

# Hydronic Road-Heating Systems: Environmental Performance and the Case of Ingolstadt Ramps

Arslan AHMED<sup>1\*</sup>, Fosca CONTI<sup>2</sup>, Peter BAYER<sup>3</sup>, Markus GOLDBRUNNER<sup>4</sup>

<sup>1,2,4</sup>*Institute of new Energy Systems, TH Ingolstadt, Esplanade 10, 85049 Ingolstadt, Germany*

<sup>2</sup>*Department of Chemical Sciences, University of Padova, via Marzolo 1, 35141 Padova, Italy*

<sup>3</sup>*Department of Applied Geology, MLU Halle-Wittenberg, von-Seckendorff-Platz 3, 06120 Halle, Germany*

**Abstract** – Snowfall and ice formation on road surface significantly impact the safety of driving conditions. To resolve this, every year salt and de-icing chemicals are sprinkled on roads. However, use of salts and snow ploughing have environmental as well as economical disadvantages. To resolve these problems, hydronic road heating systems are valid alternatives. Heat transfer fluid, i.e. mixture of ethanol and water, is pumped into a tubular circulation system under the asphalt. By this technology, the road and pavements shall stay ice-free even in times of snowfall and temperatures below the freezing point. The system can also be used to cool the asphalt in case of extreme heat, which – besides the heating effect – could also prevent road from damages in extreme summers. This study aims to compare the environmental impact of use of salts and road-heating system in terms of GHG emissions. To assess the environmental impact, an operational road heating system for a ramp in Ingolstadt, Germany, is considered. A cradle-to-grave analysis technique is used to determine the environmental effects based on a life-cycle assessment (LCA) framework. The analysis includes nine components solemnly responsible for hydronic heating of asphalt surface such as local heating pipe, insulation, pumps, and heat meters. Comparison is performed in terms of relative and total impact over 50-year lifetime of three heated ramps having 1989 m<sup>2</sup> surface area in total. The results show that the asphalt and heating-circuit causes the major fraction (65 %) of overall GHG emissions, with total life-time emissions of 28.10 kg CO<sub>2</sub> eq./m<sup>2</sup> of heated surface. During an operational life of 50 years, road heating systems emit 18 % less CO<sub>2</sub> eq./m<sup>2</sup> as compared to the use of salts.

**Keywords** – Environmental performance; de-icing; hydronic road-heating system (HRS); greenhouse gases (GHG); Life cycle assessment (LCA); snow removal

| Nomenclature                       |                                                     |                        |
|------------------------------------|-----------------------------------------------------|------------------------|
| <i>A</i>                           | Area of hydronic road heating system                | m <sup>2</sup>         |
| EN                                 | European norms                                      | –                      |
| <i>E</i> <sub>CO<sub>2</sub></sub> | Carbon dioxide equivalent emissions per kg of salts | kg CO <sub>2</sub> eq. |
| GWP                                | Global warming potential                            | –                      |
| <i>GWP</i> <sub>T</sub>            | Total global warming potential                      | kg CO <sub>2</sub> eq. |
| <i>GWP</i> <sub>A</sub>            | Annual global warming potential                     | kg CO <sub>2</sub> eq. |
| GHG                                | Greenhouse gases                                    | –                      |
| HRS                                | Hydronic road-heating system                        | –                      |
| ISO                                | International organization for standardization      | –                      |

\* Corresponding author.  
E-mail address: Arslan.Ahmed@thi.de

|       |                                              |       |
|-------|----------------------------------------------|-------|
| LCA   | Life cycle assessment                        | –     |
| $M_s$ | Mass of salt to be used for de-icing         | kg    |
| SL    | Service life of hydronic road heating system | years |

## 1. INTRODUCTION

Since the Paris Agreement, all signatories are putting special efforts into reducing the carbon equivalent emissions [1]. EU programs and regulations on environmental sustainability, protection and pollution abatement are seen as an unprecedented attempt to tackle climate change on a larger scale [2].

The use of salts and mechanical snowploughs is the most conventional method to eliminate snow accumulation on roads. Despite the low operational costs, chemical de-icing agents are harmful to the environment, whereas mechanical snowploughs are time-consuming [3] and require expensive maintenance. In the last decades, the hydronic road-heating system (HRS) was proposed as alternative snow melting method to prevent the build-up of snow and ice on roads [4], especially on slopes, bends and bridges [5] in cold regions. HRS is preferred in several cases, because it is more reliable, potentially cost-effective and environmental-friendly [6]. Differently from electric snowmelt systems, the HRSs are available to utilize different energy sources: geothermal energy, district heating, or solar energy, and in some cases, they are also combined with thermal storage [7]. A review conducted by Lund and Boyd [8] states that in 2015, an area of 2 500 000 m<sup>2</sup> world-wide was heated by HRS utilizing geothermal energy, with required power of 130–180 W/m<sup>2</sup> [8]. In addition, standalone heating solutions can be found, particularly in airports [9]–[12], and bridge decks [13]. Despite widespread applications around the globe, strong optimization potentials of HRS are evident in terms of specific working parameters. This study sets a focus on the environmental impacts of HRS in terms of greenhouse gas (GHG) emissions. To determine the environmental performances associated with all life stages of components of HRS, a life cycle assessment (LCA) framework is implemented. The case of a road system in Ingolstadt, Germany, constituted of three ramps with HRS for a total surface of ca. 2000 m<sup>2</sup> is analysed and discussed. Positive and negative aspects are compared with the corresponding use of road salts and supporting equipment over the 50-year lifetime of HRS.

