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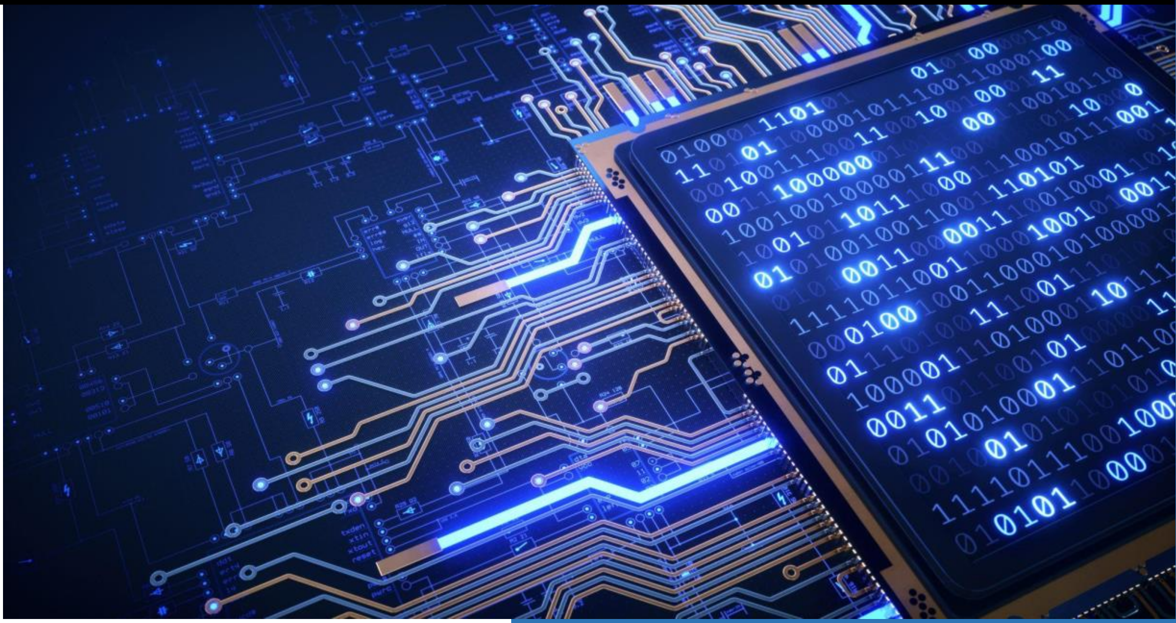
Life cycle assessment of Internet of Things(IoT) solution in Södertälje municipality – A smart waste collection system



Research Institutes of Sweden

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Preface

This report contains the result of a life cycle assessment (LCA) of Internet of Things (IoT) solutions for Södertälje municipality and using a case study of the smart waste collection system installed in the municipality. The study has been performed as a streamlined LCA meaning that data for raw materials and manufacturing processes for the components are generic from a database, apart from the assembly process and the use phase (operation of the system) which are specific**.**

This report has been reviewed internally within RISE. The data, calculations and results have been compared with similar studies. The report has not been subject to a third-party review. The results and the conclusions should be considered as guidance. The report is not intended for public comparisons with competing products or systems because of uncertainties and data gaps as well as the fact that the choice of system boundaries and other assumptions in the study can affect the results greatly.

This LCA study was performed by two LCA experts in RISE: Yoon Lin Chiew and Birgit Brunklaus. Yoon Lin Chiew is an experienced LCA practitioner and also conducting sustainability assessment in different national and international research projects. Yoon Lin was responsible for defining the systems modelled, data collection, modelling the system and generating the results, and interpreting the results. Birgit is head of the RISE LCA group and former assistant professor in LCA for social systems at Chalmers University of Technology. She is an experienced LCA practitioner in national and international research, and a variety of application, among others in IoT and safety systems for the automotive industry. Birgit was responsible for reviewing and supporting in defining the system modelled, data collection, and interpreting the results.

Acknowledgement:
We want to thank all the participants and partners (Södertälje municipality, Telge Återvinning, Norrsidans Innovation AB, Umeå University) that has been involved in the data collection and helping us understand the IoT system and waste collection system. Thanks for all the interviews, e-mailing, and sending the photos.

Gothenburg/Södertälje, 30 September 2021

Other publications in the same project:
Report: Det inkluderande, hållbara och uppkopplade samhället - Nulägesanalys
Paper: The inclusive, sustainable and connected society – IoT implementation in a Swedish municipality. LCM conf 5-9 Sept 2021. Oral and paper ID 52963.

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List of acronyms and abbreviations

AB	Aktiebolag (Swedish: Limited company)
API	Application Programme Interface
CO_2	Carbon dioxide
CO_2 eq	Carbon dioxide equivalents
CED	Cumulated Energy Demand
CN	China
EC	European Commission
ELCD	European Life Cycle Database
GLO	Global
HVO	Hydrotreated Vegetable Oils
IoT	Internet of Things
ISO	International Organization for Standardization
kg	Kilogram
LCA	Life Cycle Assessment
LDPE	Low Density Polyethylene
LoRaWAN	Long Range wide-area network
MJ	Megajoule
RER S	RER = Region Europe, S=system process
RoW	Rest of the world
Sb-eq	Antimony equivalents
SE	Sweden

Glossary of Terms

CML method	This method is an impact assessment method that developed by the Institute of Environmental Sciences, University of Leiden, The Netherlands in 2001.
Litter bin	Also called receptacle or trash bin in the streets
Trash bag	Plastic bags used for collecting the waste
SLA	Service-level agreements (SLAs) are contracts that specify the performance parameters within which a network service is provided

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Table

Summary

Internet of things (IoT) is expected to transform the way we live, work, and learn. Using IoT can be a game-changer for municipalities to move towards sustainability. Within the Vinnova financed project, the municipality wants to explore how IoT can enable route optimization and placement planning for increased operational efficiency. The aim of this study is to enhance the knowledge of the environmental benefits of IoT systems in the waste collection system in the city center of Södertälje. This life cycle assessment, LCA, will support the project by identifying environmental hotspots. The LCA study was performed in Jan-Sep 2021. The functional unit of the study has been set to 1 year of IoT system service for 160 litter bins in city center of Södertälje. The studied system is a cradle-to-grave system, including raw materials, sensors and gateways, use phase, and end of life the sensors and gateways, internet connection, as well as the cloud services. Inventory information have been collected mainly from Södertälje, suppliers, and the service providers. Generic data, such as electricity mix, and transports have been taken from the Ecoinvent database and literature. This study has evaluated the environmental impacts of IoT system in Södertälje for the case of smart waste collection system installed in the city center in a life cycle perspective. The objective of the study has been:

1. To estimate the environmental impact (with focus on climate change impact) of **IoT system** in Södertälje and find out the hotspots within the system in a life cycle perspective.

The climate change impact of the IoT system solution in Södertälje is estimated about 120 kg CO_2eq per year, which mainly contributes from the gateways (50%) and sensors (27%) and the use of internet (23%).

2. To estimate the environmental impact (focus on climate change impact) of the **waste collection system** (without IoT system) and find out the hotspots within the system.

The climate change impact of the current waste collection system in the city centre of Södertälje contributes approximately 12t CO_2eq per year, which mainly contributed from the use of fossil-based plastic trash bags (96%) and the HVO based transport (4%).

3. To compare the current with the **future waste collection system** (including IoT system for planning and service).

To compare the current with the future waste collection system, we use scenarios (see Figure 20 for results). At the starting point of the study (scenario 1), we present results that are based on assumptions and have the same CO_2 emissions for the transport and the trash bags. The results were based on diesel (50%) and recycled plastic trash bags (50%). The recycled plastic is made of 80% recycled LDPE and 20% virgin LDPE (Tingstad, 2021).

The next step (scenario 2) of the study, we present results that are based on direct data of the current system. The results were based on HVO and fossil trash bags, which results into 11.5 t CO_2 for fossil bags and 380 kg CO_2eq per year for transport and 120 kg CO_2eq extra for the IoT system.

The last step (scenario 3) of the study, we present results that are based on future assumptions. The results were based on using no bags and no CO_2 emission from bags, which results into 120 kg CO_2eq for the IoT system and 380kg CO_2eq for the transport and 0 kg CO_2eq for the trash bags.

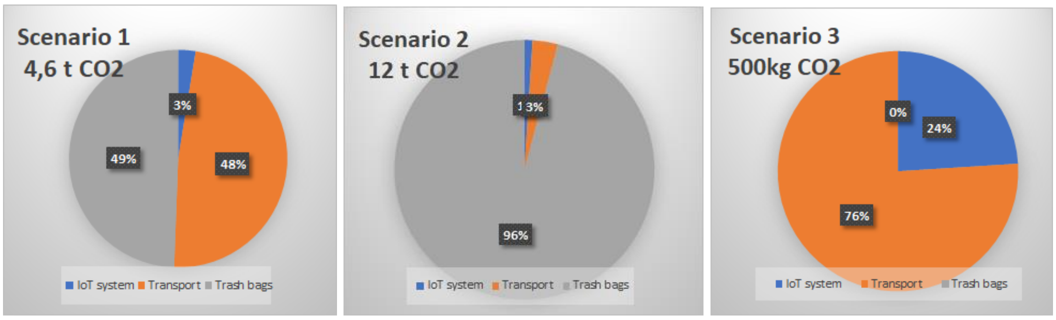


Figure 1 Results of climate change impact, CO_2 for the scenarios 1, 2 and 3.

The future waste collection system needs to be better than the current system. That means, the future waste collection system needs to reduce the CO_2eq emissions by at least 120 kg CO_2eq to break-even the extra IoT system.

For the IoT system to have an effect, at least 32% of the transport (km) or the number of trash bags used need to be reduced (50 bins of 160 bins), in order to outweighs the extra CO_2eq from the IoT system (Figure 21).

- A reduction of trp km or trash bags by 32% reduce CO_2eq by 120 kg. (=IoT system).
- A reduction of trp km or trash bags by 64% reduce CO_2eq by 240 kg. (> IoT system).

Figure 2 Results of climate change impact, CO_2eq for scenarios 3 a-c.

