the medical context, reflections on hygiene and economic factors usually go along with it:

According to Chauhan et. al, the most common arguments for the use of disposable products are hygiene and economy (Chauhan et al., 2019).

Despite the fact that severe complications like urosepsis are not common after ureterorenoscopy, if they occur, they are associated with high morbidity and mortality (Mariappan & Tolley, 2005). So, for patient safety, reusable ureteroscopes must be reprocessed according to the *Commission for Hospital Hygiene and Infection Prevention* (KRINKO). They recommend: *"Reprocessing must ensure that the reprocessed medical device poses no risk to health when it is subsequently used"* (Empfehlung der Kommission für Krankenhaushygiene und Infektionsprävention (KRINKO) beim Robert Koch-Institut (RKI) und des Bundesinstitutes für Arzneimittel und Medizinprodukte (BfArM), 2012).

The *Fraunhofer-Institut für System- und Innovationsforschung* claims that in recent years, the discussion of health care resource use has been increasingly overshadowed by the discussion of costs and adds that because manufacturers of reusable products must prove that it is possible to reprocess the product and that sterility is subsequently ensured if certain quality standards are met, there is little motivation for them to market reusable products (Ostertag et al., 2021). They go on to say that if the product is declared as single-use, no such proof is required, and the sale of single-use products also has a positive effect on sales. According to the authors, it is also easier for users to use single-use products due to the increased manpower required to ensure sterility and increasing hygiene requirements. They conclude that there was currently a lack of incentives to conserve important resources.

I.3 Scope of the study

I.3.1 Comparison of reusable and single-use fURS

Taking these considerations into account, we aimed at comparing the reusable and single-use versions of ureteroscopes regarding their environmental impact and calculating the resulting effect on human health. Thus, we started to collect data on the respective instruments to perform a comparison via the Life Cycle Assessment method.

I.3.2 Life Cycle Assessments

Life Cycle Assessment is a method to evaluate the environmental impact of products considering their whole life span "*from cradle to grave*" (Scott Matthews et al., 2014), including life stages (manufacturing, use, processing, disposal) (see methods). LCA is a commonly used method to assess the environmental impact of products (Sousa et al., 2020). It has not yet been used frequently in healthcare sector research, however (Weisz et al., 2020).

Nevertheless, some research in this field has grown for several years. Drew et al. consider that *"(...) the decarbonization of surgical and anesthetic care is a monumental task whose success depends on the rapid operationalization of LCA across a wide range of related products and services*" (Drew et al., 2021).

Drew and fellow researchers conducted a state-of-the-science review using a standardized technique (see Figure 6): a Systematic Review Checklist developed by Zumsteg et al. specifically for the examination of LCA studies, STARR-LCA = Standardized Technique for Assessing and Reporting Reviews of Life Cycle Assessment Data (Zumsteg et al., 2012). Along with this, they described how existing literature differs a lot regarding methods and accuracy and are hard to compare due to differing *functional units* ("*one use*"/ "*per kg*" / "*per procedure*"), variable inclusion and exclusion of pathways and backgrounds and diverging diligence (Drew et al., 2021).

Most studies in the review, however, were guided by ISO LCA standards (ISO 14040/14044; n=27). Also, the majority of studies reviewed by Drew et al. used ecoinvent as the inventory database (n=29). The Global Warming Potential was included as an impact category in all studies. ReCiPe was reported as the second most frequently used characterization method by the studies reviewed. About half of the included studies used impact assessment softwares like GaBi (Ganzheitliche Bilanz). Sensitivity analyses (e.g., "alternate life-spans for reusable products (n=9)") were performed by n=21 studies.

In total, the bibliographic search by Drew et al. yielded 1316 entries, 44 of which met the study criteria and were included in the study (see Figure 6 for an outline of the selection). Two of them (n=2) were based in Germany. Another two (n=2) researched in the field of urology. In a personal view from 2022, Drew et al. show, once more, that there has not been much research of this kind in urology yet (Drew et al., 2022).

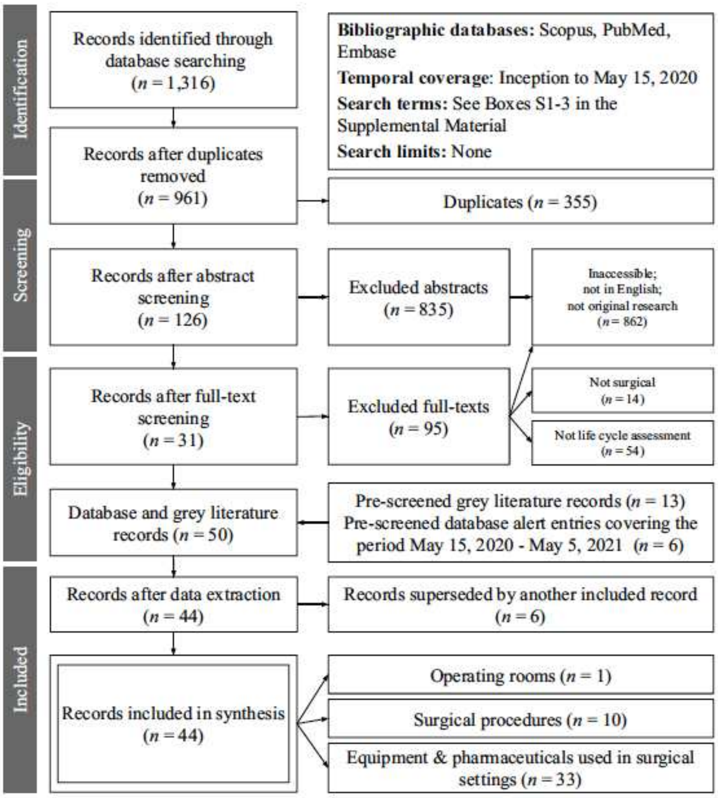


Figure 6: Flow diagram: summary of bibliographic research (from Drew et al., 2021). With kind permission of Jonathan Drew on March 28, 2023.

I.3.2.1 CONTRIBUTIONS

According to the authors of the review, the main contributors of the climate footprint in healthcare are anesthetic gases, single-use instruments and temperature regulation systems. So, the operating room, including its energy use, is seen as a major agent, with transportation, manufacturing, and disposal taking more minor roles.

However, according to the review, "*GHG emissions contributions from individual surgical procedures were found to vary considerably (6-1.007 kg CO_2eq)*" (Drew et al., 2021). The large variability of actual numerical results is shown in Figure 7:

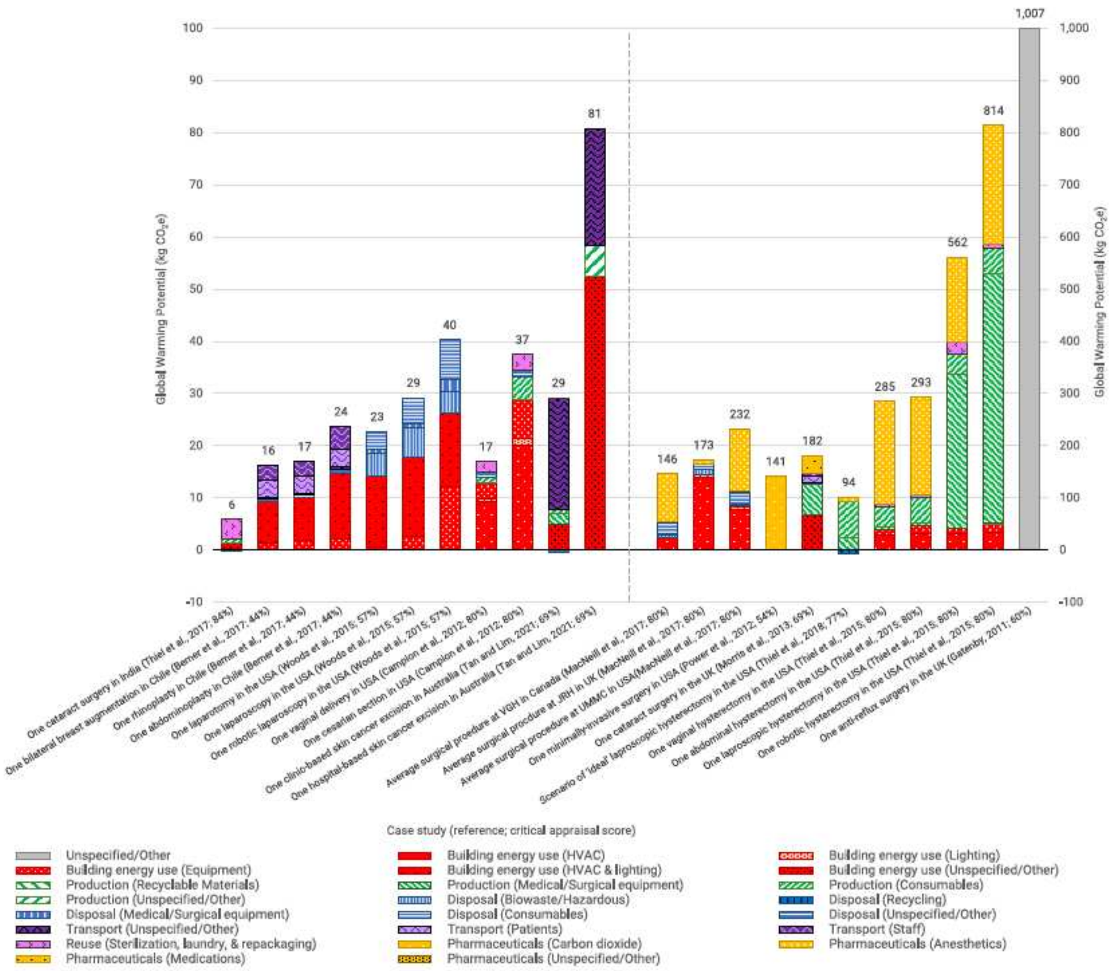


Figure 7: LCA of 21 operation procedures: respective GWP in kg CO2eq (from Drew et al., 2021) with kind permission from Jonathan Drew on March 28, 2023.

Figure 7 also once more shows the extent to which building energy use, production, transportation, disposal of pharmaceuticals and reusage contribute to the Global Warming Potential of different procedures.

I.3.3 Calls for LCAs

In line with the calls made in the aforementioned studies for medical LCA research in general, detailed analyses on *fURS* manufacturing and transport routes should be illustrated in further medical studies (Rausch, 2021). The only existing study in this field until now (Davis et al., 2018) has been described as a "*limited report*" by Ventimiglia et al. (Ventimiglia et al., 2020).

Sousa et al. formulated more generally:

"(...) it would be important to conduct further studies for the different MDs {medical devices} and to carry on an in-depth analysis of opportunities to reduce the impact, not only at the end of life, but at the different stages of the life cycle of the MDs. (...) In addition, although several LCAs have already been made focusing on MDs there is a need for more studies to a wider knowledge of its EIs" (Sousa et al., 2020).

Hess and Salas summed up:

"*Drew et al. (2012) summarized the evidence, but additional efforts will be required to move (...) forward*" (Hess & Salas, 2021).

Moreover, Drew et al. called for continued implementation of LCAs stressing that *„More LCAs are urgently needed to not only fill in the gaps, but to better elucidate the drivers of variation found to exist among available studies"* (Drew et al., 2021).

As described in the methods section of this study in more detail, we performed a Life Cycle Assessment (LCA) of reusable and single-use fURS according to ISO 14040 and 14044.

I.3.4 Measuring the Health Impact

It is not common to highlight the health impact of the global warming resulting from processes. However, as this study is based on the medical field, we considered that measuring DALYs is probably a useful parameter in order to make greenhouse gas effects more tangible for medical personnel and stakeholders.

I.3.4.1 Disability adjusted life years

Gao et al. describe DALYs as "a useful tool for quantitative assessment of environmental pollution" (Gao et al., 2015). The parameter describes the loss of years in full health. It is the aggregate of *Years of Life Lost (YLLs)* (mortality) and *Years Lived with Disability (YLDs) (morbidity)* (Porst et al., 2022):

$$DALYs = YLLs + YLDs$$

In this Life Cycle Assessment (LCA) study, we want to measure the environmental impact of single-use versus reusable fURS and demonstrate the health impact of the respective instrument using disability-adjusted life years (DALYs).

I.4 Aim of the Study

The idea to start this research was born when questions on the environmental impact of the health care sector, especially the urologic field, came up. Until now, it has been unclear whether reusable or single-use ureteroscopes perform better regarding their environmental impact and effects on human wellbeing.

Thus, we wanted to approach this field and planned to perform a comprehensive life cycle assessment of the respective devices. The idea was to calculate their Global Warming Potential (unit: CO_2 equivalents) and, in a further step, measure the Human Health Impact (unit: DALYs) to show the effects on human health. Therefore, data were needed regarding the different life cycle stages of the instruments: manufacturing, use, processing and disposal. LCA software (ecoinvent, ReCiPe2016) was then used to calculate their carbon footprint and resulting DALYs.

Considering clinical practicability, we also collected qualitative data on purchase decisions.

Another attempt of this study was to propose a methodical approach for research in the field of urology and *Planetary Health*.

II METHODS

The present study was conducted as a model LCA study for the urological/medical sector.

We performed a comparative single-center life cycle assessment of single-use and reusable fURS according to internationally accepted standard life cycle assessment methods (ISO 14040/14044) (Manfredi & Pant, 2011). Additionally, likert-scaled questionnaires on economic and processing aspects were handed out to staff at the UKT and stakeholders of companies involved in the life cycles of fURS.

Thus, in this study, an attempt was made to investigate the environmental and health impact of ureteroscopes used in the University Hospital of Tübingen, Germany.

II.1 ETHICS

This dissertation project is conducted under the number PV15107.

The study does not involve any human or animal biological material whatsoever. The conductors worked in accordance with the Declaration of Helsinki. Participants (experts questioned) fully agreed with our data collection and processing.

II.2 PRIVACY

The data used was collected strictly according to data protection regulations of the Data Protection Act. There were no patient-related data collected. Data on the life cycle of medical instruments was collected anonymously via qualitative and quantitative questionnaires.

Before questionnaires were handed out, all participants were clearly informed about their participation in the study in a standard information leaflet. The legal basis for the data processing is the voluntary consent according to Art. 6 Abs. 1 Buchst. c) of the Datenschutz-Grundverordnung (DSGVO, General Data Protection Regulation). Informed consent for the use of the anonymous data was given by returning/submitting the questionnaires. To maintain anonymity, no production company names are mentioned in this study. Collected data was saved and processed on a non-public computer.

II.3 Software

Database:

Microsoft Excel 2022® (Microsoft Deutschland GmbH, München)

Word processing program:

Microsoft Word 2018® (Microsoft Deutschland GmbH, München)

Reference management:

EndNote X9.3.3® (CPA Global Deutschland GmbH, München)

Life Cycle Assessment:

openLCA 1.10.3

Background data sets: ecoinvent v3.8

Characterization: ReCiPe2016

II.4 Life Cycle Assessment (LCA)

Life cycle assessments are systematic analyses of the environmental impact of products regarding their whole life cycle (ISO 14040, 2006). It is a method to quantify the carbon footprint of a product.

Stages of a life cycle of a product are:

- manufacturing
- distribution
- use
- disposal

Standardized steps according to ISO14040/14044 are the following (Selih & Sousa, 2006), (Scott Matthews et al., 2014):

1) Goal and scope definition:

Definition of intents, reasons and system boundaries of the study: Which products/processes are analyzed/compared and for what purpose?

2) Inventory analysis:

Collection and documentation of substance and energy flows of the matter to be assessed.

3) Impact assessment:

Assessment of the results of the inventory analysis regarding their environmental impact.

4) Interpretation:

Evaluation of the findings, putting them into perspective, suggestions for improvement.

We conducted the LCA according to these steps oriented on the International Reference Life Cycle Data System Handbook (ILCD-Handbook, 2010) as described below.

II.4.1 Goal and scope

The goal and scope of this study was, primarily, to assess the carbon footprint and resulting DALYs of reusable and single-use ureteroscopes. LCA was performed for both variants. The instruments were considered to be used and processed in the University Hospital of Tübingen. This section was inspired by similar studies (Sørensen & Grüttner, 2018).

Goals:

II.4.1.1 Intended applications

The results of this study may add an ecological dimension to basic decision-making in urologic health care. The aim is to determine the Human Health impact (HI) of reusable and single-use medical devices taking the fURS as an example and thus to propose an analysis algorithm for healthcare professionals by measuring first the carbon footprint and in a further step the DALYs resulting from it.

II.4.1.2 Limitations of LCA studies

LCA studies go along with characteristic limitations. For more comprehensive limitations of the present study, see Limitations.

a) Impact coverage limitations:
   The impacts found out using LCA are not to be used uncritically. Neither the Global Warming Potential (unit: CO_2 equivalents) nor the Human Health Impact (unit: DALYs) are absolute variables but abstract dimensions based on estimations.
b) Methodological limitations:
   Taking into account the impossibility of gathering all ecological impacts of the use of ureteroscopes, study results must not be seen as absolute results.

II.4.1.3 Reasons for study

The study was conducted because, to our knowledge, there has not yet been a similar investigation on the carbon footprint and Human Health Impact of reusable and single-use ureteroscopes in Germany. Urologic research should take environmental issues into account for future decision-making (Davis et al., 2018). This may, according to the

Planetary Health concept, lead to positive effects on the preservation of the health of humans and planet.

II.4.1.4 TARGET AUDIENCE OF STUDY

The target audience of this study are urologists and other decision-makers working in the healthcare sector. It may be used in any sector for future decisions on a larger scale, e.g. in politics. Furthermore, the method presented may be used by future researchers and act as an assessment model for similar investigations.

II.4.1.5 TYPE OF AUDIENCE

The results of this study are relevant not only for medical and ecological science experts but also controlling and other hospital workers (e.g. sterilization section) as well as the general public.

II.4.1.6 COMPARISONS INVOLVED?

In this study, we compare the functional unit *one use* for

-single-use and

-reusable fURS.

The resulting impact categories we compare are the *Global Warming Potential* and the *Human Health Impact.*

II.4.1.7 COMMISSIONER

The study was based at the Urologic Clinic of the Universtity Hospital of Tübingen in collaboration with Dr. Jan Lask (Universität Hohenheim, Fachgebiet für Nachwachsende Rohstoffe in der Bioökonomie, Stuttgart).

II.4.2 FUNCTIONAL UNIT

As mentioned above, we used the functional unit *one use* for the comparison of reusable and single-use fURS. We discussed using the functional unit *one stone free patient* as used in studies that compare the efficiency or costs of fURS; however, as we assume equivalent clinical efficiency of the devices compared, this unit did not seem to be practicable to us.

II.4.3 Inventory analysis

The inventory analysis was done with the ecoinvent life cycle database and openLCA. This means the data collected for the present study was matched with fitting life cycle inventory records from the ecoinvent database in collaboration with Dr. Jan Lask.

Example:

As part of the reprocessing of reusable fURS, a 20 ml Luer Solo Injekt Syringe is used to flush the scope. The package of this syringe weighs app. 1.28g and mainly consists of plastic. One syringe is used per fURS. The material was matched with the reference "*market for extrusion, plastic film | extrusion, plastic film | Cutoff, U – GLO*" in ecoinvent and resulted in 7.138E-04 kg CO_2eq and 6.624E-10 DALYs (U = Unit process; GLO = global).

Stage	Flow	
Reprocessing	Plastic	Syringe package

Quantity in ref	Unit	# required per application	Quantity per use
0.00128	kg	1	0.0013

Data source	Ref in ecoinvent: „market for“
Sterilization UKT	market for extrusion, plastic film | extrusion, plastic film | Cutoff, U - GLO

kg CO2eq	DALY
7.138E-04	6.624E-10

Table 1: Example data inventory.

II.4.4 IMPACT CATEGORIES

Via the characterization method ReCiPe, impacts resulting from *one use* of either variant of fURS is calculated. Impacts can be ecological aspects such as climate change, acid rain, smog, water usage, ozone depletion or individual human health aspects such as the cancerogenic potential. In addition, factors such as eutrophication and terrestrial ecotoxicity have multiple impacts on other species as well and may affect ecosystems and overall health. In this study, we use the impact categories *Global Warming Potential* and *Human Health* (Figure 8) to demonstrate the environmental and human health effects resulting from *one use* of either a reusable or single-use fURS.

Impact Category	Scale	Examples of LCI Data (i.e., classification)
Global Warming	Global	Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), Methane (CH4), Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Methyl Bromide (CH_3Br)
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Halons, Methyl Bromide (CH_3Br)
Acidification	Regional, Local	Sulfur Oxides (SO_x), Nitrogen Oxides (NOx), Hydrochloric Acid (HCl), Hydrofluoric Acid (HF), Ammonia (NH_4)
Eutrophication	Local	Phosphate (PO_4), Nitrogen Oxide (NO), Nitrogen Dioxide (NO_2), Nitrates, Ammonia (NH4)
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish
Human Health	Global, Regional, Local	Total releases to air, water, and soil.
Resource Depletion	Global, Regional, Local	Quantity of minerals used, Quantity of fossil fuels used
Land Use	Global, Regional, Local	Quantity disposed of in a landfill or other land modifications
Water Use	Regional, Local	Water used or consumed

Figure 10-2: Summary of Impact Categories (US EPA 2006)

Figure 8: Impact Categories and scale of impact adapted from Scott Matthews et al., 2014. Creative Commons Attribution-ShareAlike 4.0 International License, https://www.lcatextbook.com/.