## 2. STATE OF TECHNOLOGY

The principle of thermal activation has been used in rail transport for decades to heat railway switches in order to avoid freezing in winter and to maintain the complex rail traffic. Installing snowmelt systems to prevent the build-up of ice on drive- and walkways is not a new method either. In 1948, the earliest system was installed in Klamath Falls in Oregon, USA by Oregon Highway Department. The source of energy in this system was geothermal hot water directly pumped into heating system. This system failed after 50 years of working due to external corrosion of the steel pipes [14].

Generally, main heat sources for snowmelt systems are electric resistance heat and warm fluids obtained with geothermal heat or conventional combustion processes. In hydronic systems, the warm fluids are carried by pipes, which are installed close to the surface. Fig. 1 shows a schematic representation [15] of a hydronic road-heating system (HRS).

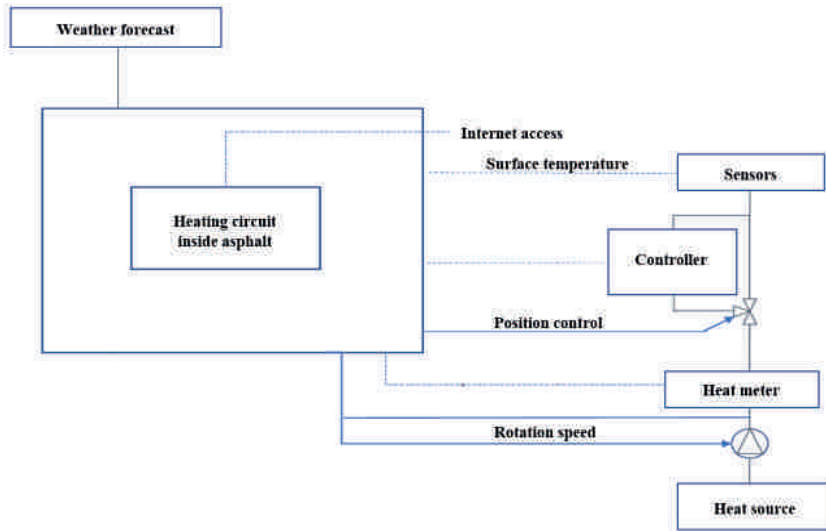


Fig. 1. Schematic of hydronic road heating system.

Apart from different control systems, road heating systems also differ in terms of pipe-register materials, laying patterns of pipes and heat exchange fluid. Rigid materials such as iron or steel have been used in some projects, but they are more vulnerable to corroding related damages. Flexible polymers, such as polyethylene and polybutylene, are convenient materials for pipes and have additional benefits, i.e., they can be laid into spiral or double-spiral patterns for extended thermal density. Initially, pure water was used as heating transfer fluid, but nowadays, a mixture of water with the alcohols having low freezing points are used:  $-98\text{ }^{\circ}\text{C}$  is the melting point of methanol, while ethanol becomes solid at  $-114\text{ }^{\circ}\text{C}$  and propylene glycol at  $-59\text{ }^{\circ}\text{C}$ . Vertical ground heat exchanger or gravity-operated eat pipes represent another established type of hydronic heat system. They consist of a sealed tube which contains a refrigerant with a low condensation point, normally ammonia (melting point at  $-78\text{ }^{\circ}\text{C}$ ). The lower end of the pipe acts as evaporator while the upper portion serves as the condenser [16]. The evaporation and condensation processes create the driving pressure potential that is required to transport the vapour upward, while the condensate returns due to gravity in the slightly slanted condenser to the vertical evaporator.

Heat pipes are bound to special construction methods due to their mode of operation. Straight steel pipes or condenser combs are used as installation patterns. Geothermal energy is used almost exclusively as the heat source. Older heat pipe systems were operated with the coolant Freon, which was replaced by ammonia after the ban on chlorofluorocarbons, which were the most established coolants for heat pipes. Recent studies [17] are also looking at the use of liquid  $\text{CO}_2$ . In conclusion, the current studies on temperature-controlled asphalt surfaces [14] suggest that temperature-controlled surfaces have great potential, but optimization in design, testing, installation, maintenance, and long-term stability are urgent requirements. While the costs for implementation and heat supply can be decisive for realizing many potential HRS applications, environmental considerations are of increasing interest for road-de-icing. In order to shed a light on one core aspect of environmental performance, subsequently the carbon footprint of such systems is evaluated in detail.