Sammanfattning

Internet of Things (IoT) förväntas förändra vårt sätt att leva, arbeta och lära. Att använda IoT skulle kunna vara en game-changer för kommuner mot hållbarhet. Inom det Vinnovafinansierade projektet vill kommunen undersöka hur IoT kan möjliggöra ruttoptimering och placeringsplanering för ökad driftseffektivitet. Syftet med studien är att öka kunskapen om miljöfördelarna med IoT-system i avfallsinsamlingssystemet i Södertälje centrum. Denna livscykelanalys, LCA, kommer att stödja projektet genom att identifiera hotspots för miljön. LCA-studien genomfördes i januari-sep 2021. Studiens funktionella enhet har satts till 1 års stödservice för IoT-system för 160 papperskorgar i Södertälje. Det studerade systemet är ett vagga-till-grav-system, inklusive råvaror, sensorer och gateways, användningsfas och livslängd för sensorer och gateways, internetanslutning samt molntjänster.

Inventerings information har samlats in främst från Södertälje, leverantörer och tjänsteleverantörer. Generiska data, såsom elmix, och transporter har hämtats från Ecoinvents databas och litteratur. Studien har utvärderat miljöpåverkan från IoT-systemet i Södertälje för smarta sophämtningssystem installerade i centrum ur ett livscykelperspektiv. Syftet med studien har varit:

1. Att uppskatta miljöpåverkan från IoT-systemet i Södertälje och ta reda på hotspots inom systemet i ett livscykelperspektiv.
   Miljöpåverkan från IoT-systemlösningen i Södertälje utvärderas med livscykelanalys och uppskattas till cirka 120 kg CO_2eq per år, vilket främst bidrar från gateways (50%) och sensorer (27%) och användning av internet (23%).

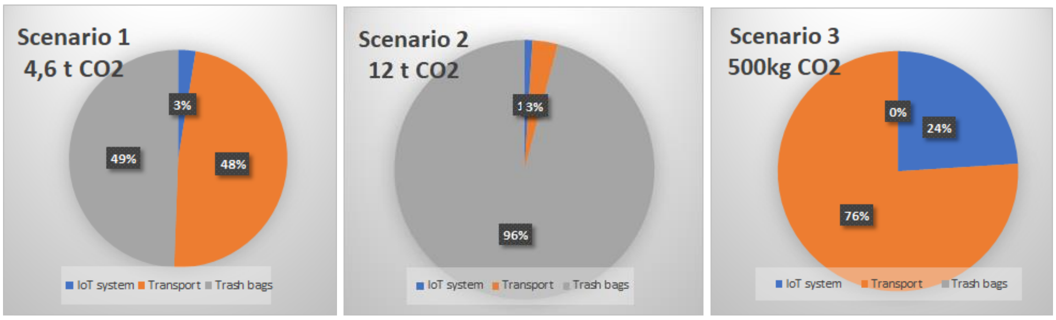
2. Att uppskatta miljöpåverkan från systemet för insamling av avfall (utan IoT-system) och ta reda på hotspots i systemet.
   Miljöpåverkan från det nuvarande avfallsinsamlingssystemet i Södertälje centrum bidrar med cirka 12 ton CO_2eq per år, främst beroende av användningen av fossilbaserade plastavfallspåsar (96%) och HVO-baserade transporter (4%).

3. För att jämföra det nuvarande med det framtida systemet för insamling av avfall (inklusive IoT-system för planering och service).

För att jämföra det nuvarande med det framtida systemet för insamling av avfall använder vi scenarier (Figur 20). Vid studiens utgångspunkt (scenario 1) presenterar vi resultat som bygger på antaganden och har samma koldioxidutsläpp för transporterna och sopsäckarna. Resultaten baserades på diesel (50 %) och återvunna soppåsar i plast (50 %).

Nästa steg (scenario 2) i studien presenterar resultat som baseras på direkta data från det nuvarande systemet. Resultaten baserades på HVO och fossila sopsäckar, vilket resulterar i 11.5 t CO_2eq för fossila påsar och 380 kg CO_2eq per år för transport och 120 kg CO_2eq extra för IoT-systemet.

Det sista steget (scenario 3) i studien presenterar resultat som baseras på framtida antaganden. Resultaten baserades på att använda inga påsar och inga CO_2-utsläpp från påsar, vilket resulterar i 120 kg CO_2eq för IoT-systemet och 380 kg CO_2eq för transporten och 0 kg CO_2eq för sopsäckarna.



Figur 20 visar resultaten av koldioxid för scenarierna 1, 2 och 3.

Det framtida systemet för insamling av avfall måste vara bättre än det nuvarande systemet. Det innebär att det framtida systemet för insamling av avfall måste minska koldioxidutsläppen till minst 120 kg CO_2eq för att jämna ut det extra IoT-systemet.

För att IoT-systemet ska ha effekt måste minst 32 % av transporten (km) eller antalet papperspåsar minskas (50 papperspåsar jämfört med 160 behållare) för att uppväga den extra CO_2eq från IoT-systemet (se Figur 21).

- En minskning med 32% minskar CO_2eq med 120 kg. (=IoT-system).
- En minskning med 64% minskar CO_2eq med 240 kg. (> IoT-system).

Figur 21 visar resultaten av KOLDIOXID för scenarierna 3 a-c.

Introduction

Internet of things (IoT) is expected to transform the way we live, work, and learn. Using IoT could be a game-changer for municipalities to move towards sustainability. Since 2019, Södertälje municipality has been one of five nominated municipalities for the Swedish Digitalisation Municipality. In accordance with its climate strategy, Södertälje municipality wants to reduce its climate impact and wants to move towards net zero greenhouse gas emissions by 2030. To move this forward, the municipality has implemented a municipality-wide Internet of Things (IoT) infrastructure. As a part of this, they installed an IoT system for waste collection system with 160 bins and sensors that measure the degree of filling.

Within the Vinnova financed project, the municipality wants to explore how IoT can enable route optimization and placement planning for increased operational efficiency. They also want to explore how automatically generated data can be used to further develop both internal processes and community involvement. The overall goal of the Vinnova project is to develop concepts for how machine-generated, open data can be used as a strategic resource in environmental work and sustainability issues. This report provides the basis for the environmental work and is part of AP2 (analysis of the current situation) and later part of AP4 (evaluation of new data driven methods for resource and cost-efficiency) of the Vinnova project “The inclusive, sustainable, and connected society”.

This study evaluates the environmental impacts of the IoT system in Södertälje for the case of the smart waste collection system installed in the city center in a life cycle perspective. The study has been performed as a streamlined LCA meaning that data for raw materials and manufacturing processes for the components are generic from a database, apart from the assembly process and the use phase (operation of the system) which are specific. This study was conducted during Jan-Sept 2021.

Objectives

The objective of the study is

1) To estimate the environmental impact (with focus on climate change impact) of **IoT system** in Södertälje and find out the hotspots within the system in a life cycle perspective.
2) To estimate the environmental impact (with focus on climate change impact) of the **waste collection system** (without IoT system) and find out the hotspots within the system.
3) To compare the current with the **future waste collection system** (including IoT system for planning and service).

General description of life cycle assessment

Principles of life cycle assessment

Life cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from cradle to grave, i.e. from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, to disposal or recycling, see Figure 1. Environmental impacts include emissions to air, water and soil as well as consumption of resources in the form of both energy and material, in the different stages of the life cycle.

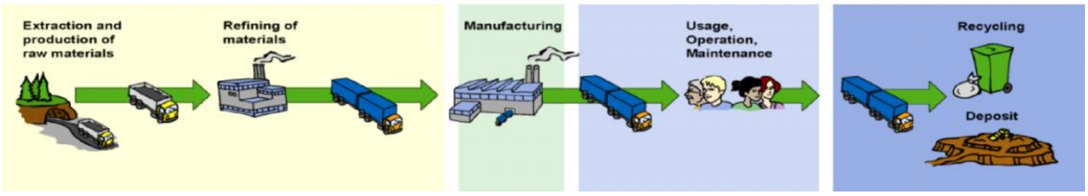


Figure 3 Schematic picture of a product's different life cycle phases.

The purpose with performing an LCA is to get a fair and comparable evaluation of the environmental performance of a product (both services and goods can be assessed). The life cycle perspective is essential in order to avoid sub-optimization, i.e. that a certain process step or component is optimized, however the whole life cycle of the product does not reach its optimal environmental performance. Sub-optimization can occur when only parts of the life cycle are studied and the overall performance is not evaluated.

This life cycle assessment is performed in accordance with International Organisation for Standardization (ISO) 14040 and 14044 standards (ISO, 2006a; ISO, 2006b) and the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010).

Phases of an LCA

The ISO 14040 standard implies that the four steps in Figure 2 shall be performed when performing an LCA. Figure 2 shows that there are interactions between interpretation and the other stages as the study is constantly measured against its initial goal and scope and refined during its duration.

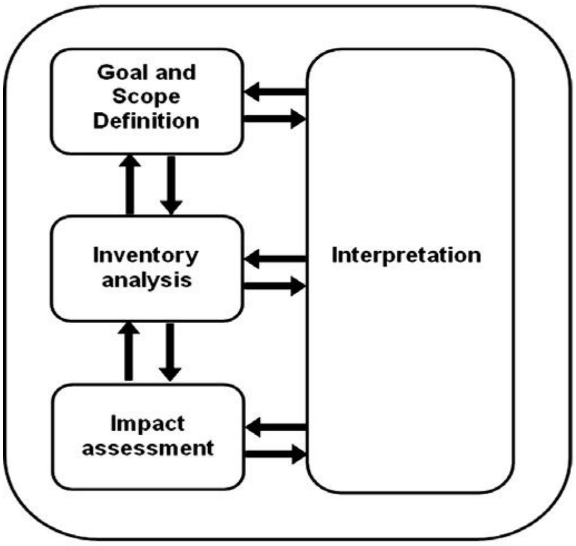


Figure 4 Phases of an LCA according to ISO.

Goal and scope definition

The goal and scope definition is the first stage of an LCA, where the purpose of the study is described. Also, the boundaries of the product system are defined according to factors such as time constraints, data availability and depth of study required. At this point a ‘‘functional unit’’ is defined, which provides a reference to which the inputs and outputs of the analysis are related.

Inventory analysis

Inventory analysis involves data collection related to the inputs and outputs of the system described in the ‘‘goal and scope definition’’. It inventories quantities of raw materials, waste flows and emissions attributed to the product’s life cycle.

Life cycle impact assessment

Life cycle impact assessment involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts.

Interpretation

Here results are interpreted, summarised and discussed, conclusions are drawn, and recommendations are made against the initial goals.