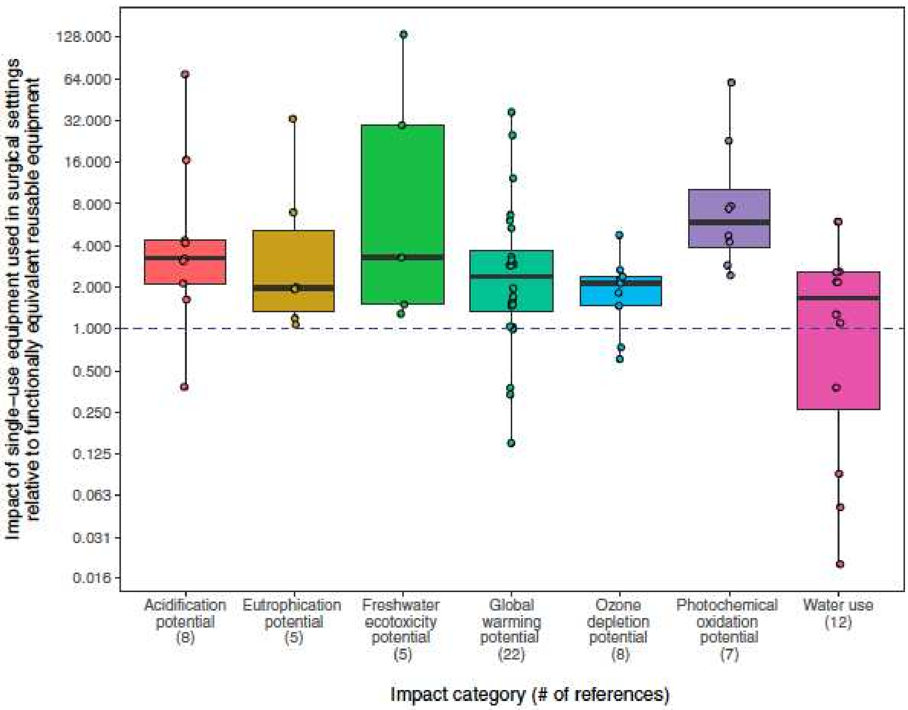


Figure 9: Impact Categories included in the studies reviewed by Drew et al. (not investigated: DALYs). From Drew et al., 2021 with kind permission of Jonathan Drew on March 28, 2023.

II.4.4.1 GLOBAL WARMING POTENTIAL (GWP)

The Global Warming Potential is a measure of the effect of the emission of multiple greenhouse gases (GHG) on the environment (e.g. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)). GHG emissions are indicators of global warming and climate change (Scott Matthews et al., 2014). The unit of GWP is kilogram CO_2 equivalents (kg CO_2eq or kg CO_{2e}). CO_2 equivalents are often used to simplify descriptions and the quantities of different greenhouse gases are converted into effectively equivalent quantities of CO_2.

II.4.4.2 HUMAN HEALTH IMPACT

On the basis of the environmental impact (defined in this study as GWP), the health impact (HI) may be identified. Aspects that are included in this are, for example, the increase in morbidity and mortality due to various lung diseases such as asthma and carcinoma caused by air pollution (Bowe et al., 2017). In this study, we use disability-adjusted life years to demonstrate the health impact of the environmental damage caused by *one use* of a fURS. In so doing, we are adding a category in our study that has not commonly been emphasized in the studies to date (see also Figure 9).

II.4.4.2.1 Composition of DALYs

According to Gao et al., several factors are included in the determination of DALYs, e.g. age of onset and weighting of disability:

$$\int_{x=a}^{x=a+L} DCxe^{-\beta x} e^{-r(x-a)} dx$$

a: the age of onset or age of death

L: the disability duration or life expectancy

D: disability weight

Cxe− βx: the age weight function

$e^{-r(x-a)}$: the time weight function

Equation 1: Complete formula for calculating DALY. From Gao et al., 2015. License granted by Elsevier on March 27, 2023. License number: 5516981298253.

Complete formula for calculating DALY. From Gao et al., 2015. (License granted by Elsevier on March 27, 2023. License number: 5516981298253)

There are diverse factors possibly leading to disability (see Figure 10):

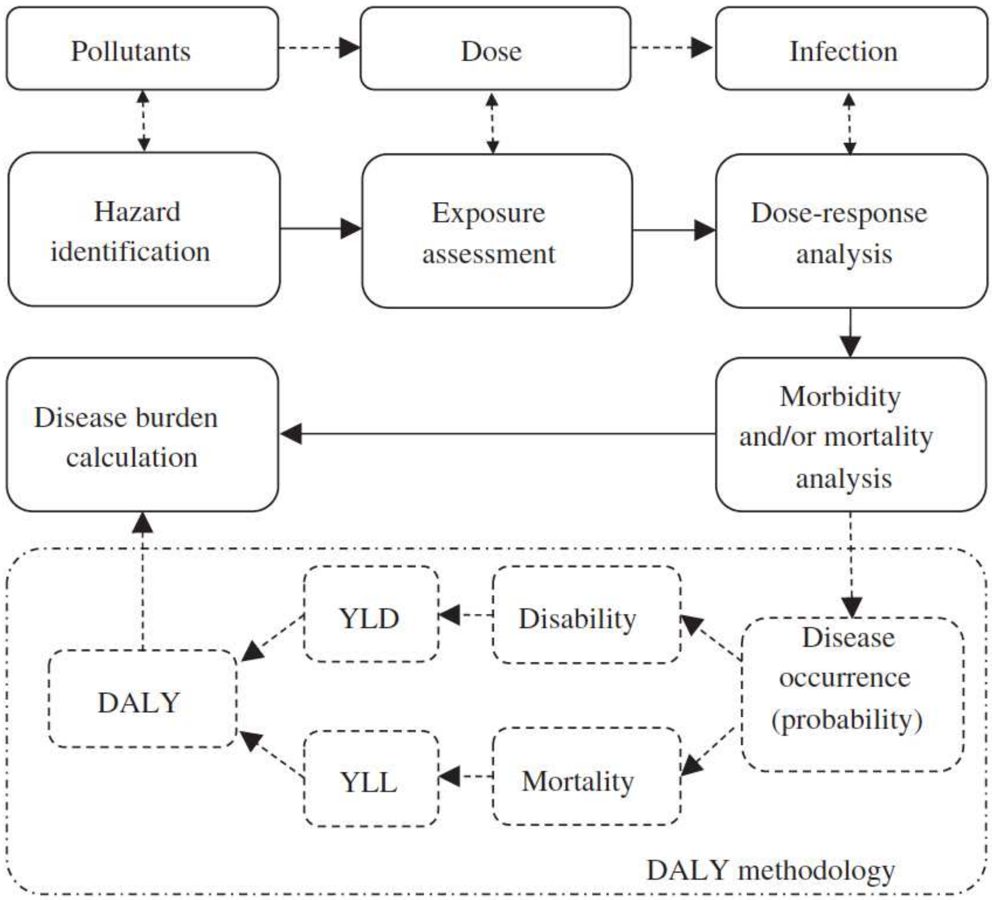


Figure 10: Framework DALYs. From Gao, 2015. License granted by Elsevier on March 27, 2023, license number: 5516981298253.

II.4.5 System Boundaries

A system means a set/collection of parts that are connected. We define a subset of this system as a boundary to set limits within this overall system and show what exactly we focus on in our assessment (Scott Matthews et al., 2014).

The system boundaries of this study are shown in the process flow diagram in Figure 11. The diagram shows the respective stages in the life cycle with input and output flows as well as interrelationships:

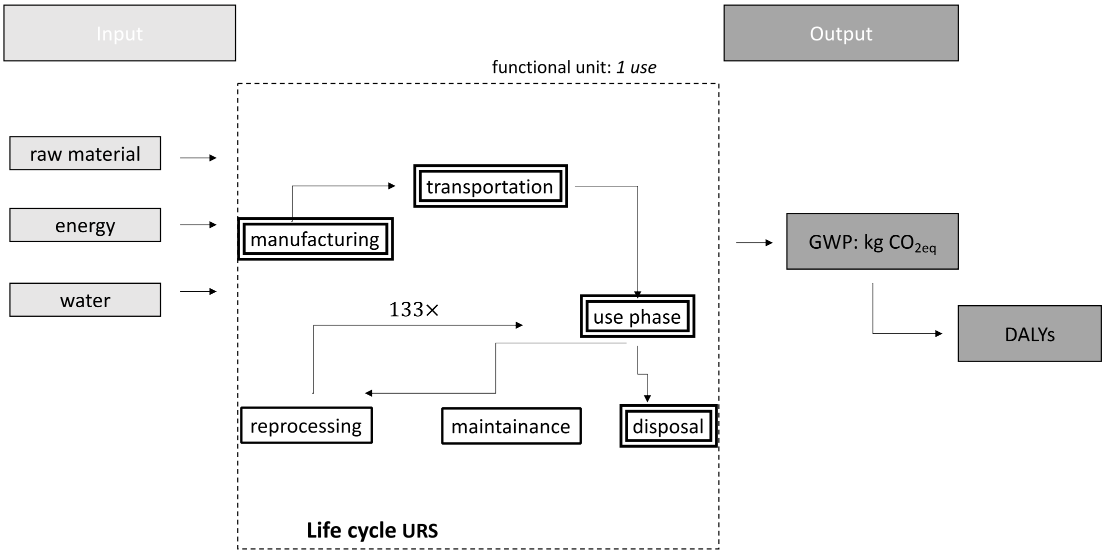


Figure 11: Product system and system boundary for LCA of su and ru fURS, own diagram. Twofold framed (inside dotted box): steps included in life cycle of reusable and single-use fURS. Single frame: steps included in life cycle of reusable fURS only.

The inclusion and exclusion criteria of steps to be included and participants to be interviewed were geared towards this system boundary framework.

II.5 QUANTITATIVE DATA COLLECTION

Granular data was collected about the life cycle stages of reusable and single-use fURS and matched with life cycle inventory databases (ecoinvent). Data collection is widely seen as the crucial part of performing an LCA. It was conducted between 2020 and 2023 and constantly extended. Data was collected in Excel tables.

Firstly, a data collection template was designed using Excel based on the system boundary. As a next step, sectors to be investigated were identified and corresponding experts searched.

As shown in the system boundary in Figure 11 we included the following life cycle stages in our LCA:

- manufacturing/production (used synonymously)
- transport
- use
- reprocessing, maintenance (reusable fURS only, see system boundary)
- disposal.

The procedure was hierarchically structured: 1. Acquisition of data by direct statements of the companies/persons involved via interview/questionnaire. 2. Personal weighting by author. 3. Acquisition of data from literature. 4. Estimates based on expert opinions: *educated guesses*.

Apart from interviewing directly (1.), the investigation involved e-mails, telephone conversations, online meetings, personal visits, conferences and using questionnaires.

The material was partly weighted by the authors of this study themselves (2., photographic documentation, see example) or by the experts interviewed using scales (measuring at least $1/100$ grams). Data was compared with comparable data from literature in a later step.

Example:

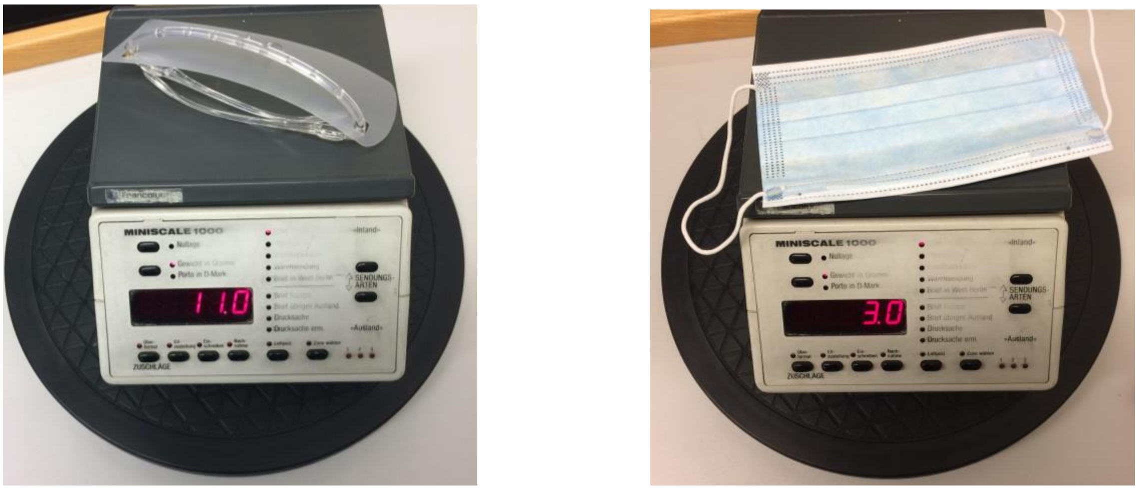


Figure 12: Postal scale of UKT measuring weight of face shield/protection glasses and face mask used by reprocessing personnel in the UKT. Pictures taken by Marlene Thöne at the UKT.

The weights of the respective materials were measured using calibrated scales from the mail room of the University Hospital in Tübingen. For the weight of one gown, for instance, the weight of a ten-pack of gowns was divided by 10; instead of one long-sleeved glove, the weight of one glove (2.5g) was taken two times.

The tables below show an overview of the data involved in this LCA, with process and respective material, instrument referred to, data collected using the functional unit *one use*, origin of data (sources: companies working in the particular fields of life cycle stages of fURS, employees of the University Hospital of Tübingen (UKT), literature research-based, estimations made by study conductors) and additional information.

II.5.1 Data overview

a) reusable fURS

Process	Material	Single-use/reusable	Data for *one use*	Unit	Source (**1=company, 2=UKT, 3=literature, 4=estimation**)	Note
Production						assuming 133uses
	plastic	ru	0.75	g	4	
	metal	ru	3.01	g	4	
	electronics	ru	0.05	g	3	
Package	cardboard & paper	ru	0.42	g	3	
	plastic	ru	0.14	g	3	
	water	ru	0.83	L	1	
Transportation		ru	0.69	km	2	
Use		ru	2.6	kWh	1	we assume same amount of energy for use of ru and su fURS
Reprossessing	electricity	ru	3.95	kWh	1,2,3	
manual cleaning	plastic	ru	64.17	g	2	
	water	ru	28.8	L	2	
	cleansing agent	ru	0.06	L	2	
machine cleaning						assuming 2 ru fURS/machine/washing cycle
	cleansing agent	ru	0.0032	L	2	
	water	ru	24	L	2	
	desinfection	ru	6.2	g	2	
	aer medicinalis	ru	0.0145	L	4	
packaging	plastic	ru	148	g	2	
sterilization	hydrogen peroxide	ru	8.12	ml	2	
energy use for sterilization	high voltage current	ru	0.5	kWh	2	

Repair						assuming repair after each 11th use
transportation			16.55	km	2	
	water		0.09	L	2	
	plastics		2.93	g	2	
Disposal		ru			2	assuming 133 uses
transportation - incineration			0.23	km	2	
	plastic, metal, other		5.12	g	4	

Table 2: Data collection overview a) reusable fURS

b) single-use fURS

Process	Material	Single-use/reusable	Data for *one use*	Unit	Source **(1=company, 2=UKT, 3=literature, 4=estimation)**	Note
Production	plastic	su	189.25	g	1	
	metal	su	18.55	g	1	
	electronics	su	0.19	g	1	
	paper	su	62.2	g	1	packaging
	cardboard	su	110.05	g	1	packaging
	other	su	0.4	bottle	1	glue
	ETO	su	8.2	g	1	ethylene oxide sterilization
	water	su	111	L	1	water use (production) around 200 ton/month, 1800pcs/month
	electricity	su	2.4	kWh	4	*educated guess*
Transportation		su	13,000	km	4	transportation by ship/truck
Use	electricity	su	2.6		1	we assume same amount of energy for use of ru and su fURS
Reprossessing	none	su	/		2	

Disposal	several	su	380	g	1	partly recyclable: cardboard and paper
transportation incineration	-	su	30	km	2	transportation by truck (UKT-Böblingen incineration plant)

Table 3: Data collection overview b) single-use fURS

II.5.2 IMPACT UNIT

In our calculation, the factor of the impact unit was taken into account: For how many surgeries is the respective material used? Reusable fURS are used for approximately 133 cases at University Hospital Tübingen according to the controlling section: Number of ureteroscopy procedures per year: n=160, number of fURS in use at the UKT: n=6. Lifespan of ru fURS: 5 years.

160 URS / 6 fURS = Number of uses per reusable device per year, x5 years -> 133 uses/reusable device/product life.

The gowns, for example, are sufficient for 1-10 uses (factor, estimated: 1/5), the gloves are estimated to be used for cleaning 3-7 devices (mean: 5; factor, estimated: 1/5). Protective visors and glasses are often kept on for the duration of the work shift and reused (see below). The mouth-nose protection is a disposable product (factor: 1).

A simplified assumption is made of one fURS reprocessed every two workdays. Permanent reprocessing of medical equipment (24h, day and night shifts) is assumed. A pair of protective goggles, for example, could theoretically be used for at least 100 fURS at a reprocessing time of about one hour/fURS. Estimate: at most 1/100 protective glasses per fURS if the glasses are reused (11g).

In the following section, data collection is elaborated in more detail.

II.5.3 LIFE CYCLE STAGES

II.5.3.1 MANUFACTURING

For data on the production of fURS, seven different manufacturing companies were contacted. Flexible ureterorenoscopes used in the UKT and exhibition pieces on conferences were inspected and photographed by the commissioner of the study. Missing information was taken from literature with a similar approach. Estimated data was compared with data from literature for plausibility (see discussion).

Data was collected on raw material, packaging material, electricity use and water use of reusable and single-use fURS, respectively, during the production process.

II.5.3.1.1 REUSABLE FURS

Process	Material	Single-use/reusable? (su/ru)	Data for *one use*	Unit	Source **(1=company, 2=UKT, 3=literature, 4=estimation)**	Note
Production						assuming 133uses of fURS
	plastic	ru	0.75	g	4	
	metal	ru	3.01	g	4	
	electronics	ru	0.05	g	3	
Package	cardboard & paper	ru	0.42	g	3	
	plastic	ru	0.14	g	3	
case	plastic	ru	18.88	g	4	
other	water	ru	0.83	L	1	
	electricity	ru	2.4	kWh	4	

Table 4: Production reusable fURS, overview

II.5.3.1.2 SINGLE-USE FURS

Process	Material	Single-use/reusable	Data for *one use*	Unit	Source **(1=company, 2=UKT, 3=literature, 4=estimation)**	Note
Production						assuming 133uses of fURS
	plastic	ru	0.75	g	4	
	metal	ru	3.01	g	4	
	electronics	ru	0.05	g	3	
Package	cardboard & paper	ru	0.42	g	3	

	plastic	ru	0.14	g	3
other	water	ru	0.83	L	1
	electricit y	ru	2.4	kWh	4

Table 5: Production of single-use fURS, overview

II.5.3.1.3 RAW MATERIAL

Flexible ureterorenoscopes mainly consist of metal (stainless steel), plastics (e.g. polyvinyl chloride (PVC), polypropylene (PP)), rubber, glass and electricity components. Total weights are estimated as 0.00381kg/*one use*/reusable fURS and 0.20799 kg/*one use*/single-use fURS.

II.5.3.1.4 PACKAGING MATERIAL

The packaging of reusable fURS was estimated using data from Sherman et al. for laryngoscopes (Sherman et al., 2018), Eckelman et al. for laryngeal masks (Eckelman et al., 2012), Sørensen and Grüttner for bronchoscopes {Sørensen & Grüttner, 2018) plus data from a brochure on fURS (LithoVue Broshure, 2015) claiming that it also contained Tyvek®, a durable nonwoven fabric made of nonwoven high-density polyethlene (Tyvek, 2021). This resulted in a total sum of 0.1747 kg for the packaging of reusable fURS:

16 g+1.7 g (laryngoscopes) and 2 g (laryngeal masks) respectively, 0.1 g+148.7 g (recycled) (bronchoscopes): Mean: 56.2 g plus 1.7 g (laryngoscopes) and 7.61 g (laryngeal masks), respectively, 43.8 g+2.4 g (recycled) (bronchoscopes), mean: 18.5 g plus 100 g (LithoVue Brochure, assumption).

We added to this data an ABS hardshell case taking data on different violin cases (violin case 1 weighing 2.8k g, violine case 2 weighing 2.2 kg. Mean: 2.5 kg).

All data is taken by 1/133 resulting in a total of 0.0201 kg packaging material for one ru fURS.

Data from literature: packaging ru fURS		Sum	174.67	**g**
Laryngoscopes	Sherman et al.	"corrugated board box"(corrugated cardboard) & "paper"	17.7	g
Laryngeal masks	Eckelman et al.	"packaging paper"	2	g

Bronchoscopes	Sørensen & Grüttner	"packaging paper and cardboard"	148.8	g
		mean paper	**56.167**	g
Laryngoscopes	Sherman et al.	"Packaging film"	1.70	g
Laryngeal masks	Eckelman et al.	"plastic packaging (PVC)"	7.61	g
Bronchoscopes	Sørensen & Grüttner	"packaging plastic"	46.2	g
		mean plastic	**18.5**	g
	LithoVue Brochure	Tyvek	**100** (estimation)	g
Violin case 1	https://www.geige24.com/shop/	ABS	28000	g
Violin case 2	https://www.geige24.com/shop/	ABS	22000	g
		mean case	**25000**	g

Table 6: Estimation for packaging of reusable fURS, methodical procedure

We were provided detailed data on the packaging of single-use fURS (0.1722 kg of cardboard, paper and adhesive printing paper in total) per case by product companies. The total weight of single-use scope we included in LCA ranges between 216 g (without packaging) and 388.2 g (with package).

II.5.3.1.5 ELECTRICITY USE

Electricity for production is highly dependent on the location. We assumed the conventional German electricity mix used by the ecoinvent software in 2021 for reusable fURS produced in Germany.

For the estimation of energy needed for the production of single-use fURS (2.4 kWh), we included Chinese electricity market data. The estimated value on the amount of electricity was confirmed by a second manufacturing company.

II.5.3.1.6 WATER USE

We lacked data on the water use in the production process for reusable fURS. We assumed 111L/production of one su fURS. In one company, around 200 tons of water are needed per month and 1800 pieces are produced.

$$200.000L/1.800pcs = 111L$$

We included this value in the assessment of both reusable and single-use fURS.

Water use depends on location as well. For reusable fURS, the European Union tap water was assumed. For single-use production abroad, the component market for tap water | tap water | Cutoff, U – ROW (Rest-of-the-World) was included in the assessment.