### 3. EXPERIMENTAL METHODOLOGY

Life-cycle assessment (LCA) is a methodology for quantitative analysis of environmental impacts associated with the stages to realize a product. It is an evaluation technique used for analysis of impacts and resource consumption of a system through its entire life cycle, starting from raw material extraction and ending at ultimate disposal [18]. The International Organization for Standardization (ISO) provides principles, framework, requirements, and guidelines to complete LCAs through ISO 14040:2006 and ISO 14044:2006 [19]. Generally, LCA is structured in four main steps, as shown in Fig. 2.

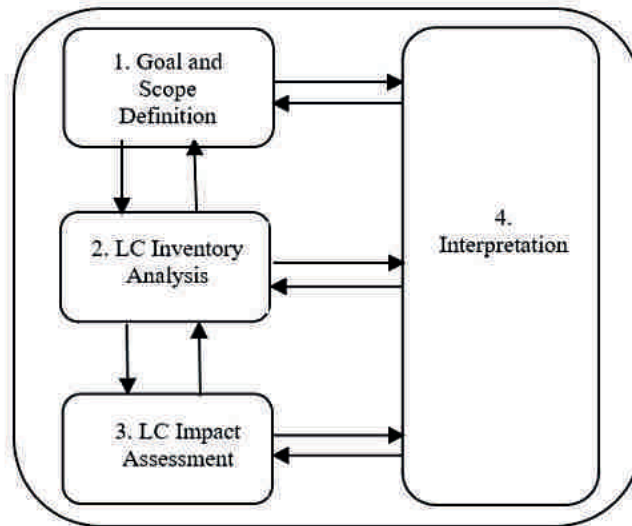


Fig. 2. Schematic structure of life cycle assessment [18].

#### 3.1. Goal and scope definition

As the basis of LCA, firstly the goal and scope are defined. This phase mainly involves determination of: 1) system boundary conditions, 2) functional unit and 3) analysis period [18]. In this step, assumptions and limitations of evaluation are defined.

The goal of this work is to assess the global warming potential (GWP) associated with HRS based on a case study, and to compare it to alternative choices.

System boundary specifies the life stage processes which are to be included within the framework of LCA. Therefore, the system boundaries include all significant life-cycle stages and cover the extraction of raw material, production and transportation of materials, their installation in the road structures and use of the construction [20]. The situation after the service life of material can also be included in the analysis if there is recovery and reuse application for the specific material. Table 1 shows the life cycle modules according to the (European norms) EN-17472 [21] and EN-15804 [22] standards.

All the stages of materials contain information about the processes and activities performed during the life cycle of road heating system. In the context of this study, CO<sub>2</sub> emission information from four stages of life cycle has been collected [23]. Table 2 enlists all the relevant activities and processes.

TABLE 1. STANDARD LIFE CYCLE ANALYSIS MODULES [21], [22]

| Product Stage       | Construction Process | Use Stage     | End of Life Stage | Potential Benefits & Loads |
|---------------------|----------------------|---------------|-------------------|----------------------------|
| Raw material supply | Transport            | Service       | Deconstruction    | Recycling potential        |
| Transport           | Installation process | Maintenance   | Transport         | Reuse                      |
| Manufacturing       | Construction         | Repair        | Waste processing  | Recovery                   |
| Extraction          | –                    | Replacement   | Disposal          | –                          |
| –                   | –                    | Refurbishment | –                 | –                          |
| –                   | –                    | Energy use    | –                 | –                          |

For assessment of operational performance, a time period has to be specified. The analysis period refers to the operational span of product/process and is set 50 years.

TABLE 2. RELEVANT ACTIVITIES AND PROCESSES

| Stage                                        | Activities and processes                                                                                                           | Values considered for this study                   |
|----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------|
| Raw material extraction and production stage | Raw material extraction, supply, aggregate crushing, screening, transportation, processing, manufacturing                          | Raw material supply, transportation, manufacturing |
| Construction/installation stage              | Transport of manufactured product, construction, demolition, installation process, demolition of existing structures if applicable | Construction, installation                         |
| Usage/application stage                      | Energy and water consumption, maintenance, rebuilding, servicing, repairs, operational equipment, labour costs                     | Maintenance, repairs                               |
| End of life stage                            | Recovery, deconstruction, transport to recycling facility, processing, disposal                                                    | Deconstruction, transport, disposal                |

The functional unit relates the inputs and outputs of system to define the comparison with other investigations. Here, the functional unit is defined as de-icing of an asphalt surface area of 1 m<sup>2</sup>. We refer to the local conditions in Ingolstadt, Germany.

### 3.2. Life Cycle Inventory Analysis

The carbon dioxide emission data on respective life stages has been collected in accordance with the principle defined by ISO 14040:2006 and ISO 14044:2006.