Method

The study has been conducted following the ISO 14040 and 14044 standards (ISO, 2006a; ISO, 2006b) and the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010) for LCA methodology. In accordance with the standards, the study comprises the usual four LCA phases, described above. The goal and scope were first defined and carried out on Teams on 24 February 2021 and then revised again on Teams on 21 April 2021, which included the following persons:

- Anthony Mccarrick, Södertälje Municipality
- Andreas Sundberg, Södertälje Municipality (Consultant Adaptit AB)
- Tomas Thernström, Södertälje Municipality
- Ted Saarikko, Umeå University
- Anders Lundström, Umeå University
- Robert Rekonius, Telge Återvinning
- Yoon Lin Chiew, RISE IVF
- Hanna Linden, RISE IVF
- Birgit Brunklaus, RISE
- Anders HelgessonNorrsidans Innovation AB
- Linfan Zhang, Norrsidan Innovation AB

The inventory analysis included numerous telephone meetings and e-mail conversations between those involved. An interpretation meeting was conducted on 10 June 2021. The inputs from project members are collected and a scenario analysis was conducted to envision the current and future scenario. The final LCA results are then presented in the project meeting on 8th September 2021.
In the following section, the Södertälje IoT system and the smart waste management system in the Södertälje city center are described briefly.

Södertälje IoT system

Södertälje municipality has implemented a municipal-wide LoRaWAN infrastructure which is the technical basis in the work to be able to develop socially, economically and ecologically sustainable digital solutions in the municipality's way forward towards the sustainable municipality. The LoRaWAN infrastructure paired with open data and the use of AI-chatbots also has the opportunity to contribute to the development of democracy-promoting services that enable the information base for a more engaged and included citizen dialogue. The work of establishing the LoRaWAN infrastructure has taken place in close collaboration with the municipal city network distributor Telge Nät and the commercial IoT operator Netmore (see Figure 3 for overview of IoT system and stakeholders involved).

The architectural image of the IoT system are shown in Figure 4. The sensors communicate with the different LoRaWAN gateways which send the data forward over the internet to the IoT-platform (Netmore portal). From Netmore portal, they have started integrating some sensor data directly to the problem management system, which is called Infracontrol. This system is the same system where citizens can report problems, for instance life buoys and streetlights etc. The first integration is the life buoys, in which a ticket will be created in Infracontrol when someone removes a life buoy, giving shorter lead times for replacement of the life buoy which gives the potential to save lives. From the Netmore portal some data flows through an IBM-cloud solution where the data is decoded. (The sensors send data in a HEX-format, and the IBM cloud transforms data into data that humans can understand). This data can be a value, true/false, a temperature and so on. From there the data flows to Node RED which is a cloud solution as well. Here, they host the open data API (Application Programme Interface) and visualizations. The data is also flowing to and from an SQL-database where they do long time storage of the data.

Data regarding the smart litter bins flow from the Netmore portal through the Norrsidans Green city application which is an mobile app used by the group manager that plans the work and the operators that carries out the daily emptying of the litter bins. The mobile app shows in real time the fill levels of the litter bins.

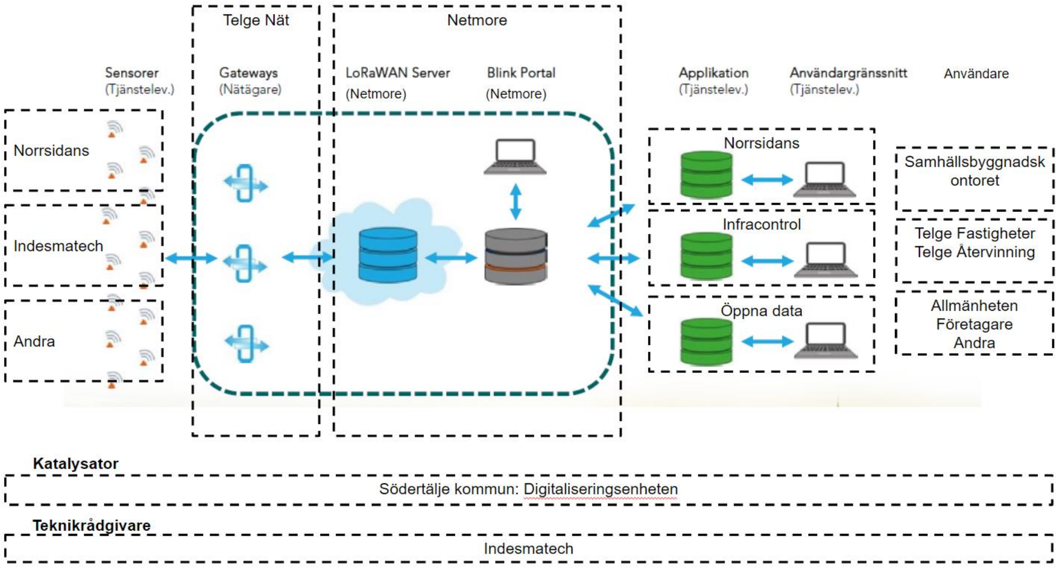


Figure 5 Södertälje IoT system.

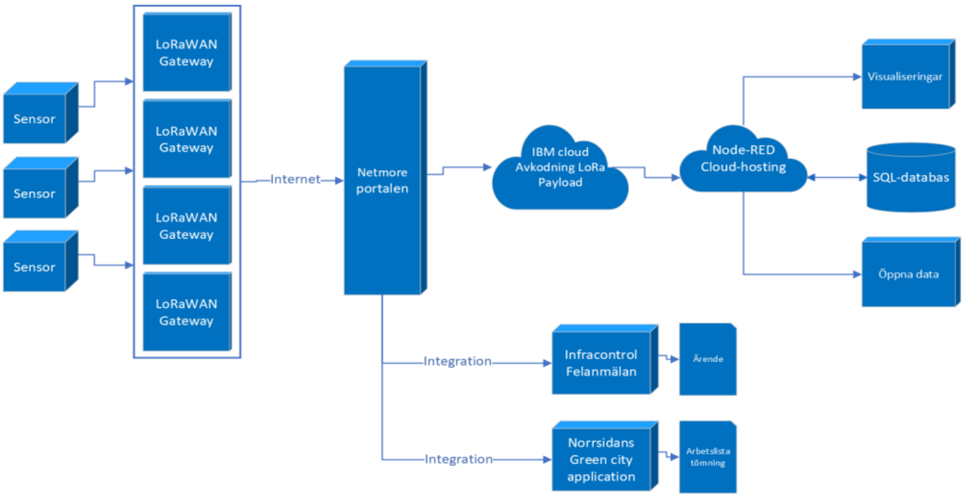


Figure 6 Architectural image of the IoT system.

Smart waste collection system

Waste management has been pointed out by Södertälje municipality as an important area to apply IoT technology to. The municipality of Södertälje has already launched a proof of concept project where 160 bins use IoT technology to measure the fill-level for route optimization and placement planning. After a successful completion of proof of concept project in filling measurement of trash and with the support of the waste plan that Södertälje municipality has developed, Södertälje municipality now wants to take the next step in the use of IoT technology for waste management.

The smart waste collection system Södertälje and the data flow of the IoT application is illustrated in Figure 7. The sensors are installed at the litter bins in the city centre to detect the level of fullness of bins. The sensors will send data to gateways through the LoRaWan connection. The data will then send to Netmore cloud and then Norrsidans servers with internet connection. Currently, the system is not using open data and infracontrol servers. The supervisor and operators can use their own computers or mobile phones to assess the information, such as the number of bins that are exceeding target level of fullness of the bins that need to be emptied, as well as location of the litter bins in Norrsidan servers via an App.

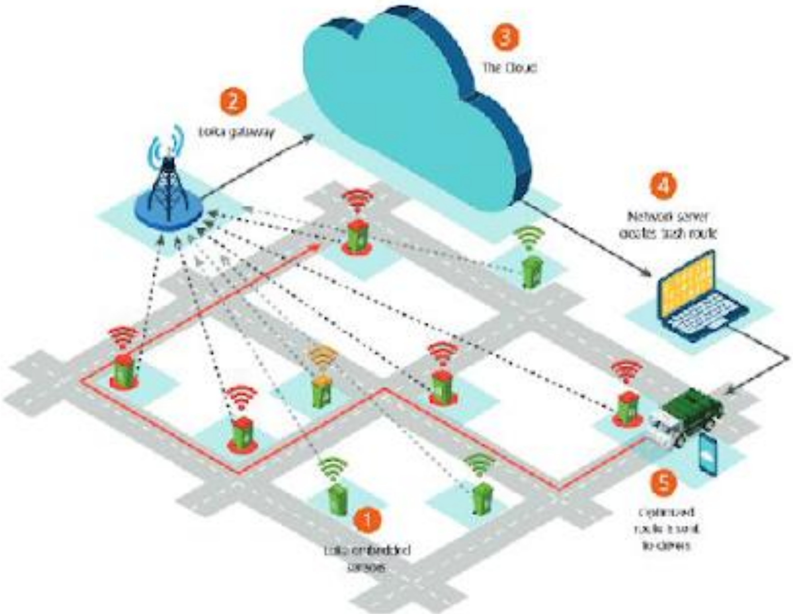


Figure 7 IoT support on smart waste collection system in the Södertälje.

System boundaries

The system boundaries are defined to correspond to the goals of the study and the functional units. The system boundary of the smart waste collection system is from ‘cradle to grave’, as shown in Figure 8, which comprise two different systems: IoT system and waste management system. In the IoT system (yellow box), the activities of the production of raw materials, manufacturing, use, end of life of electronics parts (sensors and gateways), internet network, and cloud services are evaluated. The users’ devices (e.g. computer or mobiles) that used for assessing data in Norrsidan server are not included in this study because this use is not one of the primary functions of the devices.

On the other side, to evaluate the environmental benefits of the waste collection system (pink box), the activities, such as the transportation and plastic bags used are studied. There is no change on the design of the litter bins, as well as on handling the collected waste, i.e. the waste will be transported from the Södertälje city center to recycling center and incinerated. Therefore, the litter bins and handling of the waste are not included in this study.