II.5.3.2 TRANSPORT

Companies and UKT staff were asked about the mode of transportation (transportation via truck/ship/train/plane…). Distances were calculated approximately using Google Maps (reusable fURS; one route Tuttlingen - Tübingen: 103 km, fastest route (via Balingen): 80.3 km, mean: 92 km) as well as online distance calculators: https://www.distance.to/ and http://ports.com/ (single-use fURS; over land 13,093.44 km, linear distance 9,648.53 km, mean: 11,370.985 km or, as transportation takes place by ship, 6753 nautical miles equalling 12,506.56 km plus app. 700 km from seaport to Tübingen).

II.5.3.3 USE

Energy needed for the use was provided for reusable and single-use fURS. Data on the reusable device was provided as follows (translated from data provided from the company: „*Stromverbrauch der beteiligten Komponenten des Flex-X2S.*“(E-Mail S. Meller, February 23, 2022):

Part	Function	Apparent Power (volt-ampere)
Image1 S Connect	Camera control unit	62VA
Image1 S X-Link	connection module for flexible endoscopes	80 VA
D-Light C	light source	600 VA
Monitor		Ca. 150 VA (depending on type)
	sum:	Ca. 892 VA
	sum without monitor:	742 VA

Table 7: Electricity for use of reusable fURS

We did not include the monitor into our LCA, so we calculate 742 VA.

$$P_{(kW)} = V_{(V)} \times I_{(A)} / 1000$$

$$742VA/1000 = 0.742kW$$

On the basis of companies, users' comments and product brochures, we estimated one hour for *one use* resulting in 0.742 kilowatt hours (kWh) for a reusable device.

The energy needed for *one use* of a single-use fURS was calculated to be approximately 2.6 kWh.

II.5.3.4 Reprocessing

The following section mainly deals with the reprocessing of reusable fURS. However, it should be noted that prior to their use, single-use devices are also sterilized once after production (see below).

II.5.3.4.1 Reprocessing at the UKT

Reprocessing of fURS takes place at the central sterile processing department (Aufbereitungseinheit für Medizinprodukte: AEMP) sector of the UKT. This is a certified facility according to DIN EN ISO 13485 responsible for the reprocessing of medical products (Stabsstellen des Klinikumsvorstands, 2020). The survey on the AEMP management was initially conducted as a qualitative interview using a guideline. Prior to the in-person meeting, a data protection statement was sent to the respondents and an extensive questionnaire was handed out in advance.

The survey was digitally recorded and deleted after being analyzed. The data collected was integrated into the database, revised with LCA expert Dr. Jan Lask and consequently supplemented with specific further detailed questions on missing information such as the choice of electricity mix or the composition of the cleaning solution for manual cleaning.

II.5.3.4.2 Stages of reprocessing

The processing consists of

0) Transport

1) Protective equipment

2) Manual pre-cleaning

3) Mechanical cleaning

4) Neutralization

5) Chemical disinfection

6) Flushing

7) Drying

8) Packing

9) Sterilization

10) Packing

11) Work surface cleaning

together plus water and energy consumption of the respective steps, see also Table 8: Reprocessing of reusable fURS:

Stage	Flow	Quantity in ref	Unit	# required per application	Quantity per use	Data source	Comment
Reprocessing	0) Transport						
	LDPE (low-density polyethylen)	0.004	kg	1	0.004	Sterilization UKT	in protective cover, estimated by means of plastic cover brush
	1) Personal Protective Equipment						
	PE gown (waterproof. long sleeved)	0.0439	kg	0.2	0.0088	Sterilization UKT	for 1-10 uses, https://ferroinstant.com/zubehoer--hobbygalvanik--galvanisieren--verchromen/Arbeitsschutz/Einmal-PP--Kittel-online-kaufen--Labor--Hobby-.html
	PP gown (waterproof, long sleeved)	0.0439	kg	0.2	0.0088	Sterilization UKT	for 1-10 uses, see above
	Nitril (R–C≡N) gloves (long	0.01	kg	0.2	0.0022	Sterilization UKT	used for 3-6 fURS, Polypropylene non-woven, laminated with polyethylene, Nylon (Sørensen)

	sleeved)						
Polypropylene, cellulosic fibre, polyester (Sørensen)	Screeen oder protection glasses	0.011	kg	0.01	0.0001	Sterilization UKT	data from Sørensen: 7.98g
Fleece, non woven material (glass fiber free)	Face mask	0.003	kg	1	0.003	Sterilization UKT	https://www.praxisdienst.de/Hygiene/Medizinische+Schutzkleidung/Mundschutz/OP+Mundschutz+3+lagig+blau.html
2) Manual pre-cleaning							
Natriumcumolsulfonat (<10%), CAS-No. 15763-76-5	Alkaline cleaning agent 0.5%	0.06	kg	1	0.06	Sterilization UKT	1.2LEndo Clean (Dr. Weigert Neo Disher Endo CLEAN): alkaline-enzymatic detergent (to 28.8L water (for 0.5%)). Chemische Fabrik Dr. Weigert GmbH & Co. KG Mühlenhagen 85 D-20539 Hamburg
Fatty alcohol, alkoxylated (<1%), CAS-Nr. 68439-51-0	alkaline cleaning agent	0.012	kg	1	0.012	Sterilization UKT	Dr. Weigert Neo Disher Endo CLEAN
Polypropylene	brush, single-use	0.0015	kg	1	0.0015	Sterilization UKT	Sørensen: brush: stainless steel, polypropylene. Disposable
LDPE (low-density polyethylen)	packaging brush	0.0035	kg	1	0.0035	Sterilization UKT	Plastic cover
Fleece, non woven material	cloth	0.021	kg	1	0.021	Sterilization UKT	disposable

Water		28.8	kg	1	28.8	Sterilization UKT	
Polyethylene, Polypropylene	Syringe for flushing	0.01002	kg	1	0.01	Sterilization UKT	(single-use 20 ml Luer Solo Injekt, Braun Melsungen, Germany), with plastic cover 11.3g, disposable, material: PP, PE acc to. Sørensen and https://www.doccheckshop.de/Injektion-Infusion/Spritzen/Einmalspritzen/3903/BBraun-Injekt-Einmalspritzen
Paper, plastic foil	Packaging syringe	0.00128	kg	1	0.0013	Sterilization UKT	
3) Mechanical pre-cleaning							
Sodium cumenesulfonate (<10%), CAS-No. 15763-76-5		0.0032	l	0.5	0.0016	Sterilization UKT	0.059L Dr. Weigert Neo Disher Endo Clean 0.5%, per 2 devices. With 1-10% sodium cumenesulfonate: (59ml x 1% +59ml x 10%) /2 = (0.59+5.9) /2 =3.2ml
Fatty alcohol, alkoxylated (<1%), CAS-Nr. 68439-51-0		0.00059	l	0.5	0.0003	Sterilization UKT	0.059L Dr. Weigert Neo Disher Endo Clean 0.5%, per 2 devices
Water, deionised		11.8	kg	0.5	5.9	Sterilization UKT	INNOVA E3s CMS DC GL(is located at Otfried-Müller-Strasse 4); standard reprocessing program „Endo-Normal-DC-GL"
4) Neutralisation							
Water		12	kg	0.5	6	Sterilization UKT	
5) Chemical desinfection							
Glutaraldehyd 10.5g in 100g		0.0124	kg	0.5	0.0062	Sterilization UKT	118ml so 0.118L with 10.5g glutaraldehyde in 100g are 12.4g in 118g
Water		0.0118	kg	0.5	0.0059	Sterilization UKT	
6) Flushing							
Water		12	kg	0.5	6	Sterilization UKT	
7) Drying							

Aer medicinalis	0.0145	l	1	0.0145	Sterilization UKT	https://www.linde-healthcare.de/shop/de/de-hc/medizinische-Luft; every 3 weeks change of the gas bottle (10L bottle) so 10L per 15working days, 0.7L per day, since only every 2nd day one fURS: 0.7 / 2 = 0.35. 0.35 L if the entire day only fURS blown through. Preparation approx. 1h, so 0.35L / 24h = 0.0146L = 14.5ml (rough estimate).
8) Packaging						
"Tyvek", 120m x 120m = fleece, High density Polyethylen	0.144	kg	1	0.144	Sterilization UKT	
9) Sterilization						
Hydrogen peroxide	0.0108	l	0.67	0.0072	Sterilization UKT	10.800 mycroliter H_2O_2 per sterilization process -> 10.8ml
Electricity	1.41	kWh	0.67	0.94	Sterilization UKT	in STERRAD device, installation requirements are available. Current permanent; cycle "Flex" for fURS sterilization with hydrogen peroxide.
10) Packaging						
LDPE (low-density polyethylen)	0.004	kg	1	0.004	Sterilization UKT	(so that sterile goods remain sterile)
11) Energy use	7.89	kWh	0.5	3.945	Davis, 2018, Sterilization UKT	"9.2kW/cycle"; sterilization UKT: The values should be approximately correct. Unfortunately, the company could not give more detailed information. Hogan et al: 10.5kW/cycle

Table 8: Reprocessing of reusable fURS

The respective steps are further outlined in the following section:

1) fURS are transported to the AEMP section of the UKT by hospital staff. This step is not included in the LCA, see discussion.
2) The protective equipment of the staff (Personal Protective Equipment, PPE) of the sterilization department for the reprocessing of ureteroscopes consists of gowns (waterproof, long-sleeved), gloves (long-shouldered), protective shield or goggles (according to the individual preference of the employee; protective shield partly individualized, goggles to be used several times) and mouth-nose protection (disposable). The characteristics of the various materials were determined on our own by weighing the material individually.
3) Manual pre-cleaning is performed with 1.2L Endo®CLEAN (Dr. Weigert neodisher endo CLEAN, see supplement). This is a solvent-based washing and cleaning agent produced for flexible endoscopes in washer-disinfectors (RDG-E). It contains sodium cumenesulfonate (>= 1% and <10%) CAS No. 15763-76-5 and fatty alcohols, alkoxylated (<1%). Thus, 0.06 L sodium cumenesulfonate and 0.012 L fatty alcohols were included for the calculation of the LCA.
   The devices are pre-cleaned with the aid of a fine brush (Figure 13). Such a brush is available for weighing and closer examination. It is assumed to be made of polypropylene (PP), as it is made entirely of plastic. It weighs app. 1.5 g and is a single use product.

Figure 13: Example reprocessing reusable fURS: brush. Weight of brush without cover: app. 1g; brush in plastic cover: 5g, plastic cover single: 3.5g -> weight brush: app. 1.5g. Pictures taken by Marlene Thöne at the UKT.

The cloth for pre-cleaning is made of fleece and weighs 21 g.

Manual pre-cleaning requires 28.8 L water/device.

Connection to power for leakage testing (done several times during the reprocessing process) is done manually and the power consumption is negligible. A disposable syringe (20 ml Luer Solo Injekt, Braun Melsungen, Germany) is used for flushing at the end of this reprocessing step, weight: approx. 10 g. The packaging of this syringe (1.28 g in total; plastic>paper) is included in the calculation as plastic (polyethylene, PE) due to its predominant proportion.

4) From the step of machine cleaning onwards, two devices per cycle are assumed, since the machines hold two devices. This assumption corresponds to the optimum capacity utilization during reprocessing.

   Therefore, the following reprocessing steps (machine cleaning, neutralization, chemical disinfection, drying, sterilization) are each multiplied by a factor of ½, since we have defined the life cycle of *one use* of one fURS as an impact category. The cleaning agent Dr. Weigert neodisher endo®CLEAN) is also used for machine cleaning, albeit only 59 ml. This results in approximately 3.2 ml (0.0032 L) and less than 0.59 ml (<0.00059 L) for the calculation of the life cycle assessment of sodium cumenesulfonate and fatty alcohols, respectively, in the respective concentrations. For the washing device (INNOVA E3s CMS DC GL at the Otfried-Müller-Straße 4 site) and the standard reprocessing program ("Endo-Normal-DC-GL"), fully demineralized water is used (11.8 L per 2 devices): “market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland”.

5) 12 L of water are used in the neutralization process.

6) Chemical disinfection is performed by Dr. Weigert neodisher endo®SEPT 1.0%, which is matched to the cleaning agent used. Thus, carryover of the agent from the cleaning liquid into the disinfection step does not impair the disinfection performance, according to the manufacturer (Chemische Fabrik Dr. Weigert GmbH & Co. KG, Mühlenhagen 85, D-20539 Hamburg, https://www.drweigert.com/de, accessed January 06, 2023). The antiseptic effect of the machine-applied disinfectant is based on the aldehyde glutaraldehyde it contains. With a dosage of 118 ml to 11.8 L water, 12.4 g glutaraldehyde can be

calculated (0.118 L neodisher endoSEPT with 10.5 g glutaraldehyde in 100 g means 12.4g glutaraldehyde in 118g neodisher endo®SEPT).

7) This is followed by flushing with 12 L of water and another leakage test:
   As described above, leak tests are carried out at various points in the preparation process using a manually operated pump similar to a blood pressure measuring pump. App. 14.5 ml of medical compressed air, *aer medicinalis*, is used for this purpose (rough estimation: Every 3 weeks a change of gas bottle (10 L bottle) results in 10 L per 15 working days or 0.7 L per day. One fURS every other day: 0.7 / 2 = 0.35. Processing approx. 1h: 0.35 L / 24h = 0.0146 L = 14. 5ml). Other equipment for leakage testing is frequently used and therefore not included.
8) *Aer medicinalis* (ATC code: V03AN05) (Linde, 2020) is also used to dry the equipment after flushing. This is supplied to the hospital in gas cylinders (steel), (replaced approximately every three weeks. Gas cylinders not included).
9) Due to the subsequent sterilization, special packaging of the fURS is then performed using Tyvek®. 120 cm x 120 cm are needed per fURS. The weight of this material is approx. 144 g per fURS.
10) Sterilization takes place using hydrogen peroxide (58%), which is upregulated to 98%. The energy consumption figure for this was requested by the sterilization management from the medical technology company MMM Münchener Medizintechnik Mechanik GmbH and can be gathered from the installation requirements of the device (STERRAD). Germs are eliminated by the reaction of O^-, which is produced during the reaction of H_2O_2 to H_2 and O^-. H_2O und O_2 result as "waste products".
    A more in-depth inquiry led to an amount of 10.8 ml H_2O_2: two 58% ampoules of hydrogen peroxide of 7ml each with 5400 mycroliter H_2O_2/sterilization process result in 10,800 microliters of H_2O_2 per sterilization, so 10.8ml were included in the data collection.
    High voltage is needed for the upregulation of the hydrogen peroxide ampoules for the sterilization of flexible URS. This process requires 1.41 kWh assuming two devices per process (factor ½). Two fURS can be sterilized at the same time. In 2/3 of cases, two fURS are sterilized in parallel in the STERRAD device at the UKT. In one third of cases, only one fURS is sterilized singularly.

$$\frac{2}{3} \times \frac{1}{2} + \frac{1}{3} \times 1 = \frac{2}{6} + \frac{1}{3} = \frac{1}{3} + \frac{1}{3} = \frac{2}{3}$$

Thus, we took 2/3 as factor for the input data included in the sterilization (amount of H_2O_2 and connection to high current).

11) Finally, a dust cover is applied so that sterile goods remain sterile. Low-density polyethylene is assumed as the material (approx. 4 g).
12) For the cleaning of the working surfaces, a further cloth of 21 g is assumed. Since the working surface applies to a large number of instruments processed on that surface that day, this material was omitted from the calculation (see discussion).

The energy consumption of the whole reprocessing stage could not be investigated reliably. We proposed data from literature (Davis et al., 2018) to the reprocessing managers, who confirmed it as an estimation. The companies producing the washing machines were unable to provide more detailed data. Thus, we used 9.2 kW/cycle (equivalent to 7.89kWh) as an assumption (adding to it the self-assessed 1.41kWh for sterilization), divided by 2 (two fURS/cycle).

At the UKT, reprocessing takes place with electricity from renewable energy. This is to be taken into account in the LCA and compared with a scenario with a conventional electricity mix (see Scenario A).

II.5.3.4.3 SINGLE-USE STERILIZATION

Prior to their release to the market, single-use instruments are sterilized with ethylene oxide before packaging. Due to this and other factors, the minimum durability is 3 years.

II.5.3.4.3.1 ETHYLENE OXIDE STERILIZATION

For the one-time sterilization of single-use fURS, we calculated ETO (8.2g ETO per product) according to the manufacturer's specifications.

Ethylene oxide sterilization is an effective and at the same time gentle method of decontamination. It is popular because it works at quite low temperatures (40-60°C). However, it is followed by "aeration" (degassing) to eliminate the toxic (carcinogenic, volatile, explosive) gas (ethylene oxide) (Finkiel, 2013). Thus, the process takes about 8-

16 hours and is not practicable for the reprocessing of reusable devices circulating in a hospital setting.

Ethylene itself is produced by steam cracking:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

Ethylene oxide (C_2H_4O) is produced by oxidation of ethylene.

In the LCA, we used the reference "*market for ethylene oxide | ethylene oxide | Cutoff, U - RER*", which lead to an impact of 1.558E-02 kg CO_2eq for the single-use fURS' sterilization with ETO. This figure was taken for the analysis of this life cycle step.

II.5.3.5 MAINTENANCE

The controlling department of the UKT determined that maintenance was necessary after an average of eleven (n=11) usages.

Maintenance included: Packaging, transport to Tuttlingen and back, reprocessing – all of which was attributed to the respective impact unit (every 11th time).

Finally, contributions regarding maintenance had to be estimated by the authors due to lack of information of repair companies. So, we assumed packaging to be similar to the packaging for reprocessing. We assumed transportation to be similar to the one to and from the production company to the UKT. We added to this the carbon footprint of one reprocessing instance (packaging excluded, already included separately). We assumed one device per washing machine and sterilization process.

II.5.3.6 DISPOSAL

In a cradle-to-grave setting, products meet their end of life (EoL) as the last life cycle stage.

At the respective EoL, the devices are disposed of in accordance with hospital standards (LAGA guidelines) and incinerated – disposable fURS after 1 use, reusable fURS after approx. 133 usages.

Reusable fURS weighed app. 0.6104 kg whereas the data on single-use fURS amounted to 0.21599 kg. In line with the aforementioned procedure, we calculated with selfevaluated weights in the LCA, including packaging for the disposal phase: reusable fURS + packaging (with shell): 3.285 kg; single-use fURS + packaging: 0.388 kg. This weight was included in the LCA as disposal fraction.

We estimated 30 km distance from the UKT to the waste disposal location, which was, in our case, the residual waste incineration plant Böblingen, Mußberger Sträßle 11, 71032 Böblingen: estimated distance: 25.7 km (via Bebenhausen), 31.1 km (via Dettenhausen), 32.9 km (via Ammerbuch); mean 29.9 -> 30 km as estimated distance.

This was added to the LCA as "*market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U – RER*".

Figure 14: Residual waste incineration plant Böblingen, with kind permission of Natalie Anhold (Zweckverband Restmüllheizkraftwerk Böblingen) on 30th January 2023.

II.6 Data processing

The impact assessment part of the LCA (matching of data with database and impact assessment) was conducted using the previously described software by Dr. Jan Lask, PostDoc at University of Hohenheim.

II.6.1 Break-even Point

In a break-even analysis, mostly used in profit or loss models, an equalizing value is found (Scott Matthews et al., 2014). In this case: How many uses of reusable fURS lead to a similar environmental and health impact of reusable and single-use devices. The break-even point was evaluated using the Goal-Seek function of Microsoft Excel (Data->What-If Analysis->Goal Seek) looking for the number of uses needed for the reusable fURS results to equal the single-use results for *one use*.

II.6.2 Sensitivity Analysis

Due to the fact that LCAs like many analyses (e.g. cost-benefit analysis) of this kind are highly commissioner-dependent, it should be tested if a different prioritisation of inputs/categories leads to aberrant results. This was done in this study by modelling and analyzing different scenarios.

II.7 Scenario modelling

Due to the intrinsic uncertainty of LCAs resulting from data mostly based on estimations, we modelled different scenarios that have an impact on the results of the LCA. In the course of sensitivity analyses (changing parameters/prioritization and observing resulting change in outcome) we varied the following parameters: A) Electricity mix for "use" (*renewable energy mix* vs. *conventional energy mix* of Germany) for both reusable and single-use fURS, B) number of uses of reusable fURS (133, 180, 1120), C) number of reusable fURS per washing machine (2, 1), D) numbers of uses of reusable fURS until repair (repair after 11, 10.5, 16, 44 uses) E) country of production of single-use fURS and respective energy source, F) number of ru fURS per sterilization process.

II.7.1 Scenario A)

The university hospital where the survey on use and processing took place obtains the electricity mix from *Stadtwerke Tübingen*, which since 2015 has delivered 100% green electricity.

We calculated two different scenarios in our analysis:

1) 100% renewable energy at the University Hospital of Tübingen (UKT) (*"renewable energy mix")*.
2) *Conventional electricity mix* (*market for electricity, medium voltage | electricity, medium voltage | Cutoff, U – DE*) used in Germany (nuclear power, coal, natural gas and other fossil fuels, renewable sources).

II.7.2 Scenario B)

We took 133 uses of ru fURS as an estimation for our LCA (approximately 160cases/year, 6 ru fURS used in total; 160/6=26.6 uses/fURS/year. Lifespan: 5 years: 5 x 26.6 = 133uses/fURS). Other studies assumed 180 uses per reusable fURS (Davis et al., 2018) or 1120 uses in the 7-year lifespan of cystoscopes (Hogan et al., 2022) ("roughly" 2000 cases/year, 12 cystoscopes used in total; 2000/12 = ~160 cases/cystoscope/years according to authors. Lifespan: 7y: 7 x 160 = 1120 cases/cystoscope), for instance.

II.7.3 Scenario C)

Two ru fURS fit into one washing machine. However, theoretically, there could sometimes be other endoscopes washed along with one fURS or even only one fURS in the machine. We modelled scenarios with

1) two fURS/machine and
2) one fURS/machine

II.7.4 Scenario D)

In UKT, fURS are repaired after each 11th use, approximately. Other studies estimate repair after 10.5 uses (6-15 uses until repair) (Afane et al., 2000), after each 16th time of use (Davis et al., 2018), after 27 procedures (Legemate et al., 2019) or after the 29th and the 88th use; average: every 44th time (Collins et al.).