The main focus of inventory analysis is on data collection, compilation, determination of product or process system boundaries and input allocations. The main types of inventory analysis include process, input-output and hybrid [18]. The data for relevant life stages components of HRS in Ingolstadt has been collected from various sources which includes the previous LCAs, data from manufacturers and installations companies. As reference, a case study in Ingolstadt is chosen that is depicted in Fig. 3, with a total road surface area of 1989 m<sup>2</sup>. It is composed of three ramps of same width 3.5 m, but different areas: ramp A = 734 m<sup>2</sup>, ramp B = 689 m<sup>2</sup>, ramp C = 566 m<sup>2</sup>.

### 3.3. Life Cycle Impact Assessment

The impact assessment is the evaluation of potential impact of process or product. It classifies the outputs of inventory analysis to understand the environmental sense in terms

of impact categories such as environmental damage, acidification potential and so on. Three main phases of impact assessment are:

- Classification;
- Characterization;
- Valuation.

The international standard for life cycle impact assessment, ISO 14042, considers classification and characterization to be mandatory elements of LCA [24].

In context of the present study, the carbon dioxide emissions corresponding to the labour works during the installation of system, transportation of labour to the construction site, cleaning, surveying and measurement works, additional winter maintenance services and emissions from supporting vehicles is not taken into consideration. Eq. (1) refers to the total global warming potential ( $GWP_T$ ) of road heating system over the service life ( $SL$ ).

$$GWP_T = GWP_A \cdot SL \quad (1)$$

The annual global warming potential ( $GWP_A$ ) of road heating system is calculated as follows in Eq. (2), where  $A$  represents the area to be heated/cleared with salt,  $M_S$  is the mass of salt used per unit area and  $E_{CO_2}$  indicates the  $CO_2$  eq. emissions per unit kilogram of salt.

$$GWP_A = A \cdot M_S \cdot E_{CO_2} \quad (2)$$

Therefore, in the current analysis the following values were used:  $SL = 50$  years and  $M_S = 1.28 \text{ kg/m}^2$ . Fig. 3(a) shows the actual ramps A and B in Ingolstadt while Fig. 3(b) shows the heating circuit pattern before asphaltting process.



Fig. 3. a) Ramp A and ramp B with HRS in Ingolstadt and b) laying pattern of heating pipes during installation.

The collected emissions per material are listed in Table 3. In order to compare the GWP of HRS with the use of salts as de-icers, the latest data of salt usage in Bavaria, Germany for winters from 2018 to 2021 has been acquired from Bavarian State Ministry for Housing, Construction and Transport. Average weather conditions during this period of 4 years refers to an average high temperature of  $24^\circ\text{C}$  and average low temperatures of  $-4^\circ\text{C}$ , while the warm season last about 3.4 months and the cold season last for about 3.6 months.

Data from Ministry shows that an average of  $1.28 \text{ kg}$  of salts (sodium chloride  $\text{NaCl}$  and calcium chloride  $\text{CaCl}_2$ ) per square meter of road surface was applied. The yearly values vary

as per number of ice and snowfall predictions per year. According to Winnipeg city council, Canada's report [25] on CO<sub>2</sub> equivalent emissions from various industrial chemical, the GWP of NaCl is 0.2 kg CO<sub>2</sub> eq. per kg while that of CaCl<sub>2</sub> is 0.87 kg CO<sub>2</sub> eq. per kg which refers to a 0.535 kg CO<sub>2</sub> eq. per kg when used in 50 % composition each. It is to be noted that the CO<sub>2</sub> emissions from the usage state are considered in Table 3. However, no component of HRS except the controller/heat meters produce any emissions during the usage stage. The share of emissions from controllers/heat meters during usage stage are shown in Fig. 4.

TABLE 3. RELEVANT CO<sub>2</sub> EMISSIONS PER COMPONENT LIFE STAGE

| Component            | Type/Material            | Unit                                  | CO <sub>2</sub> Emissions |              |       |          | Source |
|----------------------|--------------------------|---------------------------------------|---------------------------|--------------|-------|----------|--------|
|                      |                          |                                       | Production                | Installation | Usage | Disposal |        |
| Insulation           | K Flex ST PLUS           | kg CO <sub>2</sub> eq./m <sup>3</sup> | 195.48                    | 18.85        | 0.00  | 21.20    | [26]   |
| Local heating pipe   | UNO SDR11                | kg CO <sub>2</sub> eq./m              | 0.64                      | 0.15         | 0.00  | 0.08     | [27]   |
| Heat transfer fluid  | Geko AF-8                | kg CO <sub>2</sub> eq./L              | 0.07                      | 0.04         | 0.00  | 0.02     | [28]   |
| Self-drilling screws | Hot-dip galvanized steel | kg CO <sub>2</sub> eq./kg             | 2.00                      | 0.30         | 0.00  | 1.50     | [28]   |
| Mounting clamps      | Hot-dip galvanized steel | kg CO <sub>2</sub> eq./kg             | 2.00                      | 0.30         | 0.00  | 1.50     | [28]   |
| Heating circuit      | PE-Xa                    | kg CO <sub>2</sub> eq./m              | 0.64                      | 0.15         | 0.00  | 0.08     | [27]   |
| Asphalt              | MA 8S                    | kg CO <sub>2</sub> eq./m <sup>2</sup> | 3.54                      | 1.45         | 0.00  | 4.99     | [28]   |
| Junction box         | Hot-dip galvanized steel | kg CO <sub>2</sub> eq./kg             | 2.00                      | 0.30         | 0.00  | 1.50     | [29]   |