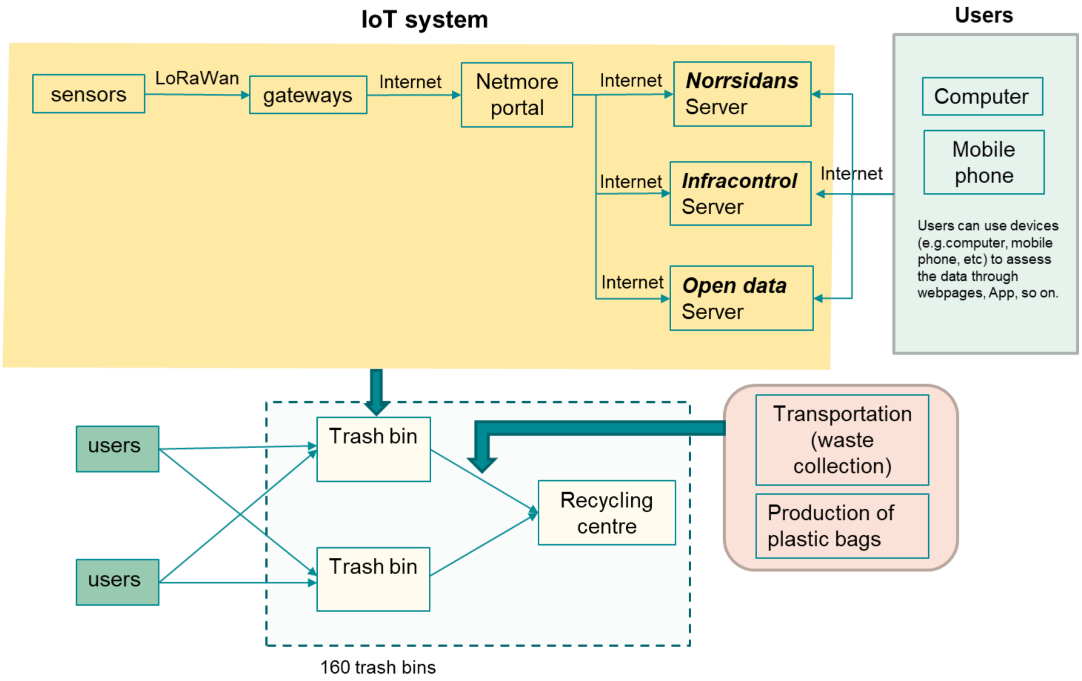


Figure 8 System boundary of the study

Functional unit

The functional units for this study are

- one year of IoT system support, which consists of 160 sensors installed, which has life span of 10 years.
- one year of waste collection system with IoT system support, which consists of 160 sensors and has a volume of 160L/bin.

The waste system collects a total waste of 584.9 t per year (for 160 bins with assumption that average waste weight collected (8-11) kg per bag/bin (Björling, 2017), therefore, an average of 9.5kg per bag/bin and collection for 365 days).

Environmental impact assessment

The following impact categories are considered:

- Global warming (kg CO_2-equivalents): Climate is most important.
- Primary energy use (MJ): Energy is important for the use phase and might be considered later.
- Abiotic depletion (Sb-equivalents): Resources are important for the IoT system and might be considered later.

The impact assessment has been performed following the CML method for the impact categories of global warming potential and abiotic depletion. For the primary energy use, it is estimated following the Cumulative Energy Demand (CED) method in SimaPro.

Data collection and modelling

The IoT system's material and production data were collected through communication with Södertälje municipality's supplier (e.g. Norrsidans Innovation AB for sensors, the Gateway supplier, etc.). The background data has been sourced from the Ecoinvent 3.5 database (Ecoinvent Centre, 2010) and any data gaps have been filled by IVF industry data and ELCD database (European Commission, 2010). The recycled content (cut-off) version of the Ecoinvent database were used. In case the materials and equipment are produced in Europe, European [RER] Ecoinvent datasets are used, or else when the materials are produced in China and other countries, [CN] and [RoW] or [GLO] datasets are used, respectively. Most of these datasets (those named Market) includes transportation of the materials.

Litter bins/Trash bins

There are total 160 litter bins in the city centre of Södertälje (and around 700 litter bins in total in Södertälje). In the city centre, about 80% of the litter bins are 160 L and 20% are 200L. The typical litter bins used are shown in Figure 10. In this study, it was not evaluated as there are no changes on the type or design of the litter bins.

Sensors production

Total 160 sensors (2nd generation) were installed in the city center of Södertälje in 2020 (see Figure 9). The sensors are installed inside at top of the litter bins (Figure 10). The supplier is currently developing the third-generation sensor, which is smaller, more energy efficient and easier to install than the second generation. The second-generation sensors were replaced when the third-generation sensor launched in May 2021. Due to data availability, the 2nd generation data were used in this study.

Figure 9 The second generation of the sensors used for the waste collection system.

Figure 10 The sensors are installed inside at top of the litter bins.

The sensors are manufactured in China. Most of the electronic components (e.g. resistance, inductance, capacitance, etc) are produced in China as well. It was transported to Sweden as a whole component, and the battery was also included. The components and weight of the sensor are shown in Figure 11. For the sensors' inventory data, the second-generation sensors are collected from Norrsidans and used for analysis (see Appendix:Table A 1). Life span of the sensor is more than 5 years (worst scenario), 8-10 years (best scenario) depending on the environment (temperature). Installation of sensor is not included. For the end of life of the products, the housing of the sensor can be granulated and recycled, while the PCBs can be reused. However, the battery cannot be recycled at this time according to Norrsidans Innovation.

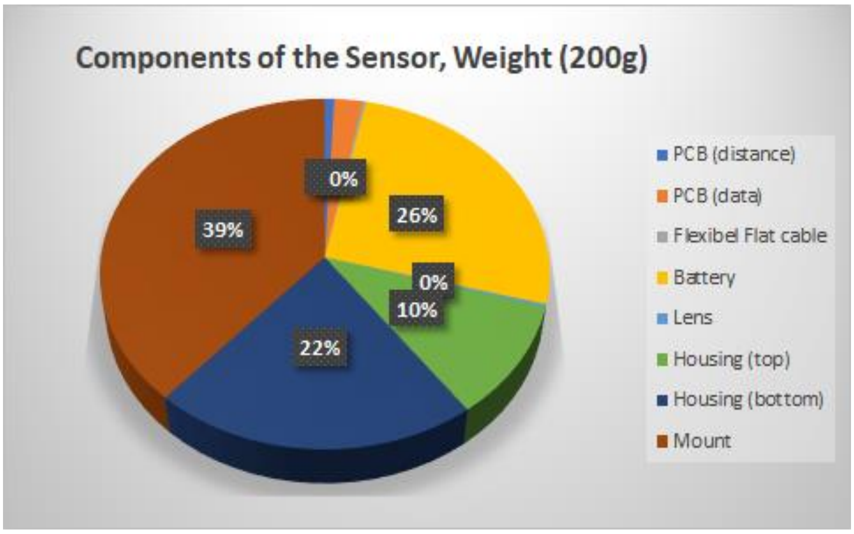


Figure 11 Components of the sensor (weight, 200g).

LoraWAN

The sensors have batteries that will provide energy to support the Lorawan network. Therefore, no other electricity or energy is required.

Gateway production

A total of 12 units of gateways are installed to support the IoT services in Södertälje. Two types of gateways are used: ten units of outdoor gateways (Kerlink iBTS compact model) and two units of indoor gateways (ifemtoccal), see Figure 12, Figure 14 and Figure 15.

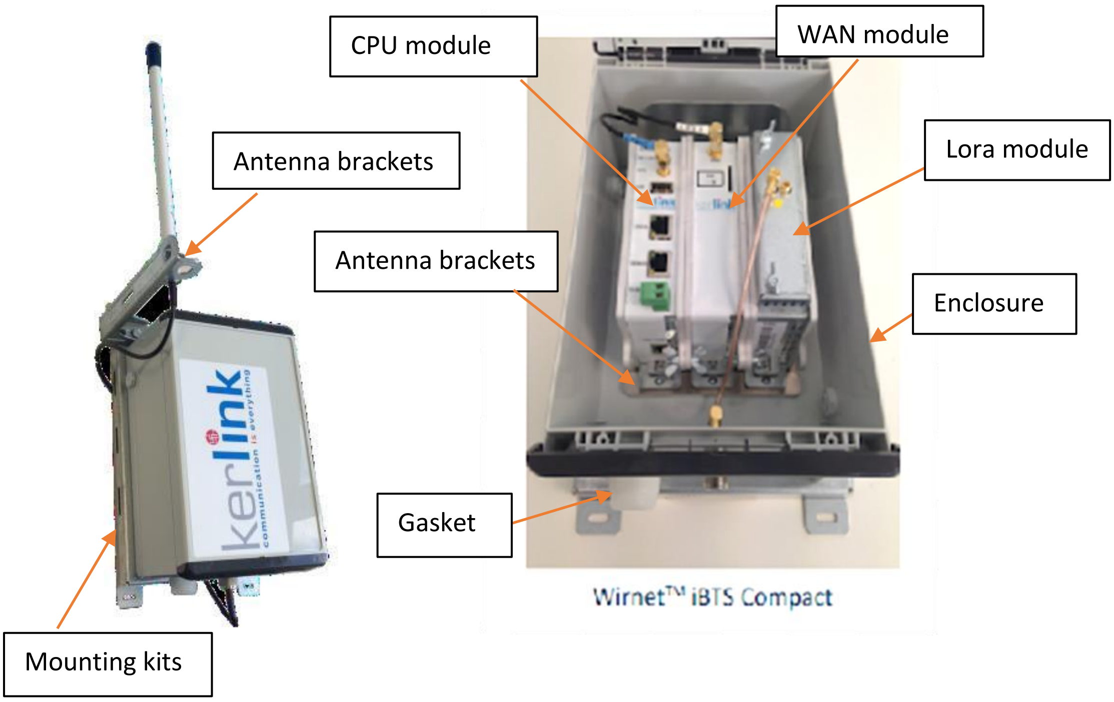


Figure 12 The outdoor gateways Kerlink iBTS compact model: external view (left picture) and internal view (right picture). Source: Indesmatech ApS, 2021.