II.7.5 Scenario E)

The single-use fURS employed in the UKT are mainly produced in China. We considered other production countries (Malaysia, Germany) to compare different scenarios with different electricity mixes.

II.7.6 Scenario F)

According to the AEMP management of the UKT, mostly (in 2/3 of cases) two fURS are sterilized at the same time. In a smaller amount of cases (1/3) only one fURS is sterilized in one process. This assumption led us to pick 2/3 (2/3 x 0.5 + 1/3 x 1 = 2/3) as a factor in our assessment. In scenario F), we designed a plot where 2 fURS are always sterilized in parallel, leading to ½ as a factor.

II.8 QUALITATIVE DATA COLLECTION

In addition to the quantitative data collected for the LCA itself, we collected some further data in an attempt to enhance the information on reusable and single-use fURS at the UKT. We thus try to provide information about the practical relevance of the implementation of our results and react to the former researchers' recommendations:

"*Studies comparing perioperative staff member comfort when using reusable versus disposable surgical gowns may provide additional information for perioperative leader and staff member consideration*" (Vozzola, 2020).

The qualitative design of the study consisted, among other things, of creating questionnaires for the respective persons participating in the product life cycle. On the basis of a table with parameters for which data were to be collected, the columns "Determined variable", "Item", "Data source" (e.g. person to be interviewed) and, consequently, the columns "Unit", " Single-use fURS", "Reusable fURS" and "Comment" were created for the data. The questions for the questionnaires resulted from the "Item" column (e.g. "transport"; "What distance and which way are the instruments transferred to the UKT?"). The items were subdivided into the respective groups of persons to be interviewed, who are experts in a specific area (production: manufacturing company, reprocessing: sterilization, disposal: waste management). The questionnaires (see supplement) were reviewed by the author team before release.

Separately, a table (see results: purchase criteria) was created for the qualitative, subjective data collected by interviewing the urologists (users).

II.8.1 CONTROLLING

The survey in the controlling department of the urological clinic in Tübingen was intended to collect economic data regarding costs, maintenance frequency, companies involved, qualitative assessments of purchase criteria for the respective instruments, locations of the companies involved, and contact persons on site. We also collected information on the number of reusable and disposable fURS currently in circulation at the UKT.

II.8.2 Users

Purchase criteria were additionally evaluated by questioning urologists. Five groups of criteria (economic, ecological, geographical criteria as well as efficiency, study results and trading conditions) were listed in likert-scaled questionnaires to rate according to personal precepted relevance (0=no relevance at all, 1=very low relevance, 2=low relevance, 3=medium relevance, 4=high relevance, 5=very high relevance).

II.8.3 Waste management

The waste management staff of the UKT was interviewed to evaluate processes regarding the disposal of fURS.

Exemplarily, we asked questions like: How does the disposal of a ureteroscope work? What is recycled (individual materials: metal, glass, plastic, rubber, electronics etc.)? Is there a contact person regarding recycling? How far is the place of waste incineration/final disposal away from the UKT? What are the pollutant emissions during incineration (CO_2, NO_2, CH_4)?

III RESULTS

III.1 QUANTITATIVE RESULTS

In the following section, the above-described materials included in the life cycles of fURS (reusable and single-use) and their amount needed for *one use* are followed by the LCA results.

III.1.1 ENVIRONMENTAL AND HEALTH IMPACT OF REUSABLE AND SINGLE-USE FURS

III.1.1.1 ASSUMPTIONS

For the life cycle assessment, we assume

- functional unit: *one use*
- electricity source reusable fURS production: *market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - DE*
- electricity source single-use production: China (*market for electricity, medium voltage | electricity, medium voltage | Cutoff, U – CN*)
- duration of *one use*: one hour
- electricity mix reprocessing: *renewable energy mix*
- electricity mix use: *renewable energy mix*
- 133 uses of reusable fURS
- maintenance after each 11^{th} time of use.

III.1.1.2 OVERALL RESULTS

One use of a reusable fURS resulted in a lower environmental and health impact than *one use* of a single-use fURS (reusable: 1.24 kg CO_2eq and 1.15E-06 DALYs; single use: 4.93 kg CO_2eq and 4.57E-06 DALYs).

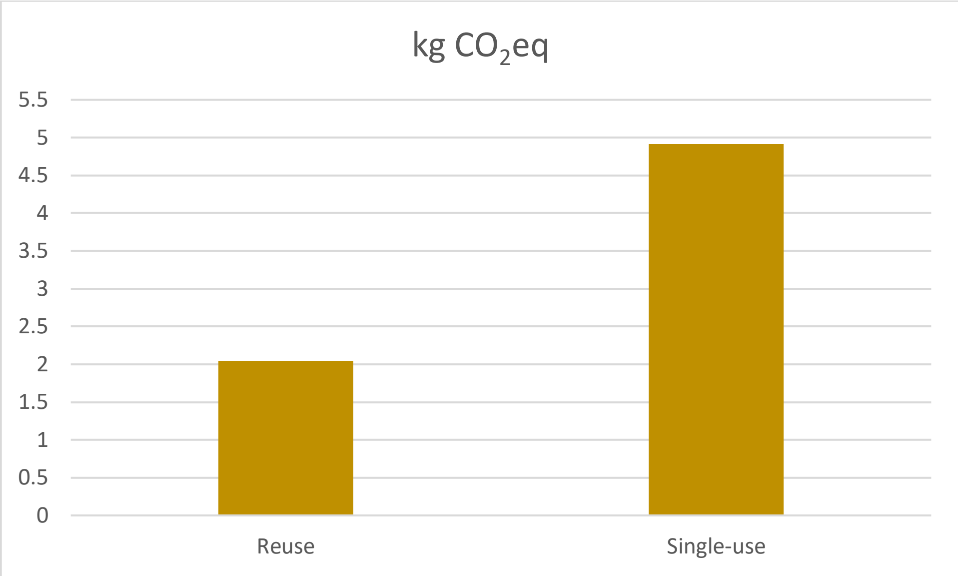


Figure 15: Environmental impact of fURS in the UKT: Kilogram Carbon dioxide equivalents resulting from LCA of reusable and single-use fURS in University Hospital Tübingen using renewable energies only.

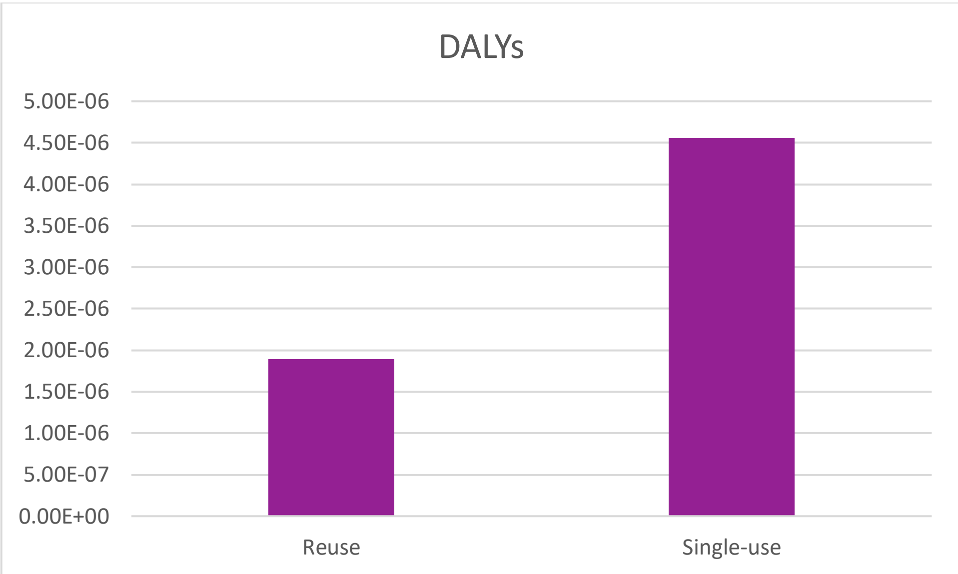


Figure 16: Human Health Impact of fURS in the UKT: Disability adjusted life years resulting from LCA of reusable and single-use fURS in University Hospital Tübingen using renewable energies only.

The carbon footprint of reusable fURS amounted to 28.84% of the carbon footprint of single-use fURS.

$$Percentage\ (p\%) = \frac{percentage\ value\ (W)}{basic\ value\ (G)} \times 100$$

$$\frac{1.24\ kgCO2eq}{4.93\ kgCO2eq} \times 100\ = 28.8372\%$$

III.1.1.3 DETAILED RESULTS

The results are presented in detail below.

III.1.1.3.1 REUSABLE fURS

The **production** of reusable fURS came to 1.556E-01 kg CO_2eq and 1.444E-07 DALYs in total. The metal component resulted in 1.340E-02 kg CO_2eq and 1.243E-08 DALYs, the plastic component in 2.698E-03 kg CO_2eq and 2.504E-09 DALYs. Rubber amounted to 2.096E-03 kg CO_2eq and 1.945E-09 DALYs; glass resulted in 1.393E-04 kg CO_2eq and 1.293E-09 DALYs; electronic components in 3.898E-04 kg CO_2eq and 3.617E-10 DALYs. Packaging amounted to 1.267E-01 kg CO_2eq and 1.176E-07 DALYs. Electricity needed for the production share for *one use* of a reusable fURS resulted in 1.015E-02 kg CO_2eq and 9.419E-09 DALYs. The water share used for the production of reusable fURS resulted in 2.838E-07 kg CO_2eq and 2.644E-13 DALYs, see also Table 9:

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	Ref in ecoinvent (market for)	**kg CO_2eq**	**DALY**
Production	Raw material							
	Metal (stainless steel)	0.4	kg	0.0075	0.003	steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | U - GLO	**1.340E-02**	**1.243E-08**
	Plastic (ABS)	0.05	kg	0.0075	0.0004	acrylonitrile-butadiene-styrene copolymer | acrylonitrile-butadiene-styrene copolymer | U	**1.811E-03**	**1.681E-09**

Plastic (PP)	0.05	kg	0.0075	0.0004	polypropylene, granulate | polypropylene, granulate | U - GLO	**8.872E-04**	**8.233E-10**
Rubber	0.1	kg	0.0075	0.0008	synthetic rubber | synthetic rubber | U - GLO	**2.096E-03**	**1.945E-09**
Glass	0.0042	kg	0.0075	0.0000	glass, for liquid crystal display | glass, for liquid crystal display | U - GLO	**1.393E-04**	**1.293E-10**
Electronics	0.0062	kg	0.0075	0.0000	battery, Li-ion, rechargeable, prismatic | battery, Li-ion, rechargeable, prismatic | U - GLO	**3.898E-04**	**3.617E-10**
Packaging							
Case (ABS share)	1.75	kg	0.0075	0.0132	acrylonitrile-butadiene-styrene copolymer | acrylonitrile-butadiene-styrene copolymer | U	**6.339E-02**	**5.8826E-08**
Case (PS share)	0.75	kg	0.0075	0.0056	polystyrene, extruded | polystyrene, extruded | U	**6.088E-02**	**5.6529E-08**
Cardboard	0.0562	kg	0.0075	0.0004	solid bleached and unbleached board carton | solid bleached and unbleached board carton | U - RER	**2.960E-04**	**2.746E-10**
Plastic	0.0185	kg	0.0075	0.0001	polyethylene, high density, granulate | polyethylene, high density, granulate | U - GLO	**3.323E-04**	**3.084E-10**
Tyvek	0.1	kg	0.0075	0.0008	polyethylene, high density, granulate |	**1.796E-03**	**1.667E-09**

						polyethylene, high density, granulate | U - GLO		
	Energy use							
	Energy use production	2.4	kWh	0.0075	0.018	electricity, medium voltage | electricity, medium voltage | U - DE	**1.015E-02**	**9.419E-09**
	Water use							
	Water	0.111	m^3	0.0075	0.0008	tap water | tap water | U - Europe without Switzerland	**2.838E-07**	**2.644E-13**

Table 9: Production of reusable fURS: flows assumed by performers of the study, quantities of contributing flows with respective unit, quantity of flow required for one use (assuming 133 uses of reusable fURS), reference in database, results.

The amount of water required for reusable fURS production might be higher than for production of single-use fURS. In a sensitivity analysis, we assumed a higher water demand for the reusable fURS production. We hypothetically calculated twice the amount of water (0.111m^3 x 2 = 0.222m^3), finally resulting in 1.24 kg CO_2eq and 1.15E-06 DALYs (identical overall results). Only when taking 40,000 x the amount of water (0.111m^3 x 40,000 = 4,440m^3) for the reusable fURS production, the total carbon footprint changes to 1.265 kg CO_2eq; the amount of DALYs rises to 1.176E-06 DALYs (Table 9). The *Planetary Health* aspect of water use will be discussed briefly in the discussion (see below).

Factor	**Water**	**kg CO_2eq**	**DALYs**
1x	0.111m3	1.24	1.15E-06
2x	0.222m3	1.24	1.15E-06
40,000x	4,440m^3	1.25	1.16E-06

Table 10: hypothetical change in amount of water for life cycle of reusable fURS

Transportation from the production site of reusable fURS to the UKT resulted in 8.813E-05 kg CO_2eq and 8.179E-11 DALYs.

Stage	Flow	Quantity in ref	Unit	# required per use	Quantity per use	Ref in ecoinvent	**kg CO_2eq**	**DALY**

Transport	92km	0.07223	tkm	0.0075	0.0005	transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | U - RER	**8.813E-05**	**8.179E-11**

Table 11: Transport of reusable fURS: flow assumed by performers of the study, quantity of contributing flow with respective unit, quantity of flow required for one use (assuming 133 uses of reusable fURS), reference in database, result.

One ***use*** of a reusable fURS at the UKT (obtaining energy from renewable sources) resulted in 3.982E-02 kg CO_2eq and 3.695E-08 DALYs.

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	Ref in ecoinvent	**kg CO_2eq**	**DALY**
Use	Electricity	0.742	kWh	1	0.742	Renewable mix	**3.982E-02**	**3.695E-08**

Table 12: Use of reusable fURS: flow assumed by performers of the study, quantity of contributing flow with respective unit, quantity of flow required for one use, reference in database, result.

Reprocessing of a reusable fURS, in total, amounted to 8.801E-01 kg CO_2eq and 8.169E-07 DALYs. The impacts of the single steps of the reprocessing process are shown in the following.

0) Transport for reprocessing resulted in 1.024E-02 kg CO_2eq and 9.504E-09 DALYs.
1) PPE material resulted in 5.789E-02 kg CO_2eq and 5.372E-08 DALYs.
2) Manual pre-cleaning amounted to 1.428E-01 kg CO_2eq and 1.326E-07 DALYs.
3) Mechanical pre-cleaning amounted to 3.274E-03 kg CO_2eq and 3.063E-09 DALYs.
4) The neutralization step required 2.7E-03 kg CO_2eq and 2.531E-09 DALYs.
5) Chemical disinfection required 1.277E-02 kg CO_2eq and 1.185E-08 DALYs.
6) Flushing needed 2.7E-03 kg CO_2eq and 2.531E-09 DALYs, again.
7) Drying required 3.426E-03 kg CO_2eq and 3.179E-09 DALYs.
8) Repackaging resulted in 3.440E-01 kg CO_2eq and 3.193E-07 DALYs.
9) The sterilization step, in total, resulted in 7.833E-02 kg CO_2eq and 7.269E-08 DALYs.
10) Packaging required 1.024E-02 kg CO_2eq and 9.504E-09 DALYs.
11) Energy use for the whole reprocessing process resulted in 2.117E-01 kg CO_2eq and 1.965E-07 DALYs.

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	Ref in ecoinvent	**kg CO_2eq**	**DALY**
Reprocessing	0) Transport							
	LDPE (low-density polyethylen)	0.004	kg	1	0.004	polyethylene, low density, granulate | polyethylene, low density, granulate | U - GLO	**0.024E-02**	**9.504E-09**
	1) Personal Protective Equipment							
	PE	0.0439	kg	0.2	0.0088	polyethylene, low density, granulate | polyethylene, low density, granulate | U - GLO	**2.25E-02**	**2.09E-08**
	PP	0.0439	kg	0.2	0.0088	polypropylene, granulate | polypropylene, granulate | U - GLO	**2.07E-02**	**1.92E-08**
	Nitril (R–C≡N)	0.01000	kg	0.2	0.0022	chemical, organic | chemical, organic | U - GLO	**4.58E-03**	**4.25E-09**
	Polypropylene, cellulosic fibre, polyester (Sørensen)	0.011	kg	0.01	0.0001	polypropylene, granulate | polypropylene, granulate | U - GLO	**2.60E-04**	**2.41E-10**
	Fleece, non woven material (glass fiber free)	0.003	kg	1	0.003	fleece, polyethylene | fleece, polyethylene | U - GLO	**9.86E-03**	**9.15E-09**
	2) Manual pre-cleaning							
	Sodium cumenesulfonate (<10%), CAS-No. 15763-76-5	0.06	kg	1	0.06	alcaline detergent (0.5%)	**4.21E-04**	**3.91E-10**
	Fatty alcohol, alkoxylated (<1%), CAS-Nr. 68439-51-0	0.012	kg	1	0.012	chemical, organic | chemical, organic | U - GLO	**2.47E-02**	**2.29E-08**

	Polypropylene	0.0015	kg	1	0.0015	polypropylene, granulate | polypropylene, granulate | U - GLO	**3.54E-03**	**3.29E-09**
	LDPE (low-density polyethylen)	0.0035	kg	1	0.0035	polyethylene, low density, granulate | polyethylene, low density, granulate | U - GLO	**8.96E-03**	**8.32E-09**
	Fleece, non woven material	0.021	kg	1	0.021	fleece, polyethylene | fleece, polyethylene | U - GLO	**6.90E-02**	**6.40E-08**
	Water	28.8	kg	1	28.8	tap water | tap water | U - Europe without Switzerland	**9.79E-03**	**9.13E-09**
	Polyethylene, Polypropylene	0.01002	kg	1	0.01	polyethylene, low density, granulate | polyethylene, low density, granulate | U - GLO	**2.57E-02**	**2.38E-08**
	Paper, plastic	0.00128	kg	1	0.0013	extrusion, plastic film | extrusion, plastic film | U - GLO	**7.14E-04**	**6.62E-10**
	3) Mechanical pre-cleaning							
	Sodium cumenesulfonate (<10%), CAS-No. 15763-76-5	0.0032	1	0.5	0.0016	alcaline detergent (0.5%)	**1.12E-05**	**1.04E-11**
	Fatty alcohol, alkoxylated (<1%), CAS-Nr. 68439-51-0	0.00059	1	0.5	0.0003	chemical, organic | chemical, organic | U - GLO	**6.07E-04**	**5.64E-10**
	Water, deionised	11.8	kg	0.5	5.9	water, deionised | water, deionised | U - Europe without Switzerland	**2.66E-03**	**2.49E-09**
	4) Neutralisation							

Water	12	kg	0.5	6	water, deionised | water, deionised | U - Europe without Switzerland	**2.70E-03**	**2.53E-09**
5) Chemical desinfection							
Glutaraldehyde 10.5g in 100g	0.0124	kg	0.5	0.0062	chemical, organic | chemical, organic | U - GLO	**1.28E-02**	**1.19E-08**
Water	0.0118	kg	0.5	0.0059	water, deionised | water, deionised | U - Europe without Switzerland	**2.66E-06**	**2.49E-12**
6) Flushing							
Water	12	kg	0.5	6	water, deionised | water, deionised | U - Europe without Switzerland	**2.70E-03**	**2.53E-09**
7) Drying							
Aer medicinalis	0.0145	l	1	0.0145	nitrogen, liquid | nitrogen, liquid | U - RER	**3.43E-03**	**3.18E-09**
8) Packaging							
"Tyvek", 120m x 120m= fleece, High density Polyethylen	0.144	kg	1	0.144	polyethylene, high density, granulate | polyethylene, high density, granulate | U - GLO	**3.44E-01**	**3.19E-07**
9) Sterilization							
Hydrogen peroxide	0.0108	l	0.67	0.0072	Hydrogen peroxide in 58% solution	**2.79E-02**	**2.59E-08**
Electricity	1.41	kWh	0.67	0.94	Renewable mix	**5.05E-02**	**4.68E-08**

	10) Packaging							
	LDPE (low-density polyethylen)	0.004	kg	1	0.004	polyethylene, low density, granulate | polyethylene, low density, granulate | U - GLO	**1.02E-02**	**9.504E-09**
	11) Energy use	7.89	kWh	0.5	3.945	Renewable mix	**2.12E-01**	**1.97E-07**

Table 13: Reprocessing of reusable fURS: flows assumed by performers of the study, quantities of contributing flows with respective unit, quantity of flow required for one use (assuming 133 uses of reusable fURS), reference in database, results.

The **maintenance** of a reusable fURS required 9.107E-02 kg CO_2eq and 8.453E-08 DALYs in total, including transport to and from the maintenance company (2 x 92 km = 184 km resulting in 2.131E-03 kg CO_2eq and 1.978E-09 DALYs), packaging (9.310E-04 kg CO_2eq and 8.64E-10 DALYs) and the impact of one reprocessing process before reuse of reusable fURS (8.801E-02 kg CO_2eq and 8.169E-08 DALYs), concerning repair every 11 uses.

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	Ref in ecoinvent	kg CO_2eq	DALY
Maintenance	184km	0.114	tkm	0.1	0.0131	transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | U - RER	**2.13E-03**	**1.98E-09**
	Packaging - plastic	0.004	kg	0.1	0.000	polyethylene, low density, granulate | polyethylene, low density, granulate | U - GLO	**9.31E-04**	**8.64E-10**
	CO_2eq Reprocessing before reuse	0.8801	kg CO_2eq	0.1	0.08801	see above: "reprocessing"	**8.80E-01**	
	DALYs Reprocessing before reuse	8.17E-07	DALYs	0.1	8.17E-08	see above: "reprocessing"		**8.17E-08**

Table 14: Maintenance of reusable fURS: flows assumed by performers of the study, quantities of contributing flows with respective unit, quantity of flow required for one maintenance (assuming maintenance after eleven uses of reusable fURS), reference in database, results.