### 3.4 Life Cycle Interpretation

Life cycle interpretation is a systematic technique to identify, quantify, check and evaluate information from the results of the life cycle inventory and/or the life cycle impact assessment. According to ISO 14040:2006, the interpretation should include:

- Identification of significant issues based on results of inventory and impact analysis;
- Valuation of the study, considering completeness, sensitivity and consistency checks;
- Conclusions, limitations and recommendations.

A key purpose of performing life cycle interpretation is to determine the level of confidence in the final results and communicate them in a fair, complete and accurate manner [30].

## 4. RESULTS AND DISCUSSION

The system in Ingolstadt with HRS consists of three separate ramps heated by a central energy control unit utilizing the waste heat from nearby industrial facility. The control unit regulates mainly the mass flow rate and the temperature of the fluid into the ramps, depending on live weather data and forecast from on-site weather stations. Historic weather data of Ingolstadt from these stations shows that warm season last about 3.4 months with average high temperature of 24 °C and cold season last for an average with 3.6 months will average low temperature of −4 °C. The data are concordant with the average weather conditions of most cities in central Europe, so that the results connected to the local conditions of Ingolstadt in Germany can be extent and applied to other European places with similar weather conditions. An ecological heat transfer fluid made by a mixture of water and ethanol is used in the pipe systems. LCA was performed separately for each ramp. As the distance of the ramps from the energy control unit is variable, a local heating pipe *Rauthermex UNO SDR11*

75/162 was used with *K Flex ST PLUS* insulation to minimize the energy losses. LCA of ramp A includes the emissions from the central control unit (119 kg CO<sub>2</sub> eq.) and respective heat meter (89 kg CO<sub>2</sub> eq.), whereas all other components are kept the same for all ramps. Eight components are considered: insulation for local heating pipe, local heating pipe, heat transfer fluid *Geko AF-8*, self-drilling screws, mounting clamps, heating circuit *PE-Xa SDR11*, mastic asphalt *MA 8S*, and junction box. Based on variable heated area (ramp A: 734 m<sup>2</sup>, ramp B: 689 m<sup>2</sup>, ramp C: 566 m<sup>2</sup>), the quantity of components and services is also different.

Table 4 refers to the overall potential impact of components for each ramp. The actual mass of controller, heat meter, self-drilling screws, mounting clamps and junction box is measured to calculate the potential environmental impact. This concludes the total emissions of component life stages based on material used in the construction of each ramp.

TABLE 4. POTENTIAL GWP IN KG CO<sub>2</sub> EQ. PER EACH COMPONENT OF THE THREE RAMPS

| Component                  | Quantity       |        |        |        | Potential GWP (kg CO <sub>2</sub> eq.) |          |          |
|----------------------------|----------------|--------|--------|--------|----------------------------------------|----------|----------|
|                            | Unit           | Ramp A | Ramp B | Ramp C | Ramp A                                 | Ramp B   | Ramp C   |
| Controller & heat meter    | kg             | 54.7   | –      | –      | 208.0                                  | –        | –        |
| Insulation of heating pipe | m              | 300.0  | 60.0   | 320.0  | 683.1                                  | 98.9     | 353.3    |
| Local heating pipe         | m              | 600.0  | 120.0  | 640.0  | 522.0                                  | 104.4    | 556.8    |
| Heat transfer fluid        | L              | 3 465  | 3 270  | 2 735  | 420.1                                  | 396.4    | 331.5    |
| Self-drilling screws       | kg             | 134.4  | 123.3  | 102.0  | 510.8                                  | 468.6    | 387.6    |
| Mounting clamps            | kg             | 448.0  | 411.0  | 340.0  | 1702.4                                 | 1561.8   | 1292.0   |
| Heating circuit            | m              | 7 310  | 6 868  | 5 660  | 6359.7                                 | 5975.2   | 4924.2   |
| Asphalt                    | m <sup>2</sup> | 734.0  | 689.0  | 566.0  | 7325.4                                 | 6876.3   | 5648.7   |
| Junction box               | kg             | 853.6  | 853.6  | 711.3  | 3243.6                                 | 3243.5   | 2703.0   |
| Total impact               |                |        |        |        | 20 975.1                               | 18 725.1 | 16 197.1 |

Fig. 4 shows the profile of GHG emissions for every ramp as relative impact of each component during its life stage as presented in Table 4. The graphs were obtained summing up the data of Table 4. The asphalt layer is assumed to have an operational life longer than 50 years as density of traffic is low on the three ramps. As expected, the total emissions are directly proportional to the amount of the heated area: however, it is evident in Fig. 4 that the largest contributors to GHG emission are asphalt works and heating circuit. These two components, among the eight, contribute to 65 % of overall emissions. Furthermore, it can be noted that half of the emissions produced by asphalt stem from the disposal/deconstruction stage, which means that these emissions can be reduced drastically by reusing and recycling asphalt.