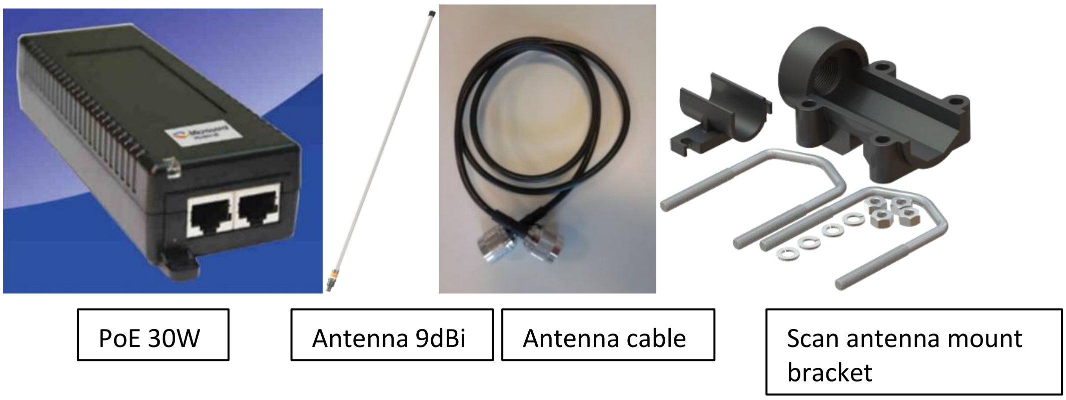


Figure 13 Other accessories used for installation outdoor gateways: PoE 30W, antenna 9dBi, antenna cable, scan antenna mount bracket. Source: Indesmatech ApS, 2021.

Figure 14 Indoor gateways used. Source: Indesmatech ApS, 2021.

All the gateways and other accessories are assembled in France. Both devices have five years of warranty and the life span of is estimated to be 10 years. Due to the suppliers not being able to provide the inventory data, the environmental impacts of the outdoor gateways and other accessories used for installations were estimated based on the material engineering appearance and the material type information available on website and installation manual guidebook (Indesmatech ApS, 2021; MGI, 2016).

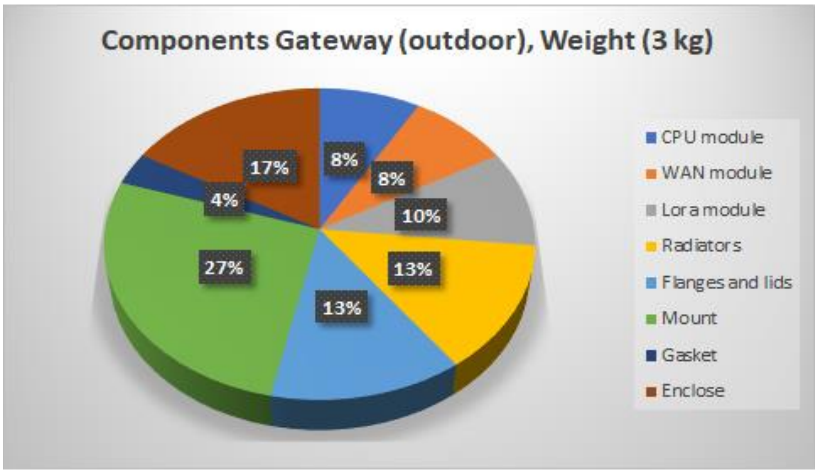


Figure 15 Components of the Gateway (outdoor), (weight, 3kg).

The components of the gateway (outdoor) are shown in Figure 15. The inventory data and assumptions used for the outdoor gateways and other accessories, from raw materials, manufacturing, use, and end of life were described and compiled in Appendix,Table A 2. For the indoor gateway, it was assumed that the Lorawan indoor gateway is similar to the internet ethernet router and the data was taken from ecoinvent database *[Router, internet {GLO}| market for | Cut-off, S].*

Internet connection

For the internet connection, ecoinvent dataset of [*Internet access, work, 0.2 Mbit/s {GLO}| market for | Cut-off, U*] was used in the model.

Netmore cloud

Netmore provides IoT connectivity between LoRaWAN devices and Södertälje IoT platform. They do not provide IoT cloud services nor data storage. However, Netmore has a buffer-storage for data if the data is not fetched real time for any reason. This storage is currently up to 6 months but may be reduced at a later stage. Metadata around network behavior is stored separately for network optimizations and analytics. As Netmore does not provide a data lake for sensor data, Service-level agreements (SLA) on the network is for availability and performance on the connectivity and not for data storage. Sensor data is buffered up to 6 months. Södertälje sensors are currently about 2% of the actual traffic in the Network. The server setup is a managed service from a professional data center provider physically located in Sweden. According to Head of Sales at Netmore, it is estimated the hardware for both production, backup and redundancy to be approximately three units of computer equipment. Netmore used a managed service by a professional data center, hence the electricity used for power the data center and keeping them cool is confidential. The data center provider offers carrier grade availability as managed service and they don’t have information on battery back-ups.

Servers

There are three servers connected to the Netmore cloud: Norrsidans, Infracontrol and Open data. So far, only Norrsidans server is being used for waste collection system, where the signal from sensors and information were collected. Therefore, in this study, only the infrastructure for the Norrsidans server is included. It is assumed that 1 unit of computer equipment and internet connection is needed for assessing the server.

Transportation for waste collection

The transportation data was estimated using theoretical calculations as there is no data on the weight of the trash and the composition of the trash collected in the city center, as well as the distance or fuel consumption used for waste collection. An interview was also conducted with the Group Manager at Södertälje municipality to understand the operation of the working flow for waste collection. According to him, the operator's daily works are described below.

Operators' daily work

Operators will follow the same route collection (travel same route) daily and check for every litter bins. The waste collection is only done once per day and no second visit on collecting the trash. Before the sensors, based on operators' experience, sometimes they will skip some litter bins located in the area that have less waste . Beside emptying the litter bins, the operators also have to hand pick up the trash around the litter bins and clean the streets. There are usually two operators assigned to conduct the daily task. One person collecting the trash and also do hand picking around the trash bin area; while another person will hand pick in the parking area and use the cleaning machine to clean the street. Therefore, in the morning, the group manager will check how many litter bins are full and decide how many operators need to do the waste collection. According to the group manager , only one vehicle is used: Volkswagen transporter that uses HVO 100 (Biodiesel).

Aside of waste collection and cleaning around the area of the litter bins, the operator has other daily tasks for different seasons, for example:

- In spring: flower planting
- In winter (shoveling in the parking area in downtown (certain days)
- After winter (sweeping the sand and stone (3 weeks job)
- Autumn (sweeping leaves in park or downtown, with tractor machine)

Before the covid 19 pandemic, the peak seasons for waste collection are before pay day, festival, or big events in city center, after the winter during weekend, school holidays. While the low season are rainy days, snowy and cold days in winter. The trash bins are located at river sides and city parks (e.g. Stadsparken, Dalparken, Badparken), as well as some popular spots (swimming pools) that usually have high volume of waste emissions, see Figure 12.

The group manager also claimed that out of the 8 hours of the working time, the task of emptying the bins is estimated to be 2-4 hours during the winter; 4-5 hours during the summer; average 4 hours for other seasons. Sometimes, there will be a lot of trash during the summer, the operators need to go back to unload the trash collected at Södertälje municipality complex. The trash is dumped in a container and the garbage truck from Telge återvinning will come and empty the container with a frequency of 3 times per week (Mon, Wed, Fri). Currently, the sensors are set to 55% fullness level to trigger for collection. This setting might change to meet different demands, which depends on seasons and weather. The fullness level will be set to 50-60% (winter), 40-50% (summer), autumn and spring (depends on weather, normally set to 55%.

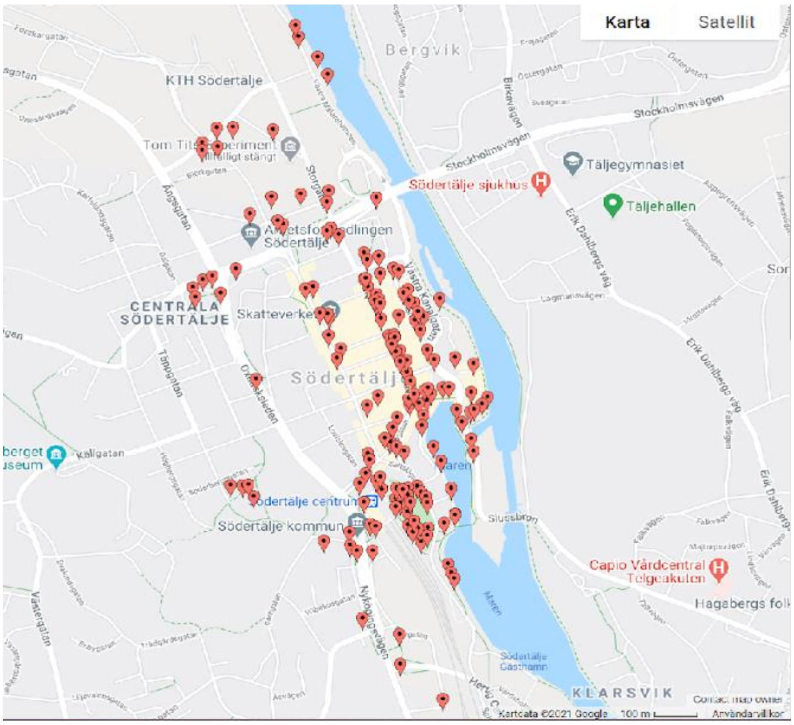


Figure 16 Overview map of all sensors in Södertälje city center.

Transportation distance

To estimate the environmental impact of the waste collection system without IoT system support, the operators are supposed to empty all 160 litter bins. Figure 17 illustrates the transportation involved and the number of litter bins that are emptied based on a theoretical estimation and pre-study conducted by Norrsidans Innovation (Zhang, 2019). The workers will visit the city center three trips per days. They travel back to the center for morning break and lunch as well as unloading the garbage. The emission factor for the transportation was taken from NTM, 2021 and using the traffic data for van less than 3.5t. The inventory data for the transportation was compiled in Table 1. For the waste collection distance, it was estimated to be 9.8 km for visiting 160 litter bins by personnel from Norrsidans Innovation AB. The truck used for waste collection is using HVO as fuel. According to the Swedish Energy Agency report, 2020 (Energimyndighetens, 2020), HVO has about 83% lower emissions than the diesel used. Therefore, the impact of the transportation is taken only 17% of the total impact estimated from NTM, as NTM emission factors are for diesel-based vehicles.