Disposal of reusable fURS resulted in 7.643E-02 kg CO_2eq and 7.093E-08 DALYs, including transport to disposal site (1.202E-04 kg CO_2eq and 1.116E-10 DALYs) and impact of plastic and electronic waste (7.631E-02 kg CO_2eq and 7.081E-08 DALYs).

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	Ref in ecoinvent	**kg CO_2eq**	**DALY**
Disposal	30km	0.099	tkm	0.008	0.000792	transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | U - RER	**1.202E-04**	**1.12E-10**
	Disposal	3.285	kg	0.008	0.02628	waste plastic, consumer electronics | waste plastic, consumer electronics | U - CH	**7.63E-02**	**7.08E-08**

Table 15: Disposal of reusable fURS: flows assumed by performers of the study, quantities of contributing flows with respective unit, quantity of flow required for one use (assuming 133 uses of reusable fURS), reference in database, results.

III.1.1.3.2 SINGLE-USE

The **production** of a single-use fURS resulted in 3.480 kg CO_2eq and 3.229E-06 DALYs in total. The metal share amounted to 1.694E-01 kg CO_2eq and 1.57E-07 DALYs in total, plastic components came to 6.46E-01 kg CO_2eq and 5.997E-07 DALYs. Electronics amounted to 1.589E-03 kg CO_2eq and 1.474E-09 DALYs. The glue component resulted in 1.644E-02 kg CO_2eq and 1.526E-08 DALYs. Packaging of single-use fURS needed 1.119E-01 kg CO_2eq and 1.038E-07 DALYs each. The energy use for the production of single-use fURS in China resulted in 2.535 kg CO_2eq and 2.352E-06 DALYs. The water required for the production of single-use fURS equalled 1.166E-04 kg CO_2eq and 1.081E-10 DALYs. All in all, production made up 71% of the impact of single-use fURS, see contributions.

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	**kg CO_2eq**	**DALY**
Production	**Raw material**						
	Metal	0.018554	kg	1	0.0186	**1.694E-01**	**1.573E-07**
	Plastic	0.1892506	kg	1	0.189 3	**6.463E-01**	**5.997E-07**
	Glue	0.008	kg	1	0.008	**1.644E-02**	**1.526E-08**
	Electronic components	0.00019	kg	1	0.000 2	**1.589E-03**	**1.474E-09**
	Packaging material						
	Cardboard	0.11	kg	1	0.11	**7.704E-02**	**7.150E-08**
	Paper	0.0622	kg	1	0.062 2	**3.482E-02**	**3.231E-08**
	Energy use						
	Energy use production	2.4	kW h	1	2.4	**2.535**	**2.352E-06**
	Water use						
	Water use	0.111	m^3	1	0.111	**1.166E-04**	**1.081E-10**

Table 16: Production of single use fURS: flows assumed by performers of the study, quantities of contributing flows with respective unit, quantity of flow required for one use (assuming 1 use for single use fURS), results.

Transport of single-use fURS resulted in 9.153E-02 kg CO_2eq and 8.494E-08 DALYs.

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	Ref in ecoinvent	**kg CO_2eq**	**DALY**
Transport	13000km ship	5.0465 3	tkm	1	5.0465 3	transport, freight, sea, container ship | transport, freight, sea, container ship | U - GLO	**4.74E-02**	**4.40E-08**
	700km truck	0.2717 4	tkm	1	0.2717 4	transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | U - RER	**4.41E-02**	**4.09E-08**

Table 17: Transport of single-use fURS: flow assumed by performers of the study, quantity of contributing flow with respective unit, quantity of flow required for one use (assuming 1 use of single-use fURS), reference in database, result.

The **use** of one single-use fURS in the UKT resulted in 1.395E-01 kg CO_2eq and 1.295E-07 DALYs.

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	Ref in ecoinvent	**kg CO_2eq**	**DALY**
Use	Electricity	2.6	kWh	1	2.6	Renewable mix	**1.3950E-01**	**1.2950E-07**

Table 18: Use of single-use fURS: flow assumed by performers of the study, quantity of contributing flow with respective unit, quantity of flow required for one use, reference in database, result.

The **disposal** phase of single-use fURS required 1.201 kg CO_2eq and 1.115E-06 DALYs, including transport to disposal site (1.890E-03 kg CO_2eq and 1.754E-09 DALYs) as well as plastic and electronic waste (1.99 kg CO_2eq and 1.113E-06 DALYs). All in all, disposal made up 24% of the impact of single-use fURS, see contributions.

Stage	Flow	Quantity in ref	Unit	#required per use	Quantity per use	Ref in ecoinvent	**kg CO_2eq**	**DALY**
Disposal	30 km	0.012	tkm	1	0.0116	transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | U - RER	**1.890E-03**	**1.75E-09**
	Disposal	0.388	kg	1	0.3882	waste plastic, consumer electronics | waste plastic, consumer electronics | U - CH	**1.990**	**1.11E-06**

Table 19: Disposal of single-use fURS: flows assumed by performers of the study, quantities of contributing flows with respective unit, quantity of flow required for one use (assuming 1 use of single-use fURS), reference in database, results.

III.1.2 COMPARISON

The comparison of the environmental and health impact as well as the break-even point is outlined below. See next section for contribution shares of the respective life cycle stages.

III.1.2.1 ENVIRONMENTAL IMPACT

Reusable fURS resulted in a lower **overall** environmental impact than single-use fURS (1.24 kg CO_2eq vs. 4.93 kg CO_2eq).

The **production** phase of reusable fURS resulted in 1.556E-01 kg CO_2eq, whereas the production phase of single-use fURS resulted in 3.480 kg CO_2eq, meaning that the carbon footprint from the production of reusable fURS for *one use* was >20-fold lower than the carbon footprint resulting from the production of single-use fURS regarding the impact factor *one use*. **Transportation** of reusable fURS resulted in 8.813E-05 kg CO_2eq whereas single-use fURS resulted in 9.153E-02 kg CO_2eq, meaning that the carbon footprint resulting from the transportation of reusable fURS was more than 1000-fold lower than that of single-use fURS. The **use** phase of reusable fURS resulted in 3.982E-02 kg CO_2eq whereas the use phase of single-use fURS resulted in 1.395E-01 kg CO_2eq, meaning that the carbon footprint resulting from *one use* of a reusable fURS was 3.5-fold lower than the carbon footprint resulting from the production of single-use fURS. Single-use fURS are not **reprocessed** or **repaired** at the UKT. The **disposal** of reusable fURS resulted in 7.643E-02 kg CO_2eq, which was 16-fold lower than the impact of the disposal of single-use fURS, which was calculated to be 1.201 kg CO_2eq.

See Table 20 for an overview of the comparison of the environmental impact of reusable vs. single-use fURS.

Compare results	**Reusable kg CO_2eq**	**Single-use kg CO_2eq**	**Ratio**	**Percentage**	**Percentage increase**
Production	1.556E-01	3.480	22.37	4.47%	2136.50%
Transport	8.813E-05	9.153E-02	1038.58	0.10%	103757.94 %
Use	3.982E-02	1.395E-01	3.5	28.54%	250.33%
Reprocessing	8.801E-01	-	-		
Maintenance	9.107E-02	-	-		
Disposal	7.643E-02	1.201	15.71	6.36%	1471.37%

Table 20: Comparison reusable and single use fURS: kg CO2eq resulting for each life cycle stage, ratio and percentage with percentage increase.

III.1.2.2 Health impact

The use of reusable fURS also resulted in less DALYs, thus, in a lower health impact (1.15E-06 DALYs vs. 4.57E-06 DALYs). By implication, *one use* of a single-use fURS results in 4 times more DALYs than reusable fURS regarding all life cycle stages except from reprocessing and maintenance, see above.

Ratios are the same as for the environmental impact for DALY values of respective instruments, see Table 21:

Compare results	Reusable DALYs	Single-use DALYs	Ratio	Percentage	Percentage increase
Production	1.444E-07	3.229E-06	22.36	4.47%	2136.15%
Transport	8.179E-11	8.494E-08	1038.51	0.10%	103751.33 %
Use	3.695E-08	1.295E-07	3.5	28.53%	250.47%
Reprocessing	8.169E-07	-	-	-	-
Maintenance	8.453E-08	-	-	-	-
Disposal	7.093E-08	1.115E-06	15.72	6.36%	1471.97%

Table 21: Comparison reusable and single use fURS: DALYs resulting for each life cycle stage, quotient and percentage with percentage increase.

III.1.2.3 Break-even point

The break-even point, meaning the number of uses of reusable fURS required so that reusable fURS have a lower impact than single-use fURS is around n=7.90092. This means that approximately eight (n=8) uses suffice for a reusable fURS to have a lower environmental and health impact than single-use fURS at the UKT.

III.1.3 Contributions

Contribution categories differ between the two devices regarding the life cycle stages we investigated. See Figure 17 for an overview of respective contributions to DALYs. Shares equal the percentages of kg CO_2eq, i.e. of the carbon footprint of fURS.

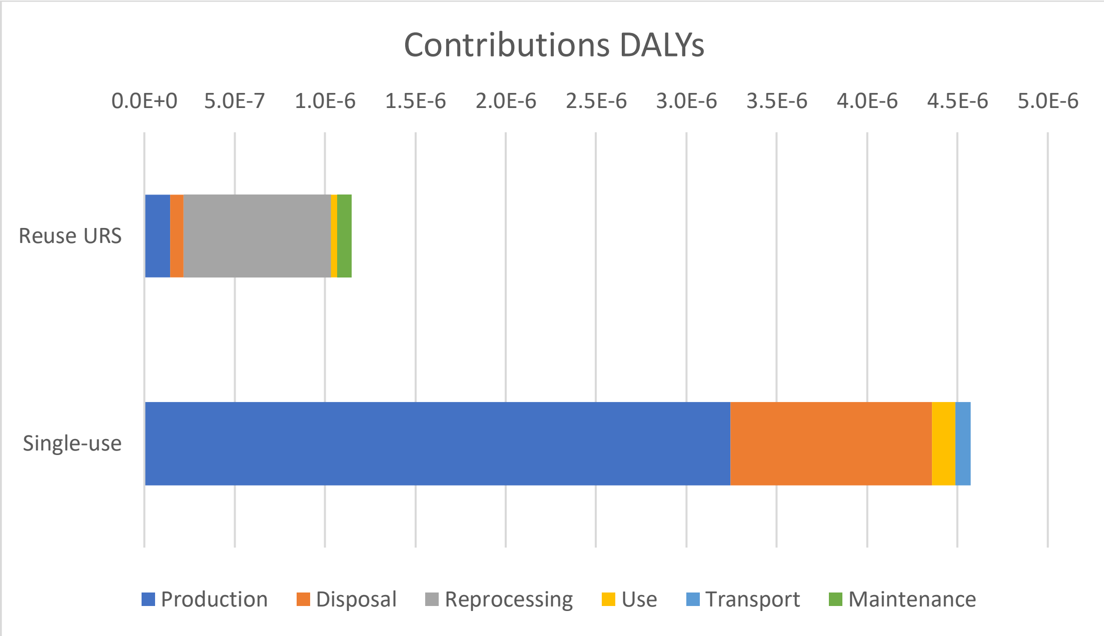


Figure 17: Life Cycle Stages: Contributions to Health Impact in DALYs

III.1.3.1 Percentages

Reprocessing (76%) contributes the largest amount to the health impact of **reusable fURS**, followed by production (14%) and disposal (7%). Use (3%), transport (<1%) and maintenance (<1%) play a minor role in the health impact of reusable fURS.

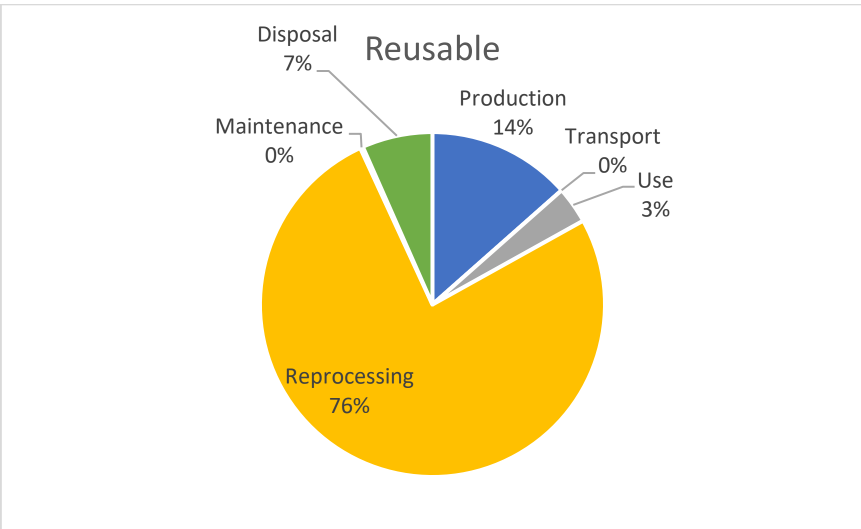


Figure 18: Contribution percentages: reusable fURS.

Production (71%) and disposal (24%) have the largest share in the health impact of **single-use fURS**. Reprocessing (0%) and maintenance are not applicable to these devices; use (3%) and transport (2%) contribute little to the health impact of single-use fURS.

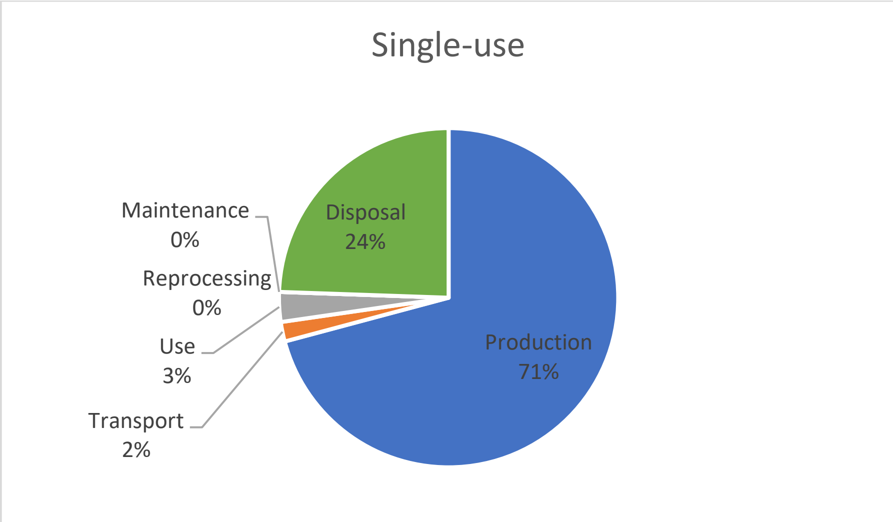


Figure 19: Contribution percentages: single-use fURS.

In comparison, production and disposal make up 21% of the reusable fURS but nearly 95% of the single-use fURS. When regarding the respective life cycle stages individually, the reprocessing phase is the one with the highest share for the reusable fURS.

The differing amount of waste generated by the respective devices leads to a higher EI and HI of single-use fURS in the disposal phase. Single-use fURS lead to a 16-fold higher amount of waste than reusable fURS:

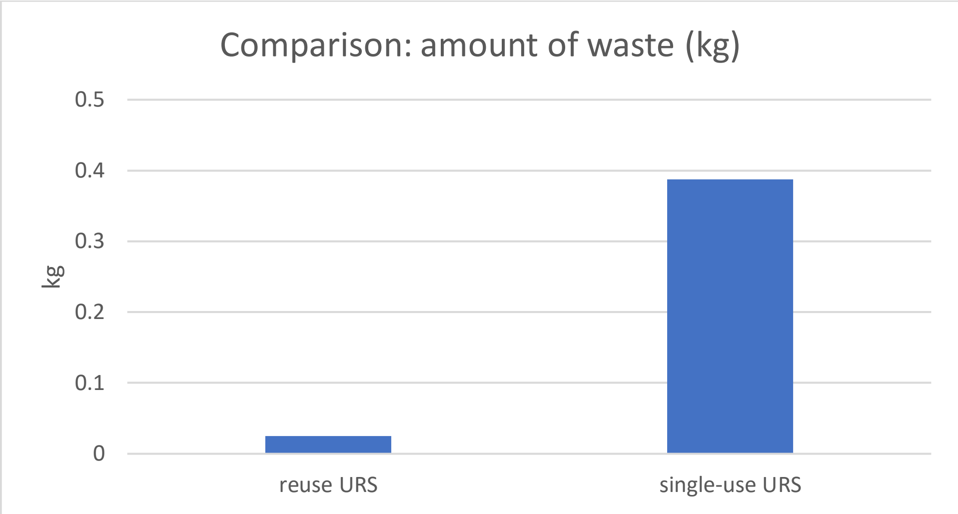


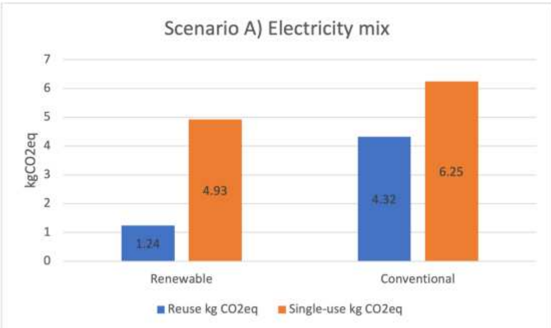
Figure 20: Amount of waste referring to the functional unit one use: 0.025 kg for the reusable- versus 0.388 kg for the single-use fURS.

III.1.4 SCENARIOS

However, the results depend on certain circumstances and differ between the scenarios.

III.1.4.1 SCENARIO A) ELECTRICITY MIX

Among other factors, the environmental and health impact of reusable and single-use fURS depends on the energy used by those using the fURS. In our hospital, reusable fURS have a lower environmental and health impact than single-use fURS (reusable: 1.24 kg CO_2eq and 1.15E-06 DALYs; single-use: 4.93 kg CO_2eq and 4.57E-06 DALYs). If, like in other German hospitals, a conventional energy mix is available, the environmental and health impact is higher for both, reusable and single-use fURS. However, the resulting impact of reusable fURS increases by 72% whereas the one of single-use fURS increases by 27%: 2.13 kg CO_2eq and 1.98E-06 DALYs for the reusable fURS versus 6.25 kg CO_2eq and 5.80E-06 DALYs for the single-use device.



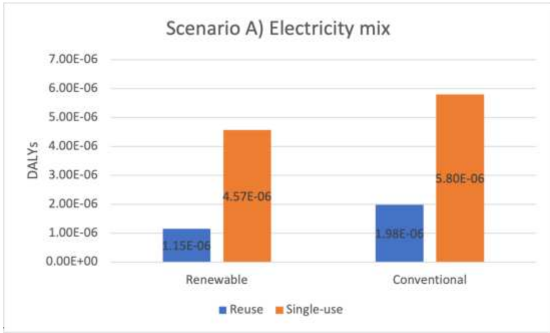


Figure 21: Environmental and Human Health impact scenario A) Renewable vs. conventional energy mix: kg CO_2eq & Disability adjusted life years resulting from LCA of reusable and single use fURS in hospitals using renewable vs. conventional energy mix.

Scenario A) shows that the electricity mix obtained by the hospital for the use of fURS results in different environmental and health impacts for *one use* of fURS. The use of renewable energies leads to a smaller environmental and health impact than a conventional energy mix.

III.1.4.2 SCENARIO B) NUMBER OF USES

Varying the number of uses of the reusable fURS leads to different results of the LCA. In our center, reusable fURS are used around 133 times (n=133) before disposal, resulting in 1.24 kg CO_2eq and 1.15E-06 DALYs. If a fURS is reused n=180 (n=1120) times, 1.17(1.03) kg CO_2eq and 1.09E-06(9.56E-07) DALYs result.

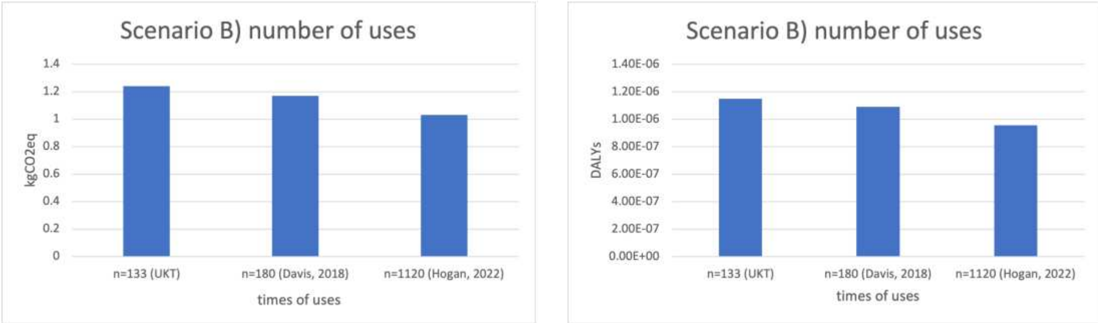


Figure 22: Environmental and Health impact scenario B) number of uses until end of life (EOL): Kilogram CO2 equivalents & DALYs resulting from n=133 (University Hospital Tübingen), n=180 (Davis 2018) and n=1120 (Hogan 2022) times of uses.

Scenario B) shows that with an increasing number of uses of a reusable fURS, the environmental and health impact decreases.

III.1.4.3 Scenario C) Number of reusable fURS/machine

Varying the number of fURS per washing machine changes the results of the LCA in the following way:

1) Two fURS per washing machine result in 1.24 kg CO_2eq and 1.15E-06 DALYs whereas
2) one fURS per washing machine results in 1.49 kg CO_2eq and 1.38E-06 DALYs.