Table 5 enlists the total emissions for every ramp as environmental impact per square meter (in accordance with the functional unit of the LCA framework) as well as total emissions per ramp. It is clear from Table 5 that ramp B has lower area-specific emissions. This is explained by the fact that the central energy control unit is located near ramp B and thus the heating pipe is shorter and less insulation is required.

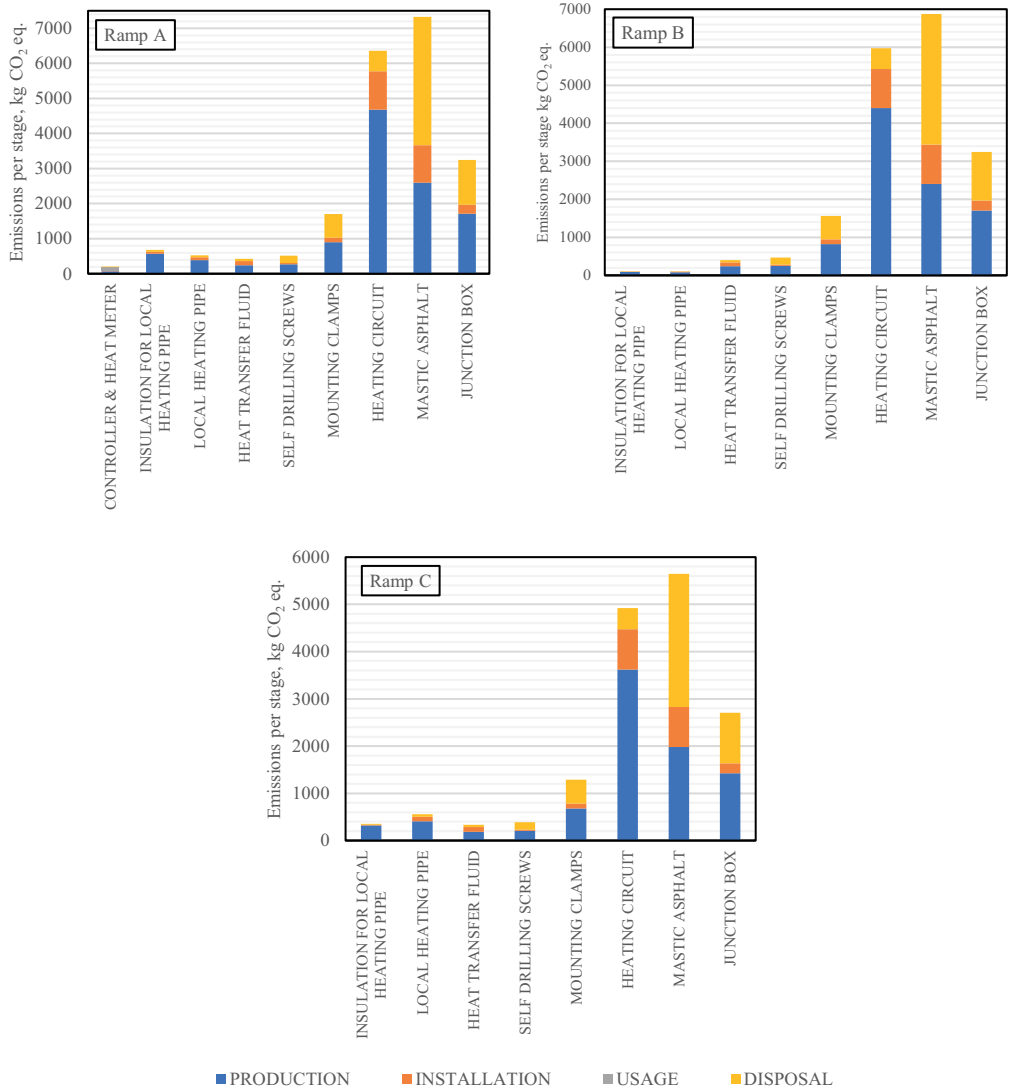


Fig. 4. Total GHG emissions of each contribution during life stages of the HRS of three ramps A–C in Ingolstadt.