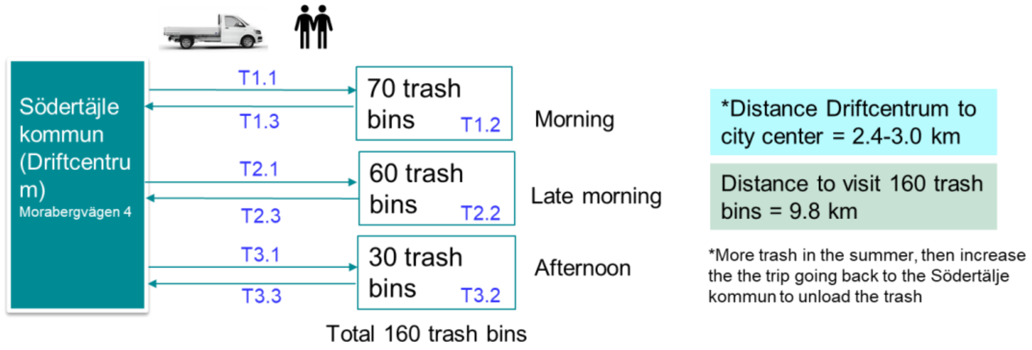


Figure 17 Illustration of the transportation involved for the daily waste collection in Södertäjle city (source: Norrsidans Innovation, 2021, personal comm.) .

Table 1 Transportation data in the use phase.

	Transportation route	Distance [km]	Loading rate [%]	Comments
T1.1, T2.1, T3.1	Södertälje municipality Driftcentrum to city center (3 trips)	2.4	0	NTM, 2021
T1.3, T2.3, T3.3	City center to Södertälje municipality (Driftcentrum)	3.0	20	NTM, 2021
T1.2, T2.2, T3.2	Waste collection (1st, 2nd, 3rd trip)	9.8	20	NTM, 2021

Trash bags

Every time the litter bin is emptied, a new trash bag will be needed to put in the litter bin. The weight of trash bag is estimated about 1.689/25 kg per bag. They are made of fossil-based polyethylene (Södertälje municipality, personal communication, 2021). The ecoinvent data *[Packaging film, low density polyethylene {RER}| production | Cut-off, U]* is used for modelling.

Waste collection system and IoT system services

The inventory data and assumptions used for the waste collection system and the IoT system services include:

- The system includes 160 litter bins and sensors, 9 outdoor gateways and 3 indoor gateways, internet, cloud and server.
- The total amount of waste collected for 365 days, and 160 bins (9.5 kg/bin) are assumed to be 554.8 t.

The complete inventory for a year of waste collection system with IoT system support is described and compiled in Appendix, Table A 3.

Results and interpretation

Climate change impacts of IoT system service

The climate change impact of one year of IoT system service is about 122 kg CO_2 eq per year. The main contribution is from the gateway: outdoor gateways and indoor sensors, where they contributed 41.8% and 8.5% to the total impact, respectively. This follows by the sensors, which contributed 27.6% to the total impact. (see Figure 18). This is mainly due to the sensors containing polycarbonate and a lithium battery.

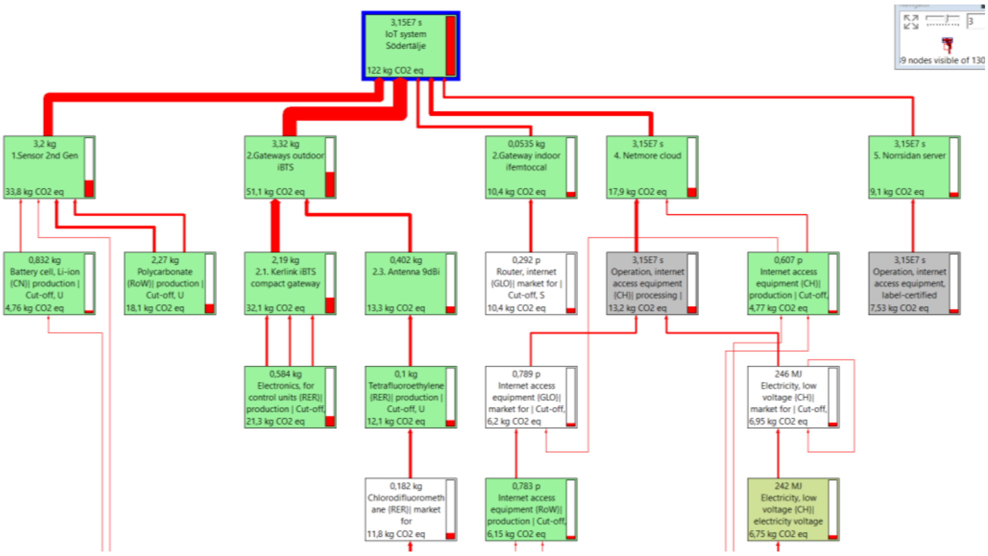


Figure 18 Climate change impact of one year of IoT system service, in kg CO_2 eq, with cut-off 3%.

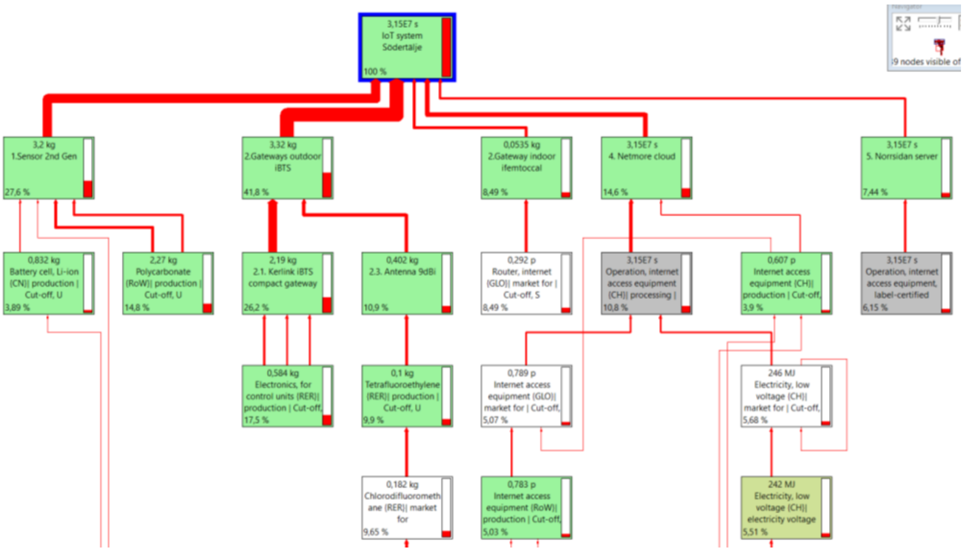


Figure 19 Climate change impact of one year of IoT system service, in percentage, with cut-off 3%.

Climate change impact of waste collection system

The waste collection system in Södertälje city center is estimated to produce about 12t CO_2eq per year if the operators visit every trash bin and replace the trash bags with new trash bags everyday (see Figure 15). This is mainly due to the currently used trash bags, which are made of fossil-based polyethylene and contribute 97% of the total impact (see Figure 16). The transportation has insignificant impacts.

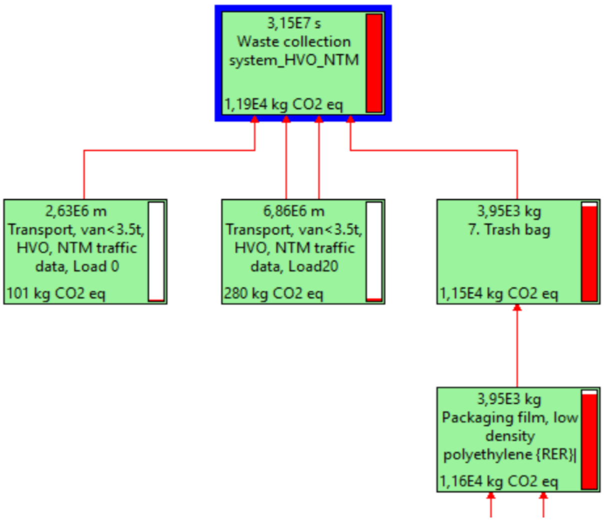


Figure 20 Climate change impact of the waste collection system in Södertälje, in kg CO_2 eq per year.

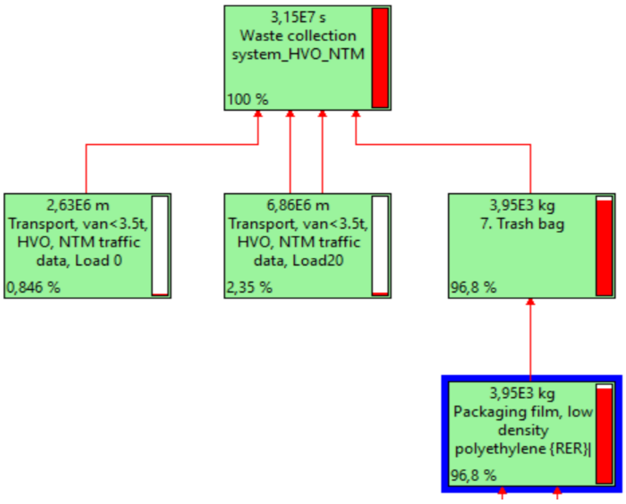


Figure 21 Climate change impact of the waste collection system in Södertälje, in percentage.

Climate change impact of current and future waste collection system

To compare the climate change impact of the current with the future waste collection system with IoT system support, scenarios analysis was used. The current waste collection system is assumed to be based on transportation that used diesel and recycled plastic trash bags. However, Södertälje is using HVO and fossil-based polyethylene (PE) trash bags. The CO_2 emissions from transportation is insignificant mainly due to the trucks use HVO in the waste collection system. Still, we would like to show how important HVO is, and that the trash bags are the hotspot in our study. Therefore, we present the results in the form of scenarios as shown in Figure 22 .

At the starting point of the study (scenario 1), we present results that are based on assumptions and have the same CO_2 emissions for the transport and the trash bags. The waste collection system with IoT system support can contribute 4.6 t CO_2 eq per year, which based on diesel (50%) and trash bags made of recycled plastics (50%). This was based on assumption that the recycled plastic consists of 80% recycled LDPE and 20% virgin LDPE (Tingstad, 2021).

The next step (scenario 2) of the study, we present results that are based on direct data of the current waste collection system. The results were based on HVO and fossil-based trash bags, which resulted in 11.5 t CO_2eq for fossil-based trash bags and 380 kg CO_2eq per year for transport and 120 kg CO_2 eq extra for the IoT system.