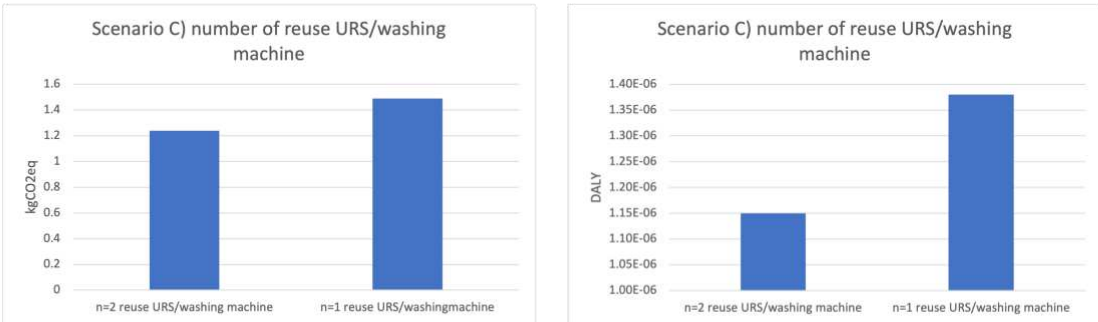
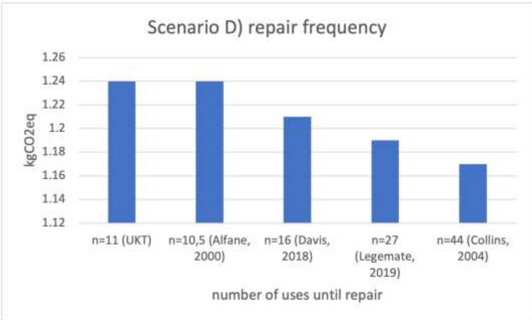


Figure 23: Kilogram CO2 equivalents & DALYs resulting in scenario C)1) two reusable fURS per washing machine and scenario C)2) one reusable fURS per washing machine

Scenario C shows that an optimal loading of washing machines (two reusable fURS per machine) leads to a lower environmental and health impact of *one use* of fURS.

III.1.4.4 Scenario D) Repair frequency

We assumed repair after each 11th time of use, resulting in 1.24 kg CO_2eq and 1.15E-06 DALYs. If fURS are repaired after 10.5 uses, the environmental impact result doesn't change decisively (1.24 kg CO_2eq and 1.15E-06 DALYs). If maintenance takes place after 16 (27) uses, the environmental and health impact is smaller (1.21 kg CO_2eq and 1.12E-06 DALYs (1.19 kg CO_2eq and 1.10E-06 DALYs)). Repairing fURS every 44th time results in an environmental impact of 1.17 kg CO_2eq. The Human Health impact of fURS changes to 1.09E-06 DALYs if the number of uses until repair increases to 44.



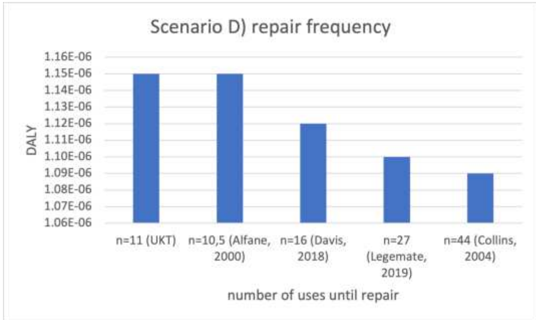


Figure 24: Environmental and Health impact scenario D) number of uses before repair: Kilogram CO2 equivalents & DALYs resulting from repair after each 11th, 10.5th, 16th, 27th and 44th time of use.

Scenario D shows that lower repair frequencies (i.e. higher number of uses until repair) result in lower environmental and health impact.

III.1.4.5 Scenario E) Single-use fURS production

We compared different possible countries of production of single-use fURS with different energy mixes. Single-use fURS production in China results in 4.93 kg CO_2eq and 4.59E-06 DALYs for the whole life cycle. Changing the production site to Malaysia results in a lower overall impact (4.41 kg CO_2eq and 4.09E-06 DALYs). A hypothetical scenario of single-use fURS production in Germany results in overall impacts of 3.74 kg CO_2eq and 3.47E-06 DALYs, respectively (with transportation from Asia to Germany still included in the LCA). The impact of the production process only results in 3.496 kg CO_2eq and 3.244E-06 DALYs for the status quo (production in China). It would be 2.978 kg CO_2eq and 2.764E-06 DALYs for Malaysia and 2.311 kg CO_2eq and 2.145E-06 DALYs if single-use devices were produced in Germany. This focus on the production impact is more practicable for a comparison as transportation is not involved.

Figure 25: Environmental and Health impact scenario E) kg CO2eq & DALYs resulting for production process of single-use fURS in China vs. kg CO2eq resulting for production process in Malaysia, Germany (hypothetically) and with renewable energy mix (theoretically).

If, as another theoretical scenario, the manufacturing company of single-use devices consumed renewable energy only, the overall carbon footprint for *one use* of the single-use device would amount to 2.52 kg CO_2eq and 2.34E-06 DALYs instead of 4.93 kg CO_2eq and 4.57E-06 DALYs. The carbon footprint resulting from the production process would be 1.09 kg CO_2eq, the health impact 1.01E-06 DALYs – instead of 3.496 kg CO_2eq and 3.24E-06 DALYs. The energy use in the production phase only would result in 1.288E-01 kg CO_2eq and 1.195E-07 DALYs instead of 2.535 kg CO_2eq and 2.352E-06 DALYs, which corresponds to 1/20th of the respective impact calculated by the authors of this study.

Also, contributions of respective life cycle stages would change; the production share would shrink from a) 71% (assumptions of this study) to b) 43% in a theoretical scenario with *renewable energy mix* single-use fURS production, see Figure 26 and Figure 27.

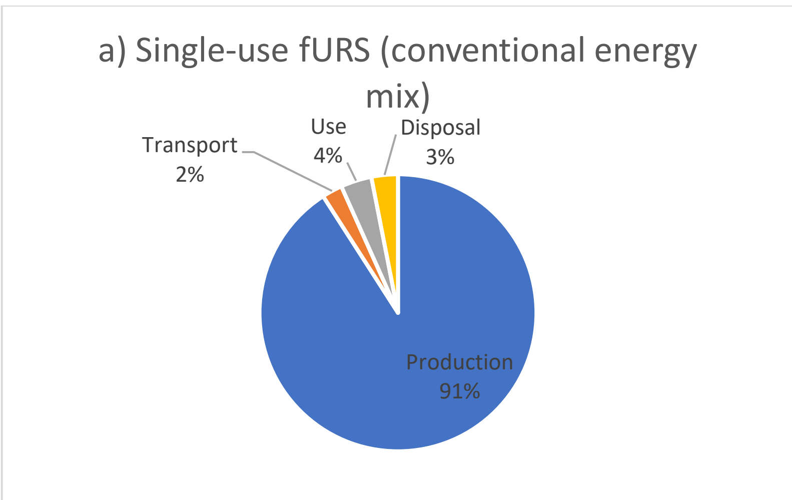


Figure 26: a) single-use fURS produced with conventional energy mix

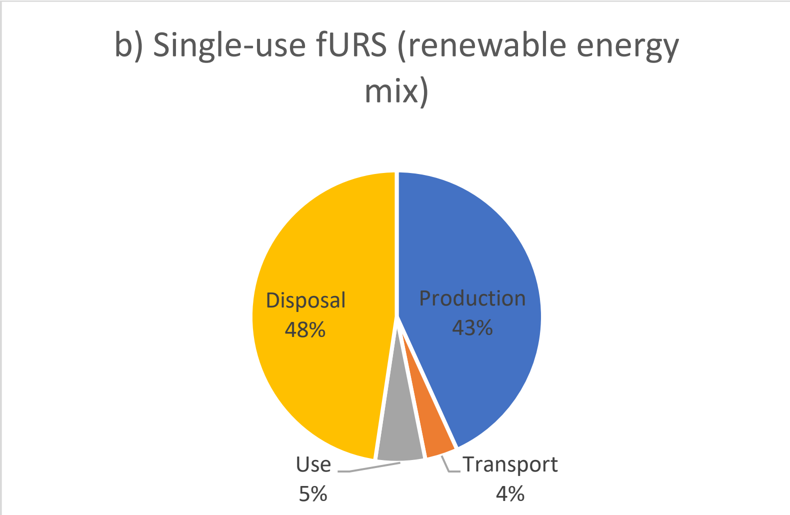


Figure 27: b) hypothetical: single-use fURS produced with renewable energy mix.

III.1.4.6 Scenario F) Two reusable fURS/sterilization process

If two fURS were always sterilized in one sterilization process, the factor for the flow required per application would change from two thirds to ½. Assuming always two fURS per sterilization, results change from 1.24 kg CO_2eq to 1.22 kg CO_2eq and from 1.15E-06DALYs to 1.13E-06. A full loading of the sterilization machine would result in lower EI and HI of *one use* of reusable fURS.

# required Per application	**2/3**	**1/2 (hypothetical)**	**Percentage decrease (%)**
kg CO2eq	1.24	1.22	1.61
DALYs	1.15E-06	1.13E-06	1.74

Table 22: Sterilization process: Flow required for 2/3 fURS or 1/2 fURS per one use

III.2 Qualitative results

Qualitative interviews of staff working in the urology department of Tübingen University Hospital, controlling, AEMP management and waste disposal management of the UKT yielded information on the purchase and cost criteria for fURS as well as waste management.

III.2.1 Purchase criteria

Qualitative assessment revealed a high relevance of clinical efficiency (5/5 "very high relevance") and results from clinical studies (4/5 "high relevance") for purchase decisions. Geographical criteria and trading conditions (0/5 "no relevance at all") were regarded as negligible while ecological criteria had medium relevance (3/5) in purchase decisions and were perceived to be increasing.

Subjective purchase criteria: To what extent do the following factors play a role in the purchase of fURS? (0=not at all, 1=a very small roll, 2=a small roll, 3=a medium roll, 4=a large roll, 5=a very large roll)	
Costs	5
Clinical efficiency (perceived by user)	4
Clinical efficieny (study results)	3
Ecological criteria	3, increasing
Faire trading conditions	0
Geographical criteria	0

Table 23: Individual purchase criteria, prioritization by users of fURS

III.2.2 Economic criteria

A disposable fURS costs 1000€ per use (purchase costs between 773€ and 1,167€). A reusable fURS costs approx. 650€ per use, with purchase costs of 10,000-20,000€, 133 uses, maintenance costs of 5,569€, maintenance after eleven uses, reprocessing costs of 34€ per unit.

III.2.3 Information on waste

Ureterorenoscopes are classified as waste code 18 01 04, which designates waste for which no special requirements apply to collection and disposal from the point of view of infection prevention. Patient contact exists/cannot be excluded. All waste treated under this code is incinerated in the residual waste incineration plant.

The residual waste from the UKT is transported to Böblingen in a truck that transports three containers. According to the waste management of the UKT, a mechanical metal separation takes place there after incineration (incineration temperature approx. 1000°C). In other plants (e.g. Berlin), such metal separation takes place by hand. In general, the remains of the incineration (30% of the incineration mass remains as "slag") are separated from the slag by means of magnets or air current separators to produce mixed scrap on the one hand and reusable metals for recycling on the other.

About 11-13 different substances are emitted in the incineration process, including CO_2, CH_4, PAH (dioxins, halogenated ethers).

III.2.3.1 Recycling

There were no usable results on the recycling of reusable fURS. According to the local recycling company (AV Möck GmbH, Tübingen), normally, when dealing with electrical scrap, it depends on the recyclable material. Scrap may be shredded, materials can be separated by NA/FA separator, floating-sinking process or "shaking table" and precious metals can be extracted if necessary. There was no specific information on whether reusable fURS would be recycled or not. Monitors may be reused or recycled; however, we do not include data on the monitors in our assessment.

Recycling of single-use fURS has not been implemented at the UKT yet.

IV DISCUSSION

IV.1 ON-SITE-SETTING AND SYNOPSIS

IV.1.1 THE IMPLEMENTATION OF SINGLE-USE DEVICES

Single-use medical instruments have been increasingly introduced during recent years in the field of endoscopic urology. At the UKT, the reusable variant is the device that is mainly used. Single-use devices are used for complicated surgery with high risk of wear or device damage due to difficult anatomical conditions.

When asked about purchase decisions, urologists at the UKT stated that they take environmental issues into account.

However, generally, urologists seem to be willing to use single-use instruments. This was evaluated by Rindorf et al. for cystoscopes and ureteroscopes:

"*On average, respondents indicated that they would consider converting to single-use in 44.5% of their cystoscopy procedures*." They add that over a half of the urologists interviewed had already used single-use fURS in their department. *"Single-use flexible ureteroscopes are already widely adopted within urology practices (...)"* (Rindorf et al., 2021).

Interestingly, interviews in other hospitals showed that surgeons would prefer single-use devices for themselves or close relatives (Rowley & Dingwall, 2007). Rowley and Dingwall conclude from their interviews in the field of anesthesia that concerns of clinicians are balanced between the fear of infection and fear of iatrogenic injury by using a single-use device. We did not include the users' personal preferences in the life cycle assessment.

Still, infection control must be taken into account when discussing the use of single-use or reusable ureteroscopes, respectively. There has been a decrease in reported infections after the use of reusable medical devices in recent years (FDA Executive Summary, 2019).

According to Unno et al., however, urinary tract infections (UTI) are less likely after single-use ureteroscopy:

"*Rates of postoperative UTI were lower in those undergoing ureteroscopic stone removal with a single-use ureteroscope compared to a reusable ureteroscope (6.5% vs 11.9%, p = 0.018)*" (Unno et al., 2022 #389).

A similar conclusion was drawn by Mourmouris et al.: "*a lower sepsis rate was detected in patients treated with single-use scope"* (Mourmouris et al., 2021).
At the same time, MacNeill et al. point out that there was *"no compelling evidence that (single-use disposals) reduce health care–acquired infections*" (MacNeill et al., 2020).

In a study from Nepal, 68% of the health care workers interviewed strongly agreed when asked if they would feel safe being treated as a patient using medical instruments sterilized in the hospital of the study (Panta et al., 2022). Reasons for these study results have not been determined.

As pointed out earlier, infection control is expected to be possible if reprocessing is done correctly. Nonetheless, our results are not supposed to be a definite purchase recommendation but a proposition to do research on these devices.

As it is, the implementation of single-use material is certainly suspected to have negative effects on human health. We wanted to take a step towards more evidence by proving this statement through LCA.

IV.1.2 LCA IN LITERATURE

The literature research done by the authors of the present thesis over the last few years (2019-2023) has been focused on studies that, similar to our study, collected and compared LCA data on reusable and single-use medical material (medical devices/instruments such as laryngoscopes (Sherman et al., 2018), catheter material (McGain et al., 2012), bronchoscopes (Sørensen & Grüttner, 2018) and ureterorenoscopes (Davis et al., 2018)). The platform https://healthcarelca.com/database provides a comprehensive overview of existing LCA in healthcare.

IV.1.2.1 OVERVIEW

In a recent review, Drew et al. included 28 individual papers that addressed equipment and materials, i.e., individual items of use in various settings. The authors categorized

a) surgical materials such as gowns (Carre, 2008, Van den Berghe & Zimmer, 2011, Vozzola et al., 2020), disposable sterile drapes (Vozzola et al., 2018), surgical scrub suits (Mikusinska, 2012), scissors (Ibbotson et al., 2013), suction containers (Ison & Miller, 2011) and other items used in the operating room,

b) anesthesia equipment such as medication trays (McGain et al., 2010), laryngeal masks (Eckelman et al., 2012), laryngoscopes (Sherman et al., 2018) and central venous catheter (CVC) sets (McGain et al., 2012),

c) items for specific procedures, e.g., titanium knee replacement elements (Lyons et al., 2021), prepackaged sets for specific procedures, e.g., childbirth (Campion et al., 2012) and supplies for hysterectomy surgery (Unger et al., 2017), for spondylodeses (Leiden et al., 2020) and ureteroscopes (Davis et al., 2018) and

d) nonspecific materials used in the operating room: personal protective equipment (PPE) such as masks, gloves, aprons, gowns, and face shields (visors) (Rizan et al., 2021), as well as items in use such as surgical masks (Allison et al., 2020, Lee et al., 2021, Schmutz et al., 2020, sterile gloves (Weisz et al., 2020), urinary catheters (Stripple et al., 2008), drop containers (Grimmond & Reiner, 2012, McPherson et al., 2019), specula (Donahue et al., 2020).

IV.1.2.2 Outcomes

Judging from the papers listed above and in line with the findings suggested in this study, reusable products have greater "climate friendliness." Only two of the studies reviewed concluded the contrary: reusable CVC sets (McGain et al., 2012) and spondylodesis materials (Leiden et al., 2020) were three and nearly seven times as CO_2-intensive as their single-use equivalents, respectively. It should be noted, however, that the Leiden et al. study was supported by the company operating the single-use products. A study on face masks also showed an environmental advantage of the single-use variant, but here a short life span (five washes) of the reusable variant was assumed (other studies on face masks assumed 30-138 washes). Two other studies from Melbourne in Australia showed no ecological advantage from the use of reusable objects but a near comparability of reusable and single-use, one of which is the study by Davis et al. (2018) on flexible ureteroscopes.

IV.1.3 FINDINGS OF THIS STUDY

Environmental aspects might play an increasing role for further decision-making in medicine. In this comparative LCA based in the University Hospital of Tübingen, reusable fURS proved to have a lower environmental and health impact than their single-use equivalent regarding the functional unit *one use*.

It must be mentioned that the term "environmental impact", in this study, is occasionally used synonymously with "greenhouse gas emissions", which, of course, does not cover all environmental impact aspects.

The outcome of the LCA is highly dependent on multiple factors. This is suggested by the scenario models presented in the study.

IV.1.3.1 COMPARISON

While reusable and single-use fURS might feature comparable clinical efficiency, the environmental and resulting health impact of single-use fURS was found to be nearly 4 times higher than the one of reusable fURS in this comparative LCA based on the University Hospital of Tübingen.

The reprocessing stage, which in former LCA-studies has been mentioned as the life cycle phase with the largest emission, also makes the biggest contribution to the carbon footprint of reusable fURS (in this assessment 0.8801 kg CO_2eq; 71% of overall reusable fURS impact).

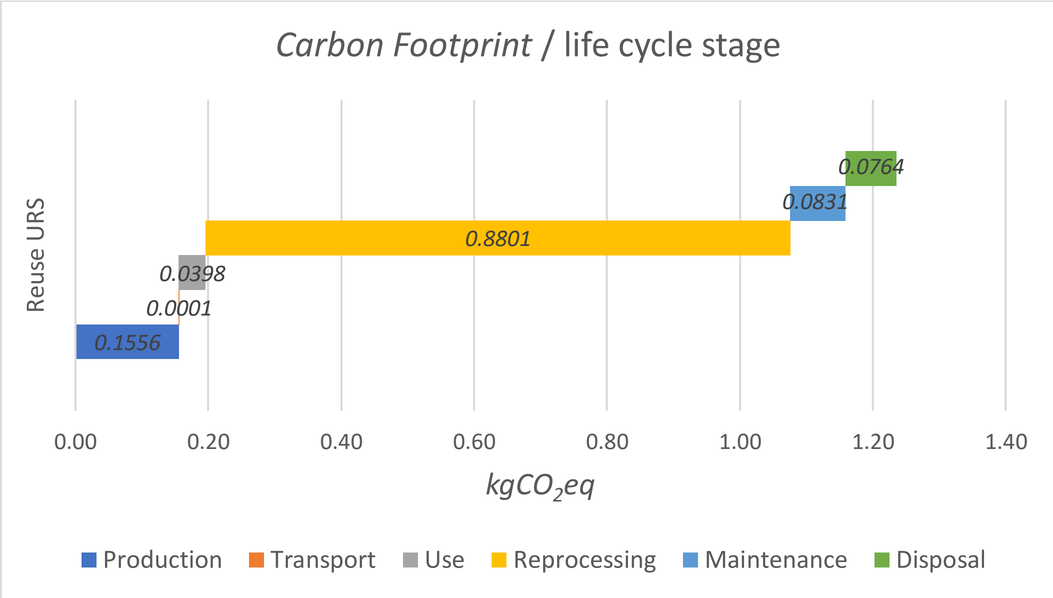


Figure 28: Contributions to carbon footprint of ru fURS per life cycle stage, unit: kg CO_2eq

However, compared to the single-use fURS impact (4.93 kg CO_2eq), it can be regarded as considerably lower, among other things because of the electricity mix used in the hospital where the study was based (*renewable energy mix*).

Today's medicine – including urology – is starting to take climate change and its impact on human health into consideration. However, there is little evidence in this field. Using a practical example, we found that ureteroscopes that are reused several times (n>8), result in lower greenhouse gas emissions and DALYs compared to single-use devices.

The scenarios outlined in this study, however, reveal parameters that may influence the outcome of the LCA in a decisive way. For instance, in hospitals where conventional energy is consumed, there would be a 72% higher environmental and health impact of reusable fURS; the impact of single-use fURS would increase by 27%. More uses, more fURS per reprocessing/sterilization machine and less repairs would lead to a lower impact. If single-use devices were produced with renewable energies, their impact would be 1.09 kg CO_2eq instead of 3.496 kg CO_2eq. More in-depth research is needed based on these data.

In the following, we will further discuss the respective life cycle stages and point out limitations that go along with it.

IV.2 QUANTITATIVE DATA

IV.2.1 COMPARISON REUSABLE VS. SINGLE-USE FURS

Based on the single components calculated from life cycle stages of the respective devices, a comparison can be drawn.

Comparing the results of reusable and single-use fURS life cycle stages, the single-use device led to >100% higher emissions than the reusable device in all life cycle stages except reprocessing and maintenance as single-use fURS are not reprocessed or repaired but disposed of after one use.

Note: Single-use fURS as disposable medical devices are assumed not to be reprocessed in our study.

IV.2.2 HOTSPOTS

In line with the LCA framework, we performed several completeness and consistency checks. We analyzed the individual sectors in order to find out about stages with significant EI/HI (hotspots). As shown in the results, the share of each life cycle stage was evaluated (see contributions).