Over the service lifetime of 50 years, it is estimated that the Ingolstadt ramps with HRS will have a total global warming potential  $GWP_T$  of  $55.897 \cdot 10^3$  kg CO<sub>2</sub> eq., i.e. a specific environmental impact of 28.10 kg CO<sub>2</sub> eq./m<sup>2</sup>.

In comparison, based on data from the Bavarian State Ministry for Housing, Construction and Transport and a corresponding life cycle investigation carried out in this study, a total  $GWP_T$  of  $68.104 \cdot 10^3$  kg CO<sub>2</sub> eq. by using salts as de-icers for the same area of 1989 m<sup>2</sup> over 50 years is calculated. Correspondingly, the emission factor for salts relative to unit area is 34.24 kg CO<sub>2</sub> eq./m<sup>2</sup>, which is 18 % higher as compared to the operational HRS in Ingolstadt.

TABLE 5. CARBON DIOXIDE EQUIVALENT EMISSIONS PER RAMP RELATIVE TO SURFACE AREA AND OVERALL EMISSIONS PER RAMP

| Ramp | Surface area, m <sup>2</sup> | Relative CO <sub>2</sub> emissions, kg CO <sub>2</sub> eq./m <sup>2</sup> | Overall CO <sub>2</sub> emissions, 10 <sup>3</sup> kg CO <sub>2</sub> eq. |
|------|------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| A    | 734                          | 28.57                                                                     | 20.98                                                                     |
| B    | 689                          | 27.17                                                                     | 18.72                                                                     |
| C    | 566                          | 28.61                                                                     | 16.19                                                                     |

In order to implement the presented LCA calculations on other road heating systems, special care has been put into consideration of only the core components of road heating system that are actually common in all heating systems. Thus, omitting and not including any site-specific or location specific components. However, the major limitation of our study is that the environment impacts of the HRS in Ingolstadt due to maintenance and repair works are not considered, since over the current lifespan (built in May 2017) no operational problems and maintenance expenditures have occurred. This restricts the implementation of current study on HRS which are in operation for longer period and with maintenance issues in terms of environmental impact. In order to compensate the aforementioned, only life stages of salts were considered for comparison. The emissions from supporting machinery that is used to sprinkle the salt every year on roads, emissions from operating personals and miscellaneous emissions were not considered. This assumption can be deemed realistic as, even if there are no emissions from maintenance works of HRS, the upper layer of asphalt needs to be replaced approximately every 7–8 years depending on the physical conditions.

## 5. CONCLUSION

The environmental impacts of two different road surface de-icing strategies were analysed and compared: use of salts and de-icing chemicals directly on the ground versus hydronic heating system (HRS) installed under the surface. The LCA was performed to evaluate the overall and relative carbon dioxide equivalent emissions over service lifetime of 50 years of an HRS operated in Ingolstadt. It is concluded that over the service lifetime, the hydronic heating systems produce 18 % less emissions as compared to the de-icing salts. In relative terms to the surface area of de-icing, use of salts produces 6.14 kg CO<sub>2</sub> eq. more emissions per square meter. Apart from these emissions, any further critical impacts of salt use by causing fine dust particles, other environmental hazards such as corrosion of vehicles and buildings, and pollution of soil, ground- and surface water can be avoided by installing HRS. The results show that the heating circuit PE-Xa and MA 8S type asphalt cause 65 % of total emissions. Therefore, there is immense potential of further research into reduction of emission by recycling and reusing the asphalt.

## ACKNOWLEDGEMENT

This work was supported by German Federal Ministry of Economics and Climate Protection within the framework of Central innovation program for small and medium-sized enterprises (ZIM) under grant code ZF 4017409RH8. The authors thank Audi AG, Dibauco GmbH, OAG mbH and IB-eat for their cooperation during the research work.