The last step (scenario 3) of the study, we present results that are based on assumptions for future waste collection with IoT system support. The results were based on using no bags and no CO_2 emission from bags, which results into 120 kg CO_2eq for the IoT system and 380kg CO_2eq for the transport and 0 kg CO_2eq for the trash bags.

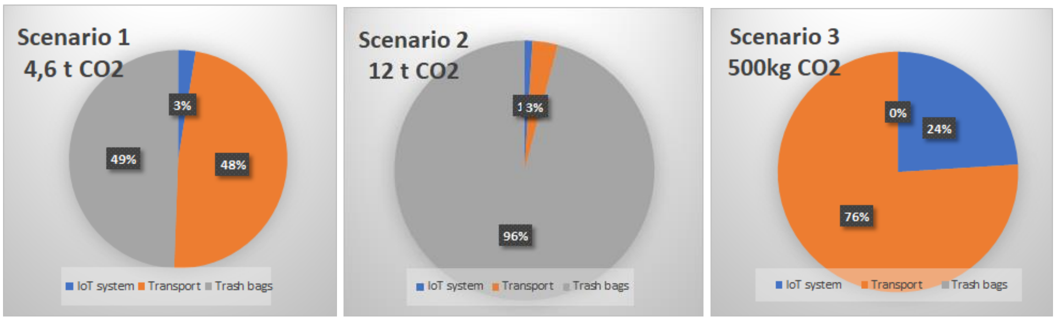


Figure 22 Results of climate change impact, CO_2 eq for the scenarios 1, 2 and 3.

In case, the future waste collection system is using no bags as in scenario 3, the transport is the hotspot of the IoT based waste system (380kg CO_2, 75%). The future waste collection means an additional 120 kg CO_2eq to the current waste collection system 380kg CO_2eq.

The future waste collection system needs to be better than the current system. That means, the future waste collection system needs to reduce the CO_2eq emissions to be at least 120 kg CO_2eq to break-even the extra IoT system.

For the IoT system to have an effect, at least 32% of the transport (km) or number of bins need to be reduced (50 bins of 160 bins), in order to outweighs the extra CO_2eq from the IoT system (see Figure 23).

- A reduction of trp km by 32% reduce CO_2eq by 120 kg. (=IoT system).
- A reduction of trp km by 64% reduce CO_2eq by 240 kg. (> IoT system).

Figure 23 Results of climate change impact, CO_2eq for scenarios 3 a-c.

Discussion

Data availability

Current data available in the Norrsidans servers and data collected are not sufficient for understanding the specific resource and cost effectiveness of the IoT system in Södertälje. Specific data is necessary for assessing the benefits of the IoT system for the waste collection system, for example the transportation data (km, type of fuel), number of trash bags used per year, travel distances, and daily operation of the work for the workers (hours spent on collecting, cleaning and other activities), etc.

On the other hand, it is worth mentioning that it is vital to improve data quality and also the LCA results, so it reflects the reality of the situation. To improve the data, it will be helpful that the LCA practitioner can see the real components (sensors and gateways) and also how the cloud and servers are set up.

Pilot study

In regards with data, a pilot study is proposed to better understand the waste collection system and collect solid data for further evaluating the environmental benefits of the IoT system solution for waste collection system. Two activities are suggested:

- Waste composition assessment (plockanalys)
- Transportation data: distance, fuel used, and weight of waste collected, daily operation task (time spent for waste collection), time used, no. of trash bags used, etc.

Challenge of the smart waste collection system

Non-uniform waste distribution of waste in the bins can cause the sensors not to function as they intended. Sensors use distance measurement to determine the fill levels of the trash bins, so if trash has been deposited unevenly in the bin, the sensors may read that the bin is full, but, in reality it is only half full. Therefore, operators have no confidence on information received from the sensors.

Suggestions for operation, target waste and transport

Below are suggestions that can be considered and explored to improve the current waste collection systems with IoT system support:

1. Daily operation plan for waste collection
    - Replace trash bags that are fossil-based (worst) to recycled bags or not using any bags (best)
    - Use sensors to plan operations to reduce transport and consumption of the trash bags
2. Improve the issue of the sensors with the non-uniform waste distribution in the bins

Of course, there are more aspects can be investigated to optimize the benefits of installing IoT systems in the waste collection system (e.g. time saving, cost saving, etc.) and other qualitative parameters: better management, cleaner city, etc. In the next section, several scenarios and analysis for shaping a better future waste collection system are discussed.

Suggestions for future scenarios

IoT system

The capacity of the gateways can accommodate more than 219 sensors. The CO_2 emissions from 160 sensors is 33kg CO_2eq per year and the total IoT system is 122 kg CO_2 per year. Is it possible to connect more sensors? For example, 10 more sensors mean 2.1 kg CO_2 eq per year.

Transport system

The fuel data is different, and it is vital to make comparison for diesel and HVO (absolut, %). The distance and weight are based on assumption in this study. It is necessary to compare with real data collected from pilot study (absolute, %).

Waste collection system in the city center

Time spent on waste collection leads to less CO_2/bin should be evaluated. The impact of waste collection system with fossil-based trash bags, bio-based bags and no bags also should be further evaluated.

Upscaling for wider area and more litter bins

Compare the current system and future scale up e.g. plan and choose the scaling up to 700 litter bins. How will the future system be when scaling up to 700 litter bins? How will the CO_2 emissions change for the IoT system? Scaling up to 700 sensors means 258.9 kg CO_2 eq (13.5%) for the IoT system and 1662.5 kg CO_2 eq for the transport system (86.5%). For the transportation and plastic bags used, the CO_2 emissions will depend on the distribution of the liter bins and operation of collection. However, the CO_2 emission per sensors will be lower when more sensors are included. (The calculations for 700 sensors are found in the appendix).

Management and operation on waste collection system

Compare current system and future system, e.g plan and choose with help of IoT is telling about full bin in long distance and collecting bags (5-10 km) instead of currently (2-3 km). How will the future waste system be planned? How will the total km and fuel consumption change? How will the CO_2 emissions change? Compare current service and future service, e.g. time spent on transport and bins (2h might change to 1h) and cleaning (2h might change to 1h) and other activities (4h might change to 6 h).

Outlook

Below are points discussed during the LCA results presented on 2021-09-08.

Södertälje (IoT):

- *The coverage of gateways is enough. We only need more for the forest area, not in the city center. We have 11 gateways outside and 4 indoor.*
- *We do not use 160 trash bags per day. Maybe use fossil free bags (bio-based).*

Researcher RISE:

- *We need to talk about and show different perspectives!*

Researcher UMU:

- *Interesting results for transport and trash bags!*
- *Retrofitting bins might be cheaper in the long run!*

Norrsidan Innovation:

- *The next generation of sensors is with one third less plastic!*
- *Only 30% of the bins are emptied. Saving bags just by installing IoT!*
- *Substitution with fossil-free bags! Possible also a bigger transport area!*
- *The IoT system saves also the number of trucks used!*

Södertälje (management and operation):

- *We need to look at other gains, such as clean city from litter, less environmental impacts and an operational management tool, less traffic in the city, and KPIs for management!*
- *Daily routines are important! Management and planning the work!*
- *The current travel distance (km) for waste collection is due to lunch and coffee breaks, if we could make the breaks in the city center instead. This might reduce the trips forth and back to the city center and means that can lead to a better management!*

Conclusions

This study has evaluated the environmental impacts of the IoT system in Södertälje for the case of smart waste collection system installed in the city center from a life cycle perspective. The main results are listed below:

- The **climate impact of the IoT system solution** in Södertälje is evaluated using life cycle assessment and is estimated to be about 122 kg CO_2eq per year, which mainly contributes from the gateways (50%) and sensors (27%) and the use of the internet(23%).
- The **climate impact of the current waste collection system** in the city center of Södertälje contributes approx. 12t CO_2eq per year, which mainly contributed from the use of fossil-based plastic trash bags (96%) and the HVO based transport (4%).
- To compare the current with the **future waste collection system** (including IoT system for planning and service).
  - Hypothetical (with assumption): Scenario 1, Transport (diesel) and recycled plastic bags. Total CO_2 emission is about 4.6 t CO_2 eq per year. Results showed transport and recycled plastic trash bag contributed 50/50.
  - Current: Scenario 2, Transport (HVO) and fossil-based plastic bags. Total CO_2 emission is approximately 12 t CO_2eq per year. Results showed 96% of the toal impact is from trash bags.
  - Future: Scenario 3, Transport (HVO) and no bags. Total emission reduced to only 500 kg CO_2eq per year, reduction carbon footprint by over 90%.

Adopting IoT solution in the waste collection system in the city center only added a small impact to the system. Furthermore, the results also show that the potential for improving future smart waste collection systems lies in revising the usage of fossil plastic bags and smart planning of waste collection to reduce transportation. Several suggestions on improving the waste collection systems itself are discussed, e.g. keep using HVO fuel, use recycled bags/biobased bags, reduce transportation and number of trash bags, or use no trash bags. The IoT system also can be scaled up for a bigger area by installing more sensors without adding a huge impact, as the gateways can accommodate much more than the current capacity. Above suggested scenarios should be further evaluated with real data, and hopefully the results can be used as a guidance in shaping the future smart waste collection.

The main challenge regarding LCA is to have access to the data needed to estimate the actual environmental benefits that the IoT solution can bring to the waste collection system. A pilot study is needed to collect specific data in order to obtain good LCA results that can use for decision making in developing the future concept.

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Appendix

Table A 1 Inventory data for sensors 2nd generation.