IV.2.2.1 REPROCESSING, PRODUCTION, DISPOSAL

The **reprocessing phase** is the most influential life cycle stage of the reusable fURS in our study (76%). Similar to earlier studies comparing reusable and single-use medical instruments (Drew et al., 2022), the **production phase** turned out to be the most influential life cycle stage of the single-use fURS (71%). Also, the **disposal stage** contributes greatly to the carbon footprint and health impact of single-use fURS (24%). Production and disposal together make up 21% of the impact of reusable fURS, but 95% of single-use fURS. The weight of the waste generated by single-use fURS is 16-fold higher than that of reusable fURS.

IV.2.2.2 USE AND TRANSPORTATION

These outcomes are primarily a function of the number of uses: While reusable fURS are, in our assumption, used 133 times, single-use fURS are produced for and disposed after each application. The impact of the **use** phase itself turned out to be relatively small for both variants (around 3%). The impact of **transportation** is over 1.000-fold higher for the single-use variant, as it is manufactured abroad.

IV.2.2.3 DALYs (exemplification)

Considering the impact on e.g. Germany (84,300,000 citizens (Statistisches Bundesamt, 2022)), single-use fURS lead to 288 more years with disability (reusable fURS: 1.15E-06 DALYs, single-use fURS: 4.55E-06 DALYs).

A recent assessment from Li et al. calculated DALYs of 1.394/100,000 (global population) for urolithiasis (Li et al., 2022). Relating these findings on the burden of urolithiasis to the results of the present study (1.15 DALYs/100,000 or 4.57 DALYs, respectively, for ureterorenoscopy), it becomes evident how prevention and early intervention of this disease has a positive effect on human health globally.

IV.2.3 Discussion of life cycle stages

IV.2.3.1 Manufacturing

In the course of the assessment, more detailed data on the production phase was provided for single-use fURS by several companies. In other studies, the production phase was not considered for reusable instruments (Sørensen & Grüttner, 2018); however, we included data on reusable fURS if available.

IV.2.3.1.1 Material

For the reusable fURS, we did not include smaller components such as labels and brochures as we considered those negligible. Apart from that, material contributions (e.g. plastic, metal, electronics (<1%)) that resulted from our research were compared to percentages of material calculated by a group working on bronchoscopes, see Figure 29:

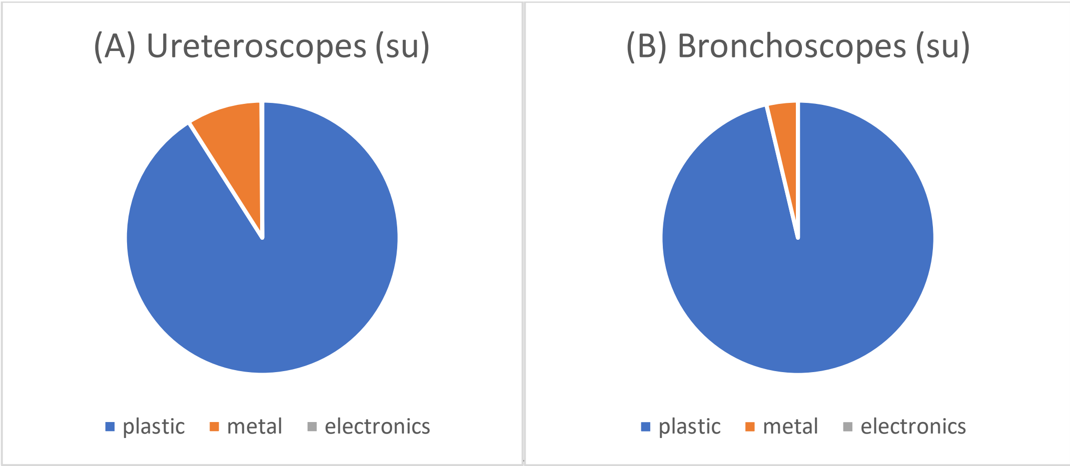


Figure 29: (A) share of material in su fURS, (B) share of material in su bronchoscopes (Sørensen & Grüttner, 2018).

An earlier doctoral thesis at the University Hospital of Tübingen (Haberstock, 2020) listed approx. 300g for a single-use fURS, taking data from BostonScientific: 277.5g (Proietti et al., 2017) and Pusen: approx. 330g (Reis Santos, 2018). A statement from another company read: "*single use fURS including all components weight about 260 g*", confirming that our data are reliable.

Different kinds of plastic were taken into account and calculated separately; however, in a sensitivity analysis, subdividing plastic into different kinds of plastic did not make a difference for the overall results. Packaging for the reusable fURS contributed to a considerable extent to its overall impact because we considered that the device comes with a case. The case could be reused more often than a reusable fURS, which would result in a lower impact. For simplification, we considered one case for one reusable fURS, leading to a rise of the results for the reusable fURS by no fewer than 1.243 kg CO2eq and 1.154E-07 DALYs.

IV.2.3.1.2 Energy use

Furthermore, we examined the effects of different energy data. The energy input in the production of single-use instruments was based on an expert *guesstimate*: "*2.4 kWh per pcs. or less (...) maybe 2 kWh*" (e-mail manufacturing company, November 16, 2022). These data are hard to estimate. In general, companies produce a wide range of products and sometimes it was unfeasible to provide specific energy data on fURS. Partly, we were quoted energy prices as information about electricity only and estimated energy amounts from those.

As shown in scenario E): comparing different energy mixes in different possible production countries, it became evident that this factor influences the results significantly. For a hypothetical production in Germany, the “transport” factor would play a role as well (in results: 9.153E-02 kg CO_2eq and 8.494E-08 DALYs for Malaysia-Germany versus only 8.813E-05 kg CO_2eq and 8.179E-11 DALYs for transport within Germany) and would result in a nearly 100% decrease (99.9037%). However, production of single-use fURS in Malaysia would have a lower environmental and health impact than production in China (which was assumed in this study).

IV.2.3.1.3 Water use

Earlier studies have concluded that water use for the production of reusable fURS is higher (McGain et al., 2017), so we calculated the carbon footprint and DALYs of a higher amount of water (see Table 10) which resulted in no change of results unless the amount of water was multiplied by 40 thousand.

Unless those results seem to have not much meaning for the overall thesis, water use has to be discussed in a wider *Planetary Health* context. Water scarcity or insecurity indirectly leads to adverse health effects (Prior, 2018). It became apparent that the use of a reusable device causes a higher need of water than the use of single-use fURS. From that perspective, single-use instruments appeared to be favorable. The comparison of water use as an *impact category*, however, was not focus of this study.

IV.2.3.2 Transportation

The per-use impact of transportation is small for reusable devices. Transportation to and from reprocessing (for the reusable fURS) was left out of the calculation as it takes place inside the hospital. The protective cover (4g, LDPE, *market for polyethylene, low density, granulate | polyethylene, low density, granulate | Cutoff, U – GLO*) for in-hospital transportation of the reusable fURS, however, is included in the LCA. The single-use instruments have to be shipped from abroad (approximately 13,000 km, *market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U – GLO*) and driven to Tübingen (app. 700 km, *market for transport, freight, lorry 16-32* *metric tons, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER*) – one piece per use. In a plausibility check we found that, by changing the production location to China, for instance, there is no relevant change in the overall results due to similar distances (13,000 km-15,700 km: no change in overall result; distance Pulau Penang-Hamburg 9553.42 km, distance Hongkong-Hamburg 8916.05 km).

IV.2.3.2.1 End-of-Life transportation

We assumed the same distance to the disposal site for both reusable and single-use scopes. However, again, one single-use device is transported to the waste processing company per use whereas for the reusable device, the distance by lorry (30 km, *market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U – RER*) is divided by 133 (n=133 uses). That way, the impact of transportation for reusable fURS proved to be less relevant than for the single-use fURS.

IV.2.3.3 Use

The use phase accounted for 3% of each impact (ru and su).

IV.2.3.3.1 Parameters

For the use phase, we hypothesized the same amount of energy required for the application of reusable and single-use fURS in the operating theater. As we assumed durations of surgeries to be similar per use (app. 1h according to users), we did not compare different durations of procedures.

Other emission parameters linked to ureteroscopy (e.g. electricity needed for air conditioning or heating (climatization) of the operating room (OR) or anesthetic gases) were not included in the LCA as they were assumed to be similar for reusable and single-use devices due to similar procedure durations and auxiliary material. Hence, we considered them not decisive for the outcome of the comparison.

IV.2.3.3.2 Monitors

We did not include the monitors used during ureteroscopy surgery. Monitors show the images of the camera at the tip of the fURS to the operating team. In the UKT, they are rented from the company UroRent. They function via picture and light signal and HDMI connection. According to the company, the monitors are used for at least three to five years and can be updated when/if necessary. In our LCA, we focused exclusively on the surgical instrument (the scope itself).

IV.2.3.3.3 USE + REPROCESSING

If for the reusable fURS the *use* steps are calculated together with the *reprocessing* steps, this life cycle phase (*use + reprocessing*) has a health impact of 8.54E-07 DALYs whereas the use phase of single-use fURS has an impact of 1.295E-07 DALYs. Considering this, the carbon footprint and health impact of single-use devices only results in 1/7th of the carbon footprint and health impact reusable fURS for that life cycle phase.

The number of disability-adjusted life years resulting from the use stage of reusable fURS, reprocessing included, was calculated as 0.000000854:

$$DALYs(use) + DALYs\ (reprocessing) = DALYs\ (use + reprocessing)$$

$$3.695\mathrm{E}-08\ \mathrm{DALYs} + 8.169\mathrm{E}-07\ \mathrm{DALYs} = 8.540\mathrm{E}-07\ \mathrm{DALYs}$$

Comparing it that way, the use phase of reusable fURS results in a seven times higher health impact compared to the use phase of single-use fURS.

IV.2.3.3.4 BREAK-EVEN POINT

The analysis of the *break-even* point resulted a number of eight uses for the reusable fURS, meaning that approx. eight uses suffice to make reusable fURS more beneficial for human and planetary health. This is roughly in line with other studies' findings (break-even point for laryngeal mask airways: 10 (Eckelman et al., 2012), scissors: 9 (Ibbotson et al., 2013).

IV.2.3.4 REPROCESSING

Sterilization is done with H_2O_2 (hydrogen peroxide) at the UKT and would probably result in a different impact if it was done by gas or water vapor. Vapor sterilization requires temperatures which are too high for sensitive devices such as endoscopes (134°C). Gas (e.g. ethylene oxide), however, would take too long to outgas (12h), which is not practicable for reusable fURS in the clinical context. Single-use fURS are sterilized with ETO (gas) once after the production process, which may be favorable regarding their environmental footprint compared to other sterilization options.

IV.2.3.4.1 Background data dependency - example

Generally, the impact depends on the source and background data used. As an example, for ETO sterilization, at first, we found out that these processes lead to an emission of approximately 0.46 metric tons CO_2/metric ton ethylene oxide produced (Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019, 2021), corresponding to 0.46 kg CO_2eq per kilogram ETO. 8.2 g ETO are needed for one sterilization of one single-use fURS for *one use*, so

$$0.0082\,kg\ \times 0.46\,kgCO_2eq\ = 0.003772\,kgCO_2eq$$

was primarily assumed as an approximate value for the amount of ethylene oxide needed. We considered adding 3.77E-03 kg CO_2eq to the calculation in the LCA. However, the data from ecoinvent used in our LCA led to a higher impact (1.558E-02 kg CO_2eq) for single-use fURS sterilization using ETO.

IV.2.3.4.2 Number of fURS/sterilization

If we assumed optimal loading (always 2 fURS/sterilization process), the environmental impact would be 1.6% lower and the health impact 1.74% lower than assuming the probable occurrence of singular sterilization (see scenario F).

Note: In practice, *all* devices in use at the UKT from multiple sectors are reprocessed in the sterilization department of the UKT. Therefore, the factors presented should be considered as an approximation, not at all as absolute in each case.

IV.2.3.4.3 Hazardous sterilization?

The Boston Scientific LithoVue brochure claims an advantage of single-use devices due to the danger of toxic chemicals and disinfection material for the reprocessing staff. However, the product information for Dr. Weigert neodisher endo CLEAN claims that it is no hazardous substance according to the European chemicals legislation (Sicherheitsdatenblatt gemäß Verordnung (EG) Nr. 1907/2006, 2020). Dispelling further concerns in this field, there is no direct skin contact with endoSEPT during the sterilization process.

IV.2.3.4.4 Inclusion of reprocessing steps

We considered the cleaning of working surfaces with a cloth (21g). This step is carried out as per the regulations once a day and in the event of substantial contamination:

"*The working surfaces in the reprocessing room and the examination room must be cleaned and disinfected with surface disinfectants of proven efficacy (...) each working day, and promptly in the event of visible contamination*" (Empfehlung der Kommission für Krankenhaushygiene und Infektionsprävention (KRINKO) beim Robert Koch-Institut (RKI) und des Bundesinstitutes für Arzneimittel und Medizinprodukte (BfArM), 2012).

Due to this and the high amount of (diverse) instruments reprocessed apart from fURS, this step was omitted from the analysis. The same applies to documentation, which is primarily done digitally and considered negligible for the calculation by the authors.

IV.2.3.4.5 REPROCESSING – OTHER STUDIES

Interestingly, earlier studies have evaluated the carbon footprint of certain materials also included in the reprocessing calculation of the present study in more detail and found higher amounts of CO_2eq than we did.

Examples:

Single-use **gowns**: 0.905 kg CO_2eq and **face shields**: 0.231 kg CO_2eq (Rizan et al., 2021) vs. data of the present study: 0.216 kg CO_2eq for one gown (used for five fURS; in this LCA: 0.0432 kg CO_2eq per fURS) and 0.02596 kg CO_2eq for a face shield (used for 100 fURS; in this LCA: 2.596E-04 kg CO_2eq per fURS).

Single-use **surgical face masks**: 0.580 kg CO_2eq (Lee et al., 2021) vs. data of the present study: 9.859E-03 kg CO_2eq (used for one fURS in the present assumption).

For the **brushes** in the publication on bronchoscopes (Sørensen & Grüttner, 2018), stainless steel and polypropylene is given as the material instead of plastic only.

All this shows how different assessments done by different authors in different locations can result in different LCAs. We considered including their LCA-results in our inventory. However, as LCAs are always based on limited evidence, we decided to consistently try to measure what we could on our own and use the personally collected, measured values for the LCA.

Data **for energy use** of the reprocessing stage was mainly taken from literature. This might lead to higher energy amounts than in reality.

Comparatively, for the reprocessing of reusable fURS, Davis et al. arrived at 3.95 kg CO_2 (in our study, reprocessing with the *conventional energy mix* would result in 3.365 kg CO_2) (Davis et al, 2018). However, the results by Davis et al. may not be directly comparable to our results: The Australian research reports 4.43 kg CO_2eq for single-use fURS and 4.47 kg CO_2eq for reusable fURS (compare present study: 4.32 kg CO_2eq (*conventional energy mix*) and 1.24 kg CO_2eq (*renewable energy mix*) for reusable fURS and 6.25 kg CO_2eq (*conventional energy mix*) and 4.93 kg CO_2eq (*renewable energy mix*) single-use). In Australia, electricity is generated mainly by coal, see below.

IV.2.3.5 Maintenance

The maintenance phase concerns only the reusable devices.

IV.2.3.5.1 Inclusion of maintenance stage

The maintenance process was left out of some former LCA studies. It doesn't impact the results a lot: One third of a kg CO_2eq resulted for one repair (repair per fURS: 2.769E-02 kg CO_2eq, every eleventh use resulting in 0.30459 kg CO_2eq per maintenance). However, we included it in our assumption.

IV.2.3.5.2 Maintenance – other studies

Our figure was lower compared with literature data (Koo et al.: repair 5 kg CO_2eq/cystoscope) (Koo et al., 2021), suggesting, again, how limited access to data may influence results. If we took the results from Koo and colleagues as data for the maintenance of fURS, 1.66 kg CO_2eq (1.24-2.769E-02 + 5/11 = 1.66) would result for *one use* of reusable fURS, which would, however, not change the essence of the study.

The maintenance frequency depends primarily on the care of the surgeons and the complexity of the procedures, but other factors may also play a role. In the literature, the maintenance frequency varies between once every 6 and every 59 uses (Afane et al., 2000, Collins et al., 2004).

As described in scenario D, different frequencies were assessed. Less repair results in lower greenhouse gas emissions and health impact.

IV.2.3.6 Disposal

As mentioned in the introduction, the healthcare sector contributes to a large amount of national waste generation.

IV.2.3.6.1 Hospital waste

This is probably one of the first studies in Germany taking a closer look at hospital waste. As laid down by the LAGA, waste should be treated in a way that neither health nor environment are damaged (Bund/Länder-Arbeitsgemeinschaft Abfall, 2015). In Germany, regulations are based on a circular economy law (*Kreislaufwirtschaftsgesetz* (KrWG)) stipulating that waste should generally be avoided in the first place. If materials need to be disposed of, they should be recycled, and only if that is not possible should they be disposed of, see introduction.

Unless hospitals are also subject to waste hierarchy guidelines, separation of recyclable and non-recyclable waste is often avoided for fear of possible contamination (United States Environmental Protection Agency, 2023).

IV.2.3.6.2 Recycling

Former studies pointed out that

"Recycling will lead to significant benefits in terms of protection of health and the environment (...)" – about mercury (Sousa et al., 2020).

We lacked consistent information about recyclable parts of fURS and packaging. However, we found that for the present LCA, including a recycling option would not alter the overall results. We thus considered the relevance of recycling negligible for our calculation and assumed disposal of fURS.

However, we attempted to ascertain some more precise information on waste management at the UKT (see qualitative results). We believe that further investigations (e.g. on concepts of circular economy (Schulte et al., 2021)) would be necessary in order to include a recycling scenario in an LCA like the present one.

IV.2.3.6.3 Interfering variables

Furthermore, it can be assumed that there will be isolated cases of premature disposal and other deviations (e.g. n=50 uses of ru fURS only or n=0 uses of su fURS – direct disposal). Interfering variables may be, for example, inappropriate use (doctors, nurses, transport and reprocessing personnel).

IV.3 SCENARIOS

IV.3.1 ELECTRICITY MIX

The results of the present assessment suggest to discuss Scenario A) Electricity mix in more detail.

IV.3.1.1 INFLUENCE OF ELECTRICITY MIX

The electricity mix, generally, has a considerable impact on the environmental impact of processes. In Germany, discussions about e.g. e-mobility and political regulations regarding the implementation of renewable energies are ongoing.

Within the framework of the sensitivity analysis of this study, we found that for *one use* of fURS, the electricity mix used by the hospital has a large influence on the environmental and health impact of the devices as the use of renewable energies led to a two thirds reduction of the impact of reusable fURS. Also, if renewable energy was used in production, the impact of single-use fURS would only be one twentieth of the status quo.

IV.3.1.2 ANALOGOUS PROJECTS

In 2020, Helmers et al., for instance, performed a comparative LCA of electric vs. combustion engine cars and showed how various factors created a broad variation in the results. Car battery production using renewable energy instead of coal-based electricity in China decreased its impact by 69%, for instance. This is comparable to our results for scenario A): reduction of impact: 72%.

Earlier studies in the medical field suggested that, as an example, reprocessing using renewable-based electricity (UK/European mix) or natural gas-based electricity (U.S. mix) as opposed to energy obtained from coal (Australia) could reduce the climate impact of reusable anesthetic equipment by 52-86%.

IV.3.1.3 GEOGRAPHICAL CRITERIA

In line with the studies mentioned above, the carbon footprint is highly dependent on the local electricity mix (McGain et al., 2017).

In our study, we considered different energy scenarios occurring in Germany. Scenario A) describes the different results caused by the use of conventional or renewable energy, respectively.

Generally, geographical criteria play an important role for LCAs: production in China vs. Malaysia vs. Germany (Scenario E) influenced the results due to differing energy mixes. However, literature from e.g. Australia is difficult to compare. Also, differing countries lead to different results for similar procedures (e.g. cataract surgery: 30 times lower impact in India compared to same procedure in the US) (Eardley, 2022).

As mentioned in the introduction, this was also one of the driving factors behind the study: The only LCA project on ureteroscopes found was based in Australia, where, at that stage, energy was mainly obtained from coal (Davis et al., 2018).

IV.3.2 OTHER SCENARIOS

IV.3.2.1 SCENARIOS IN LITERATURE

As shown above, the findings from this study's scenarios have been compared to other studies. For instance, in line with the findings of a study by Eckelman et al. (10 laryngeal masks result in -25% GHG emissions), several devices reprocessed simultaneously result in a lower impact (Scenario C) (Eckelman et al., 2012).

IV.3.2.2 CALL FOR SCENARIOS

The design of different scenarios proposed in this study could be expanded indefinitely.

More in-depth scenario research should be developed and considered more comprehensively in future studies.

IV.4 QUALITATIVE DATA

As mentioned in the introduction, there are reasonable arguments for urologists to include *Planetary Health* considerations into their daily practice. In the present study, urologists in the University Hospital of Tübingen were found to take environmental factors as purchase criteria into consideration. In any event, more comprehensive studies on decision-making and usage preferences are urgently needed and should be interlinked with results from studies like the present one.

IV.5 Limitations

IV.5.1 LCA methodology and quantitative data collection

IV.5.1.1 General limitation

An exact statement about the carbon and health footprint of reusable and single-use fURS is not feasible due to the typical limitations of LCAs (see methods: impact coverage and methodological limitations).

IV.5.1.2 New methodology

Life cycle assessments in interventional medicine are still in their infancy (Drew et al., 2021). There is little literature in this field, which makes it difficult to compare the results and to scientifically substantiate the data (Drew et al., 2022). It is indicated to promote the development of life cycle assessments in the medical field in order to optimize and expand LCAs as a standard methodology for in-depth process assessment. Furthermore, re-evaluation of evidence is needed continuously as new conclusions are presented.

IV.5.1.3 Data sources

In general, data collected for LCAs are mainly based on estimations. The investigators always had to make a rather subjective selection of items to be considered and find specific allocations in the respective database. Inconsistency in the level of detail of primary data on the reusable vs. single-use instruments does not impact the robustness of the study.