## REFERENCES

- [1] Pakere I., *et al.* Ranking EU Climate and Energy Policies. *Environmental and Climate Technologies* 2021:25(1):367–381. <https://doi.org/10.2478/rtuct-2021-0027>
- [2] Laktuka K., *et al.* Long-Term Policy Recommendations for Improving the Efficiency of Heating and Cooling. *Environmental and Climate Technologies* 2021:25(1):382–391. <https://doi.org/10.2478/rtuct-2021-0029>
- [3] Ho I.-H., Li S., Abudureyimu S. Alternative hydronic pavement heating system using deep direct use of geothermal hot water. *Cold Regions Science and Technology* 2019:160:194–208. <https://doi.org/10.1016/j.coldregions.2019.01.014>
- [4] Johnsson J., Adl-Zarrabi B. Modeling the thermal performance of low temperature hydronic heated pavements. *Cold Regions Science and Technology* 2019:161:81–90. <https://doi.org/10.1016/j.coldregions.2019.03.007>
- [5] Adl-Zarrabi B., Mirzananadi R., Johnsson J. Hydronic pavement heating for sustainable ice-free roads. *Transportation Research Procedia* 2016:14:704–713. <https://doi.org/10.1016/j.trpro.2016.05.336>
- [6] Wang H., Chen Z. Study of critical free-area ratio during the snow-melting process on pavement using low-temperature heating fluids. *Energy Conversion and Management* 2009:50(1):157–165. <http://dx.doi.org/10.1016/j.enconman.2008.08.019>
- [7] Pan P., *et al.* A review on hydronic asphalt pavement for energy harvesting and snow melting. *Renewable and Sustainable Energy Reviews* 2015:48:624–634. <https://doi.org/10.1016/j.rser.2015.04.029>
- [8] Lund J. W., Boyd T. L. Direct utilization of geothermal energy 2015 worldwide review. *Geothermics* 2016:60:66–93. <https://doi.org/10.1016/j.geothermics.2015.11.004>
- [9] Zwarycz K. Snow Melting and Heating Systems Based on Geothermal Heat Pumps at Goleniow Airport, Poland. Reykjavik: The United Nations University, 2002:21:431–464.
- [10] Shen W., *et al.* Life cycle assessment of heated apron pavement system operations. *Transportation Research Part D: Transport and Environment* 2016:48:316–331. <https://doi.org/10.1016/j.trd.2016.08.006>
- [11] Shen W., *et al.* Sustainability Assessment of Alternative Snow-Removal Methods for Airport Apron Paved Surfaces. Atlantic City: Federal Aviation Administration, 2017.
- [12] Chi Z., *et al.* Long-term thermal analysis of an airfield-runway snow-melting system utilizing heat-pipe technology. *Energy Conversion and Management* 2019:186:473–486. <https://doi.org/10.1016/j.enconman.2019.03.008>
- [13] Zhang N., Yu X., Li T. Numerical Simulation of Geothermal Heated Bridge Deck. In Proceedings of the International Conference on Transportation Infrastructure and Materials (ICTIM 2017). Qingdao, China, 2017.
- [14] Pan P., *et al.* A review on hydronic asphalt pavement for energy harvesting and snow melting. *Renewable and Sustainable Energy Reviews* 2015:48:624–634. <https://doi.org/10.1016/j.rser.2015.04.029>
- [15] John W. L. Pavement Snow Melting. *GHC Bulletin* 2000:21(2):12–20.
- [16] Nydahl, John E. Evaluation of an Earth Heated Bridge Deck. Laramie: University of Wyoming Mechanical Engineering Dept, 1984.
- [17] Dilshad S., Kalair A., Khan N. Review of carbon dioxide (CO<sub>2</sub>) based heating and cooling technologies: Past, present, and future outlook. A review. *International Journal of Energy Research* 2019:44(3):1408–1463. <https://doi.org/10.1002/er.5024>
- [18] Jin Li., *et al.* Life cycle assessment and life cycle cost analysis of recycled solid waste materials in highway pavement: A review. *Journal of Cleaner Production* 2019:233:1182–1206. <https://doi.org/10.1016/j.jclepro.2019.06.061>
- [19] ISO 14040 & ISO 2006b. ISO 14044 Environmental Management – Life Cycle Assessment – Principles and Framework. Geneva: ISO, 2006.
- [20] Mroueh U., *et al.* Life Cycle Assessment of Road Construction. Report 17/2000. Helsinki: Finnish National Road Administration, 1999.
- [21] CEN European Committee for Standardization. EN-17472 Sustainability of Construction Works. Sustainability Assessment Civil Engineering Works, Calculation methods. 2020.
- [22] CEN European Committee for Standardization. EN-15804 Sustainability of construction works. Environmental product declarations, Core rules for the product category of construction products. 2019.
- [23] Riekstins A., Haritonovs V., Straupe V. Life cycle cost analysis and life cycle assessment for road pavement materials and reconstruction technologies. *The Baltic Journal of Road and Bridge Engineering* 2020:15(5):118–135. <https://doi.org/10.7250/bjrbe.2020-15.510>
- [24] Environmental Protection Agency. Life Cycle Assessment. Volume 1. Washington: EPA, 2001.
- [25] Winnipeg City Council. Emission factors in kg CO<sub>2</sub>-equivalent per unit. Appendix 7. Winnipeg: WCC, 2012.
- [26] K FLEX. Environmental Product Declaration (EPD) of thermal insulation products. The International EPD® System. Registration number: S-P-01947. Stockholm: EPD International AB, 2020.
- [27] Rehau: Environmental product declaration. Crosslinked Polyethylene (Pex) Pipe System. Rehau: Rehau, 2022.
- [28] Dibauco. Bill of materials for HRS in Ingolstadt. 2017.
- [29] World Steel Association. Methodology report. Life cycle inventory study for steel products. Brussels: World Steel Association, 2020.
- [30] Cao C. Sustainability and life assessment of high strength natural fibre composites in construction. *Advanced High Strength Natural Fibre Composites in Construction* 2017:529–544. <https://doi.org/10.1016/B978-0-08-100411-1.100021-2>