Component of sensor	Value	Unit	Ecoinvent database
Raw material			
PCB(measure distance)	1.5	g	Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| production | Cut-off, U
PCB(send data)	4.5	g	Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| production | Cut-off, U
Flexible Flat cable (FFC)	0.5	g	Cable, ribbon cable, 20-pin, with plugs {GLO}| market for | Cut-off, U
Battery	52	g	Battery cell, Li-ion {CN}| production | Cut-off, U
Lens	0.5	g	Polycarbonate {RoW}| production | Cut-off, U
Housing Top	21	g	Polycarbonate {RoW}| production | Cut-off, U
Housing bottom and four stainless steel screws	43	g	Polycarbonate {RoW}| production | Cut-off, U;
Mount	77	g	Polycarbonate {RoW}| production | Cut-off, U
Manufacturing			
Electricity (electricity used for mounting 2 PCBs (Surface mount technology) + electricity used for assembly the sensor in 20 sqm (assuming lighting for factory: 17W/sqm)	0.044	kWh	Electricity, medium voltage {CN}| market for | Cut-off, U
End of life			
Electronics (PCBs)	4.8	g	Waste electric and electronic equipment {GLO}| market for | Cut-off, U
Battery	52	g	Used Li-ion battery {GLO}| treatment of used Li-ion battery, hydrometallurgical treatment | Cut-off, S
Plastics (Lens, Housing, Mount)	142	g	Waste plastic, mixture {Europe without Switzerland}| market for waste plastic, mixture | Cut-off, U
Transportation			
Transport from China to Europe (sea) 8000km	200*8000 /1000	kg/km	Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U
Transport in China (factory to port) 100km	200*100/ 1000	kg/km	Transport, freight, lorry, unspecified {RoW}| transport, freight, lorry, all sizes, EURO6 to generic market for | Cut-off, U
Transport in Europe (port to market) 1000km (Rotterdam to Gotherburg)	200*1000 /1000	kg/km	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO6 to generic market for | Cut-off, U

Table A 2 Inventory data for one unit of outdoor gateway.

Items	Value	Unit	Ecoinvent database
Raw material			
Kerlink outdoor iBTs compact	3.0	kg	Consists of three different modules:CPU (0.5kg), WAN(0.5kg), Lora(0,6kg); mounting kits (stainless steel, 0.8kg); gaskets(polyurethane0.1kg) and enclosure (polycarbonate, 0.5kg)
CPU module (50% Electronic parts and 25% radiators, 25% flanges and lids)	0.5*0.5	kg	Electronics, for control units {RER}| production | Cut-off, S
WAN module (50% Electronic parts and 25% radiators, 25% flanges and lids)	0.5*0.5	kg	Electronics, for control units {RER}| production | Cut-off, S
Lora module (50% Electronic parts and 25% radiators, 25% flanges and lids)	0.6*0.5	kg	Electronics, for control units {RER}| production | Cut-off, S
Radiators for the modules	(0.5*0.25*2)+(0.6*0.25)	kg	Aluminium, cast alloy {GLO}| market for | Cut-off, S ; Metal working, average for aluminium product manufacturing {RER}| processing | Cut-off, S
Flanges and lids	(0.5*0.25*2)+(0.6*0.25)	kg	Steel electrogalvanized steel/EU; Metal working, average for steel product manufacturing {RER}| processing | Cut-off, S
Mounting kits, antenna mounting bracket, and screws (stainless steel)	0.8	kg	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Cut-off, S ; Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, S
Gasket	0.1	kg	Polyurethane, rigid foam {GLO}| market for | Cut-off, S; Injection moulding {RER}| processing | Cut-off, S
Enclosure	0.5	kg	Polycarbonate {RER}| production | Cut-off, S; Injection moulding {RER}| processing | Cut-off, S
30W PoE	0.2	kg	50% Plastics, 30% stainless steel, 20% copper
Plastic	0.2*0.5	kg	Polybutadiene {GLO}| market for | Cut-off, S ; Injection moulding {RER}| processing | Cut-off, S
Stainless steel	0.2*0.3	kg	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Cut-off, U; Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, U
Copper	0.2*0.2	kg	Copper {RER}| production, primary | Cut-off, S; Wire drawing, copper {RER}| processing | Cut-off, S

Antenna, 9dBi	0.55	kg	PU-painted glassfibre (35%), copper (25%), PTFE(20%), PE(10%) and chromed brass (10%)
PU-painted glass fibre	0.55*0.35	kg	Glass fibre {RER}| production | Cut-off, S; Injection moulding {RER}| processing | Cut-off, S
Polyester	0.55*0.1	kg	Polyester resin, unsaturated {RER}| production | Cut-off, S; Injection moulding {RER}| processing | Cut-off, S
Copper	0.55*0.25	kg	Copper {RER}| production, primary | Cut-off, S; Wire drawing, copper {RER}| processing | Cut-off, S
PTFE	0.55*0.25	kg	Tetrafluoroethylene {RER}| production | Cut-off, U; Injection moulding {RER}| processing | Cut-off, S
Chromed brass	0.55*0.1	kg	
Scan Antenna Mount bracket	0.6	kg	It consists of rail mount bracket, which made of PU powder-lacquered die-cast aluminum(50%), 2x U shaped bolts and 4 x screws and nuts, which made of stainless steel
Rail mount bracket	0.6*0.5	kg	Aluminium, cast alloy {GLO}| market for | Cut-off, S; Metal working, average for aluminium product manufacturing {RER}| processing | Cut-off, S
U shaped bolts, screws and nuts	0.6*0.5	kg	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Cut-off, U; Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, S
Antenna cable, 1m	0.2	kg	1 m cable (50%) and 2x stainless steel screw cap (50%)
Cable	0.2*0.5	kg	Cable, unspecified {GLO}| market for | Cut-off, S
Screw cap	0.2*0.5	kg	Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Cut-off, U; Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, S
Transportation			
Transport from France to Stockholm	2250*(3+0.2+0.55+0.6+0.2)	kgkm	Transport, freight, lorry, unspecified {RER}| transport, freight, lorry, all sizes, EURO5 to generic market for | Cut-off, S
Use			
Electricity	30	W	Electricity, low voltage {SE}| market for | Cut-off, S
End of life			
Outdoor gateways and all accessories	3+0.2+0.55+0.6+0.2	kg	Waste electric and electronic equipment {GLO}| treatment of, shredding | Cut-off, S

Table A 3 Inventory data for a year of waste collection system with IoT system support.

Element	Value	Unit	Comments
Sensors (raw material, production, use, end of life)	0.2*160/10	kg	160 units of sensors with 10 years of life span.
LoRaWan	24*365	h	Communication between the sensor and the gateway. The sensor battery supplies the energy needed for this communication and there is no extra energy needed.
Outdoor gateways (raw material, production, use, end of life)	(3+0.2+0.55+0.6+0.2)*10*(160/219)/10	kg	Total 12 units of gateways support a total of 219 sensors in Södertälje (10 outdoor, 2 indoor- 24-05-2021). Assumed that the outdoor gateways have 10 years of life span.
Indoor gateways (raw material, production, use, end of life)	(0.183*2)*(160/219)/5	kg	Assumed that the indoor gateways have 5 years of life span.
Netmore cloud	3*24*365*0.02	h	3 units of computer equipment. Södertälje is only 2% of the Netmore services. Electricity used (power and keeping it cool are unknown)
Internet	24*365	h	24 hours per day of internet connection
Norrsidan server	1*24*365	h	1 unit of computer equipment.
Internet	24*365	h	24 hours per day of internet connection
Transportation	[(2.4*3)+(3*3)+9.8]*365	km	9.8km for waste collection and three back and fold trips from service center to the city center (2.5km).
Trash bags (160 L)	0.06756*160*365	kg	Assuming changing all the trash bags in the litter bins. The trash bag is weighted 0.06756kg.

Table A 4 Information and calculation for Scenarios 1,2 and 3, as well as for 3a-c.

Scenario results	Value	Unit	Comments	Contribution
Transport system (9.8km + 2.4km + 3km)	2235	kg CO_2eq per year	Diesel	
Transport system (9.8km + 2.4km + 3km)	380	kg CO_2eq per year	HVO (17%)	
IoT system	120	kg CO_2eq per year		
Trash bags (fossil)	11 500	kg CO_2eq per year	Fossil	
Trash bags (80% recycled)	2300	kg CO_2eq per year	80% recycled	
No trash bags	0	kg CO_2eq per year	No Bags	
Scenario 1				
IoT system	120	kg CO_2eq per year		3%
Transport system (9.8km + 2.4km + 3km)	2235	kg CO_2eq per year	Diesel	48%
Trash bags (80% recycled)	2300	kg CO_2eq per year	80% recycled	49%
	4655	kg CO_2eq per year	Transport the same as trash bags!	
Scenario 2				
IoT system	120	kg CO_2eq per year		1%
Transport system (9.8km + 2.4km + 3km)	380	kg CO_2eq per year	HVO	3.2%
Trash bags (fossil)	11 500	kg CO_2eq per year	Fossil	95.8%
	12000	kg CO_2eq per year		
Scenario 3a				
IoT system	120	kg CO_2eq per year		24%
Transport system (15.2km)	380	kg CO_2eq per year	HVO	76.0%
No trash bags	0	kg CO_2eq per year	Fossil	0.0%
	500	kg CO_2eq per year	More than before (IoT system)	
Scenario 3b				
IoT system	120	kg CO_2eq per year		24%
Transport system (-5km)	-120	kg CO_2eq per year		
Transport system (15km)	380	kg CO_2eq per year	HVO	76.0%
No trash bags	0	kg CO_2eq per year	Fossil	0.0%
	380	kg CO_2eq per year	Same as before (without IoT system)	
Scenario 3c				
IoT system	120	kg CO_2eq per year		24%
Transport system (-10km)	-240	kg CO_2eq per year		
Transport system (15km)	380	kg CO_2eq per year	HVO	76.0%
No trash bags	0	kg CO_2eq per year	Fossil	0.0%
	260	kg CO_2eq per year	Better as before (without IoT system)	

Extra future scenario (scale up from 160 sensors to 700 sensors)

Results for the sensors

160 sensors = 33.8 kg kg CO_2eq. 700 sensors = 147.8 kg CO_2eq (33.8kg CO2/160sensors *700sensors)

Results for the gateways (10 units outdoor and 2 units indoors) are 69.9 kg CO_2eq+ 14.2 kg CO_2eq = 84.1 kg CO_2eq
Results for internet is the same = 27 kg CO_2eq

Current IoT system (160 sensors) = 122.3 kg CO2

(33.8 kg CO_2eq sensors + 61.5 kg CO_2eq gateways + 27 kg CO_2eq internet)

Future IoT system (700 sensors) = 258.9 kg CO2

(147.8 kg CO_2eq sensors + 84.1 kg CO_2eq gateways + 27 kg CO_2eq internet)

Transport system

Current (160 bins)= 380 kg CO_2eq. Future (700 bins) = 1662.5 kg CO_2eq

Current system (25% IoT, 75% transport). Future system (13.5% IoT, 86.5% transport).

The CO_2 emission per sensors is getting lower when more sensors are included. That means it’s better to connect more in the IoT system!