IV.5.1.4 Data availability

It was impossible to include some data due to lack of access to information. We only investigated some of the fURS available on the market.

Some data depended on literature, some of which, as described above, is of very poor quality. For instance, we evaluated the amount of energy used for the reprocessing of fURS on the basis of a limited Australian study (Davis et al., 2018), and this was confirmed by the sterilization sector of UKT.

For some data, inclusion was unnecessary. In-house transport of reusable fURS, for instance, was not included in the LCA as it was considered negligible.

Some data was excluded after performing a sensitivity analysis. For instance, a hypothetical reduction or increase in the amount of energy used in the production stage did not change the results of the whole analysis of the reusable instrument. We were unable to obtain qualified data on the production energy of reusable fURS and therefore used the same amount of energy as for single-use devices in our calculation.

Also, the analysis of the impact of single life cycle stages – their proportion in the overall output – helped us to decide whether or not to include certain data clusters.

Generally, as described above, the aim of this study was not only to generate figures that would allow a comparison between reusable and disposable ureteroscopes, but also to create a model for similar analyses. For this purpose, the exact data – which, as described above, are mainly estimates – are less significant.

IV.5.1.5 System boundary selection

Generally, the system boundary selected by the authors of the study has an impact on the inclusion of in- and outputs of the LCA.

IV.5.1 Qualitative data

The qualitative part of this study is based on an unsystematic methodology, but qualitative research was not the focus of this study. It may be seen as additional information on costs, purchase decisions and waste treatment. The main goal of this study was the life cycle assessment of reusable and single-use fURS according to ISO 14040/14044.

IV.5.2 Single-center study

This study was performed based on the devices used and processes performed in one hospital in Germany (Universitätsklinik Tübingen). To our knowledge, sterilization processes and waste management, for instance, vary in every facility. Also, energy supply differs from country to country and sometimes even from hospital to hospital (UKT: *renewable energy mix*). For sensitivity, we included calculations with different scenarios (e.g. *conventional energy mix* of Germany) in this study.

IV.5.3 Objectivity of the researchers

The level of depth and detail of the investigation of specific processes is highly dependent on the individual investigator.

The limitations of the present work mean that interobserver variability is likely due to the selection of parameters surveyed, limited data available, and limited access to data. Therefore, an attempt was made to counteract investigator dependency by conducting the broadest possible literature search and carefully selecting data sources, followed by conducting interviews in the most targeted way possible. In part, subjective numerical and process data ("*educated guesses*"/ "*guesstimates*") were provided by employees of companies whose goal is to market their respective product as successfully as possible in line with the company's mission statement. Despite the anonymity of the companies that provided the data, a bias in this respect can be assumed. However, it can also be assumed that the present study is comparable to others of its kind – depending on the respective design – as the limitations mentioned above equally apply to similar studies.

IV.5.4 RELIABILITY

Replication of an LCA on fURS would likely yield divergent results even under similar conditions. For this reason, this analysis must be read keeping in mind that the calculation underlies typical LCA limitations.

Drew et al. remind the reader: "*Any conclusions drawn should be interpreted with caution and reevaluated as new evidence becomes available*" (Drew et al., 2022).

IV.5.5 VALIDITY

LCAs are generally of limited validity as the extent of a life cycle analysis can be refined indefinitely.

In our study, we attempted to achieve the highest possible validity through detailed intra-center interviews with stakeholders or responsible parties. We aimed to collect data as meticulously as possible. Sensitivity analyses served to improve validity.

We would like to stress that this model study demonstrates a methodological approach. It is certainly not fully transferable on reusable and single-use medical instruments in general.

However, adding this approach to the existing collection of LCA studies in medicine might help to contribute to reliability and validity of future research in this field.

IV.5.6 FOCUS OF THE STUDY

We did not consider the personal preferences of the surgeons or patients. Nor did economic factors play a role. We only examined sample devices.

In order to focus on the health aspect of the topic, we limited the impact categories examined to GWP and HI instead of including a wide range of impact categories that could be characterized by ReCiPe (ozone depletion, eutrophication etc.). The aim was to add the results to the existing data base on healthcare LCAs, especially adding evidence about urologic practice and purchase decisions. By focusing on the carbon footprint and the DALYs resulting from it, a first attempt was made to find a method to connect and describe not only the environmental but also the health impact of *one use* of one fURS.

IV.6 IMPLICATIONS AND OUTLOOK

IV.6.1 USER DEPENDENCY

Our study suggests that the environmental and health impact of ureteroscopes is highly user-dependent: The diligence of the user and the reprocessing staff has an impact on the instrument's lifetime. As shown in scenario B), a longer lifetime causes an inverse GWP: 180 uses, for instance, lead to a smaller amount of carbon dioxide equivalents and DALYs. At the same time (scenario D), more frequent repairs (e.g. 44 repairs) lead to a higher environmental and health impact.

For our LCA, we assumed careful handling and optimal circumstances on the part of the users. See scenario B ("number of uses") for possible deviating flows. The user's diligence could be advantageous for patient and planet, with the latter, in turn, meaning another benefit for the patient.

IV.6.1.1 IMPLICATIONS FOR CLINICAL USERS

The outcome of this assessment could address different groups of staff.

IV.6.1.1.1 TEAM OF USERS

Thus, high diligence and care when using fURS can lessen the environmental and health impact of the devices. Surgeons may, for instance, use lubricant before (re-)inserting the instrument to avoid erosions on the sheath (Wason et al., 2022). Apart from that detail, the whole operating room team should work together closely:

"*Close cooperation between the surgical assistants, nursing staff, and surgeon ensures better outcomes and more efficient, safer ureteroscopies*" (Wason et al., 2022).

Regular training courses are held for hospital employees working with the devices by the respective product manufacturer.

IV.6.1.1.2 DISPOSAL

Also, waste management needs attention and development and, most importantly, awareness on the part of the clinical and extra-clinical users of the products in order to improve environmental and health issues. Last but not least, in our study, disposal contributes 24% (data for single-use fURS; reusable fURS: 2%) to the carbon footprint of fURS.

IV.6.1.1.3 STRUCTURAL ADAPTATION AND COST CO-BENEFITS

All in all, a structural adaptation of conditions and processes – e.g. the energy mix of a hospital or company – may be helpful.

Last but not least, the current purchasing decisions of the UKT are primarily based on financial considerations. While a disposable fURS costs 1000€ per use, one can assume that a reusable fURS costs approx. 650€ per use. Reprocessing costs 34€/fURS. Costs, according to the controlling sector of the UKT, is currently the main reason for the primary use of the reusable version of fURS. Cost factors could be a political lever in order to systematically promote improvements at diverse levels.

Still, according to a study from 2012, avoiding 9.000 preventable kidney stone events (e.g. through prophylactic fluid intake) could save the French national health system 237million Euros (Lotan et al., 2012).

However, as described in the section on "Calls for LCA", the environmental cost has not been studied thoroughly yet.

IV.6.2 WHAT MAKES THIS STUDY DIFFERENT FROM OTHERS

LCA is an established method to objectify the life cycle of different products/processes with regard to various parameters. Outcomes can be compared in a further step of the assessment. LCA is applied in numerous areas. In recent years, LCA studies in medicine have increased in number. Determining the carbon footprint of products/processes is one approach used for comparison. However, for many, the unit kg/Mkg/ton CO_2eq is an abstract quantity that at first glance is not linked to human health. For this reason, in this model, so-called DALYs were determined based on the carbon footprint in terms of greenhouse gas emissions. That way, DALYs serve as a unit for the environmental impact on human health. This could help to visualize the medical aspect of LCA and show physicians and other health professionals how individual purchasing and diagnostic/therapeutic decisions affect not only the climate, but also their patients' health.

The present study, to our knowledge, is the first German study on the Global Warming Potential (unit: kg CO_2eq) of urologic devices. Until now, ureteroscopes have only been investigated in a limited way. The second impact category calculated in the course of the LCA, the Human Health Impact (unit: DALYs), is introduced for the first time in this study in addition to the calculation of the carbon footprint of ureteroscopes.

IV.6.3 The link between GWP and human health

As pointed out above, Global Warming Potential has no concrete meaning for many people. The aspect of "health" as a unit may be understood more easily by decision makers in the medical field and users working with medical instruments. By calculating not only the abstract amount of kilogram CO_2 equivalents but the life years affected by it, this study suggests a way of making medicine related LCA results more understandable for medical personnel.

IV.6.4 Human Health Impact

According to Drew et al., there have been only three studies in the last two decades assessing the human health impact of the pollution resulting from healthcare-related processes (US and Canadian healthcare systems) (Drew et al., 2022) out of a total of 152 studies included in their investigation. Jodi Sherman analysed that the US healthcare system results in 614,000 DALYs/y and said in her presentation at the CleanMed Conference 2021: "*Pollution is the new patient safety issue*" (Sherman, J., November 30, 2020).

We left out other impact categories in favour of the focus of this study.

We also did not include the amount of work (or, more specifically, the calory-intake) of people working in the production, transportation, reprocessing or disposal sections. This could be done if there is an "*additional need for calories (...) relevant according to the cut-off criteria"*, according to ILCD handbook (ILCD Handbook, 2010).

Neither did we evaluate the impact on economic efficiency due to the impairment of human health. Economic considerations (loss of workforce -> less profitability) could be taken into account in further LCA studies to further explore the effects of environmental damage.

IV.6.5 OUTLOOK – UROLOGY AND PLANETARY HEALTH

In light of the analysis performed in this work, the question arose as to the relevance of the results in urologic practice and the *Planetary Health* context.

Generally, the implementation of *Planetary Health* aspects in urological research and practice is only in its infancy.

Urologists and other medical disciplines are starting to face the problems that climate change causes and will cause for human health.

Urology, as a surgical discipline, probably needs more resources than other disciplines.

Additionally, as urology may be one of the disciplines most effected by demographic change, there is a certain requirement for urologists to take responsibility in the field of environmental prevention research. Some researchers even state that small improvements achieved by environmental protection approaches are counteracted by the impact of an increased need for surgical and other health-related care of an aging and increasingly chronically diseased population (Brownlee et al., 2017, Lenzen et al., 2020).

In any event, it may be helpful to implement the findings of *Planetary Health* research into urological practice. This may also work as a tool to avoid "unnecessary medicine" in line with quaternary prevention.

Other topics in urology related to climate change could include the critical selection of anesthesiologic procedures as anesthetic gases have an enormous ecological footprint (Sherman et al., 2012, McGain et al., 2020). Furthermore, one could question the frequent use of antibiotics in urology, as antibiotics can have a significant impact on the ecosystem (Jimenez et al., 2023) and consider the establishment of digital consultation services, congress formats or alternative therapy procedures (Edison et al., 2020, Misrai et al., 2020). This may become increasingly relevant in the future.

Overall, the implementation of *Planetary Health* in medical-therapeutic and economic purchasing decisions in the health context should be envisioned in the future.

IV.6.5.1 Pilot character of the study

Last but not least, this work could have a pilot character and motivate other urological researchers to perform similar studies and refine existing evidence in this field. Considerations and models such as those presented in this study could be considered as a standard process, especially considering the worsening problem of climate change-related health hazards and the challenge this poses to medical professionals. Future research might pick up on the scenarios we started to discuss and expand the investigation.

Also, it may be appropriate to include data from a wider range of hospitals. Multi-center studies could improve the validity of future LCA.

Additionally, a wider range of impact categories could be considered by future research projects of this kind.

All in all, a broader survey of a wide variety of processes that could be applied in the context of health care would be useful.

IV.7 Conclusion

The results of this study indicate that expanding the purchase criteria for ureteroscopes by adding ecological aspects can be important for human and planetary health. Crucial factors in the life cycles of fURS are the electricity source used by hospitals and manufacturing companies and the diligence of the clinicians and reprocessing personnel, which might influence the number of uses and repair frequencies and thus lead to changes in the environmental and health impact. Ongoing regular training for employees might be helpful. This study may work as a methodological approach for the development of a framework for future research in this field. Last but not least, a smaller environmental impact of urologic patient care could – indirectly – act as a tool to lower the *Planetary Health* burden of disease, e.g. the incidence of kidney stones.

V SUMMARY

Flexible ureteroscopes are used for the diagnosis and treatment of urologic diseases such as urolithiasis. Reusable and single-use devices have been introduced to the clinical routine. While clinical efficacy is assumed to be equivalent for both technologies and purchasing is mainly driven by aspects of economy, sterilization and maintenance, the question of whether reusable or single-use devices are more beneficial to planetary and human health has been poorly investigated and valid LCA data are lacking. In the present study, we investigated the environmental footprint of flexible ureteroscopes as well as their impact on human health via LCA.

Reusable fURS resulted in a less harmful outcome (1.24 vs. 4.93 kg CO_2eq; 1.15E-06 vs. 4.57E-06 DALYs). Reprocessing contributed most to the impact of reusable fURS, the production phase made up the biggest part of the single-use fURS' impact (>70%, respectively). Eight reuses of the reusable fURS marked the break-even point. High user diligence may lead to more uses and less repairs of ru fURS and result in lower impacts. Single-use fURS led to a 16-fold higher amount of waste than reusable fURS (per use). If conventional energy was used by the hospital instead of a renewable mix, the carbon footprint would rise from 1.24 to 4.32 kg CO_2eq and from 4.93 to 6.25 kg CO_2eq, respectively.

It thus became apparent that the reusable device performs better for the carbon footprint and resulting DALYs, especially when renewable energies are obtained by the hospital. These results may help to add *Planetary Health* considerations to decision-making in urology.

V.1 ZUSAMMENFASSUNG (DEUTSCH)

Nierensteine können unter Einsatz von Ureteroskopen diagnostiziert und therapiert werden. In der klinischen Praxis sind sowohl Mehrweg- als auch Einweggeräte etabliert.

Während die klinische Wirksamkeit beider Geräte als gleichwertig angenommen wird und die Anschaffung hauptsächlich von ökonomischen Aspekten, Aufbereitung und Wartung abhängt, ist bisher nur unzureichend untersucht worden, ob Mehrweg- oder Einweggeräte vorteilhafter für die planetare und menschliche Gesundheit sind – valide

LCA-Daten fehlen. Ziel dieser Studie war deshalb, die CO_2-Bilanz von Ureterorenoskopen sowie deren Auswirkung auf die menschliche Gesundheit mittels LCA zu untersuchen.

Es ergaben sich geringere Auswirkungen durch die Mehrweg-Variante (1.24 vs. 4.93 kg CO_2eq; 1.15E-06 vs. 4.57E-06 DALYs). Die Aufbereitung machte den größten Anteil des Ergebnisses der Mehrweg-Geräte aus, bei den Einweg-fURS fiel die Produktionsphase am stärksten ins Gewicht (jeweils >70%). Der Break-Even-Punkt für Mehrweg-fURS lag bei n=8 Wiederverwendungen. Hohe Anwendersorgfalt kann zu längerer Nutzungsdauer und weniger Reparaturen von Mehrweg-fURS führen und dadurch geringere Auswirkungen auf Umwelt und Gesundheit haben. Einweggeräte führten zu einer 16-fachen Abfallmenge im Vergleich zu Mehrweggeräten (pro Gebrauch). Für Kliniken, die konventionelle Energie beziehen, würde sich die CO_2-Bilanz von 1.24 auf 4.32 bzw. von 4.93 auf 6.25 erhöhen.

Es zeigte sich also, dass Mehrweg-fURS in Bezug auf die CO_2-Bilanz und die daraus resultierenden DALYs Vorteile aufweisen, insbesondere wenn die Klinik erneuerbare Energien nutzt.

Diese Ergebnisse könnten dazu beitragen, die Entscheidungsgrundlage für den Einsatz von Instrumenten zur Diagnose und Therapie von urologischen Erkrankungen wie Nierensteinen um Aspekte der planetaren Gesundheit zu erweitern.

VI LIST OF PUBLICATIONS

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VIII DECLARATION OF THE AUTHOR'S OWN CONTRIBUTION TO THE THESIS

I, Marlene Thöne, hereby declare that this thesis was written by me independently and that I have not used any auxiliary materials other than those specified here. I have marked all passages taken verbatim and in content from other works as such.

The idea and the concept of the present work were developed by Marlene Thöne and decisively supported by the LCA expert Dr. Jan Lask (data processing). Prof. Dr. med. Dr. h.c. Arnulf Stenzl, Prof. Dr. med. Steffen Rausch and Dipl.-Biol. Jörg Hennenlotter enabled and supervised the project to be conducted in the Urologic Clinic of the UKT. The University Hospital Tübingen along with various companies involved and their employees fed the data collection and allowed the distinct detailedness of this thesis.

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med. Uwe Schlittenhardt, Jörg Schmid, Fritz Schmuhl, Prof. Dr. med. Christian Schulz, Michael Schur, Dr. med. Jodi Sherman, Dr. med. Carsten Sippel, Prof. Bhaskar Somani, Birgitte Lilholt Sørensen, Marco Stengel, Karl Stetter, Dr. med. Michael Straub, Jan Stratil, Kevin Stuber-Rouselle, Dr. med. Julia Tabatabai, Leonard Terres, Dr. med. Henning Thole, Prof. Dr. Rita Triebskorn, Dr. Karsten Tourna, Manon Videau, Prof. Dr. Tobias Viere, Mr. Wächter (Purchasing UKT), Franziska Wägerle, Stefan Walter, Rain Wang, Annette Weidtmann, Aline Weis, Prof. Dr. Dr. Urban Wiesing, Bernd Willenberg, Prof. Dr. med. Henning Wilts, Prof. Dr. Christian Zwiener.

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Dresden, 23th May 2023

X APPENDIX

X.1 FIGURES AND TABLES

X.1.1 LIST OF FIGURES

X.1.2 LIST OF TABLES

XI SUPPLEMENTARY MATERIAL

XI.1 QUESTIONNAIRES

Universitätsklinikum Tübingen
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Sprechstundentermin online: www.uro-tuebingen.de/termin

13.08.20

Erhebung Einkauf/Betriebswirtschaft
Bitte beantworten Sie die Fragen nach Ihrer persönlichen Einschätzung

1) **Wie viel kostet ein Einweg-Ureterorenoskop?**

2) **Wie viel kostet ein Mehrweg-Ureteroskop?**

3) **Wie häufig wird das Mehrweg-Ureterorenoskop gewartet?**

4) **Wie viel kostet die Wartung eines Mehrweg-Ureterorenoskops im Durchschnitt?**

5) **Nach welchen Kriterien entscheiden Sie beim Kauf von Ureterorenoskopen?** *Mehrfachantworten möglich*

   a) Kosten
   b) Klinische Effizienz (Informationen durch Anwendende)
   c) Klinische Effizienz (Informationen durch evidenzbasierte Studien)
   d) Faire Handelsbedingungen
   e) Ökologische Kriterien
   f) Geographische Kriterien
   g) Sonstige: ________________________________ ___________

Stellvertretender Ärztlicher Direktor:
Prof. Dr. med. J. Bedke

Oberärzte:
Dr. med. B. Amend
Dr. med. S. Aufderklamm
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Prof. Dr. Bernd Pichler
Klaus Tischler

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BIC (SWIFT-Code): SOLADES1TUB

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Supplement. Figure 1: Excerpt from: Questionnaire controling

7) Welche der folgenden Kriterien sind für Sie relevant bei der Wahl des Gerätes?

	Sehr relevant	**Eher relevant**	**Eher nicht relevant**	**Nicht relevant**	**Keine Angabe**
a) Hygienische Aspekte					
b) Steingröße					
c) Steinzusammensetzung					
d) Steinlokalisation					
e) Geschlecht Patient*in					
f) Handhabbarkeit					
g) Studienlage					
h) Kosten					
i) Umweltbelastung durch anfallenden Abfall					

Supplement. Figure 2: Excerpt from: Questionnaire users (urologists)

Universitätsklinikum Tübingen
Klinik für Urologie
Ärztlicher Direktor:
Prof. Dr. med. Dr. h.c. A. Stenzl

Fragenkatalog

02.12.2020

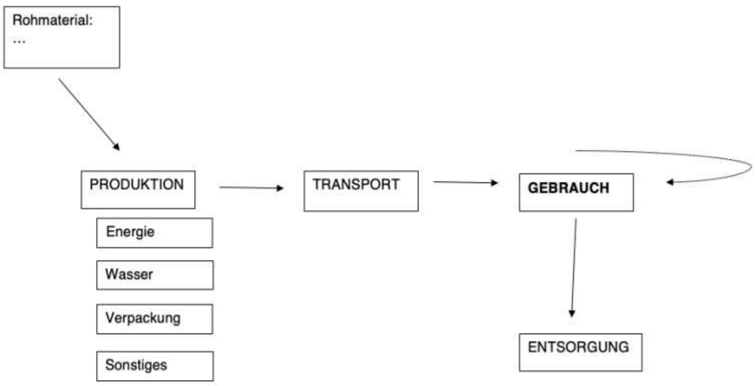
Im Rahmen des Promotionsprojektes **„Vergleichende Analysen über die Umwelt- und Gesundheitsverträglichkeit von Einweg- und Mehrwegureterorenoskopen“** der
Klinik für Urologie Tübingen

Priv.-Doz. Dr. med. Steffen Rausch
Doktorandin: Marlene Thöne

<u>Einweg- und Mehrweg-Ureterorenoskope (URS)</u>

<u>Herstellung:</u>

1) **Skizzieren Sie bitte die jeweiligen Schritte, die ein URS während des Herstellungsprozess durchläuft (stichpunktartig, gerne auch graphisch als Fließdiagramm, siehe Bsp.)**



2) **Welche Materialien werden für die Herstellung der Geräte benötigt? Wie viel des jeweiligen Materials wird zur Herstellung eines Gerätes benötigt (in Gramm)?**

Supplement. Figure 3: Excerpt from: Questionnaire production company

XI.2 ADDITIONAL VISUALS

Supplement. Figure 4: Neodisher endo clean 5L, provision and friendly permission by Stefan Walter, Marketing / Product Management Dr Weigert – Hygiene mit System

List of supplementary figures