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Digitalisation potential analysis for sustainable waste management

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 01.06.2019

Affidavit

I, **Olivia Klemmer**, hereby declare

1. that I am the sole author of the present Master's Thesis, "Digitalisation potential analysis for sustainable waste management", 62 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and

2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The following thesis aims to assess the inherent potential that cyber-physical systems hold in creating a more sustainable management of waste. For this reason, an upscaling model is derived in which the possible ecological as well as economical changes brought about by two localized Industry 4.0 projects are upscaled onto a larger region.

Industrial Revolutions are commonly associated with developments in urban areas. Despite affecting the society as a whole, their impact on rural regions is not often subject of research. Nevertheless, innovations of both pioneer projects have been tested in rural municipalities, providing an interesting research setting, primarily as a result of its relative obscurity. This approach is maintained throughout this work. Moreover, inherent urban-rural differences pose very particular demands on waste management. Generalised deductions of outcomes obtained from rural areas might therefore be ineligible to urban sites. Ultimately, digital transformation undeniably spurs new innovations. The outcome of the Utopian Model contributes to the understanding of changes possible by the digital transformation within the waste management system.

Keywords: Waste Management, Industry 4.0, Environment, Sustainability, Upscaling

Preface

This thesis is conducted in cooperation with Saubermacher AG and the Montanuniversität Leoben.

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List of abbreviations

AWG 2002	federal law for sustainable solid waste management (Bundesgesetz über eine nachhaltige Abfallwirtschaft, Abfallwirtschaftsgesetz 2002)
CNN	Convolutional Neuronal Network
EU	European Union
GHG	Greenhouse Gases
IPPU	Industrial Processes and other Product Use
LULUCF	Land use, land-use change, and forestry
StAWG 2004	provinical law for solid waste management (Steirermärlisches Abfallwirtschaftsgesetz 2004)
WEEE	waste elecrical and electronic equipment

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This work is dedicated to my dad. You are deeply missed.

1 Introduction

"Municipal solid waste reflects the culture that produces it…"

(Vergara and Tchobanoglous, 2012)

On a global scale, the quantities discarded are rising. Moreover, waste separation has become increasingly difficult, as products such as plastic and electronic items are gaining in complexity. However, as previously cited, different cultures claim different waste management solutions as the waste produced greatly differs. In industrialized nations, waste management tends to be highly regulated. Still, key challenges such as reducing consumption to prevent waste production and increasing recycling rates for resource protection must be overcome, especially due to the fact that their citizens produce more waste than in non-industrial countries.[1] Emerging technologies might provide a tool to do so.

The intention of this master thesis is to investigate the potential of Industry 4.0 to drive economic as well as ecologic changes within the waste management sector. In order to find a scientifically based answer a model is developed which upscales the outcome of two digitalisation projects.

The nexus of economy, environmental policy, scientific research as well as the experience of different stakeholders of the Route Optimisation project as well as the Smart Waste project demanded a flexible setting of the thesis.

The intention of chapter 2 is to provide general information on waste management. Additionally, as requirements on waste management are diverse, waste management is examined from different perspectives, thus acknowleding its global importance, illustrating its implementation into Austria's national law, and its role to meet environmental targets such as the protection of resources and reduction of greenhouse gas emissions.

As the title "Industry 4.0" indicates, an overview of the digital transition and its antecedents are given in chapter 3. Within the first sections of this chapter, latest literature is reviewed and a special focus is placed on the technological potential of the digital transition for the waste management sector. The second half of this chapter greatly contributes to the understanding of the later mathematical model, as the two

[1] Vergara and Tchobanoglous, 'Municipal Solid Waste and the Environment'.

digitalisation projects Route Optimisation and Smart Waste are introduced. Furthermore, simplifying assumptions of the model are explained. Information was provided by different stakeholders from the industry, such as Saubermacher AG, a waste management company and Adenso, an environmental consulting firm, as well as the sustainability coordinator of Styria. In order to review the municipal perspective an interview with experts in this field was conducted.

Based on the insight gained, the Utopian Model was developed. Chapter 4 describes, among others, the model design. The outcome of both digitalisation projects is upscaled for the rural municipalities of Styria. In order to assess the economical and ecological potential in terms of financial relief and emission reduction, comparisons to Styria's status quo are undertaken when possible.

A summary of the findings is presented in chapter 5. Based on the Utopian Model outcome the potential of this digitalisation innovation to foster economic as well as environmental changes is assessed.

This thesis concludes with the chaper 6 in which the potential for further research is highlighted. Moreover, policy and other recommendations are given in this chapter.

2 Waste Management

2.1 Waste Management: globally recognized

"Sustainability is development that satisfies the needs of the present without compromising the capacity of future generations, guaranteeing the balance between economic growth, care for the environment and social well-being. "

(World Commission on Environment and Development, 1987)

With increasing amounts of waste being generated, greater and greater strain is put on the environment's finite capacity. The following shall provide an insight into the development of waste management and its efforts to support a sustainable society as understood by the Brundtland report that was quoted in the beginning.[2]

If waste is interpretated as in Article 3 of the EU Waste Framework Directive as "any substance or object which the holder discards or intends or is required to discard", then waste generation is as old as humanity itself.[3] Undeniably, our first ancestors produced waste when a spear was damaged or a clay jug was broken. First recorded landfills were to be found in Ancient Greece, where in the Cretan capital of Knossos garbage was buried in large pits as early as 3000 BC.[4] Over the course of history, the diversity and quantity of waste, its persistence and subsequent impacts on environment and public health if not properly managed, and waste management itself have changed drasitcally. Waste Management, as defined by the Environmental Glossary of the United Nations are "characteristic activities [that] include (a) collection, transport, treatment and disposal of waste, (b) control, monitoring and regulation of the production, collection, transport, treatment and disposal of waste and (c) prevention of waste production through in-process modifications, reuse and recycling".[5] In short, waste management starts with the creation of waste and ends with its final disposal, with all activities and actions having regard to the reduction of adverse effects of waste.[6]

But even today, no archetype of an ideal waste management system with global applicability can be established, as different lifestyles demand different systems. Waste managing in developing countries has to meet different requirements than in developed ones. Generation of waste is usually stimulated by the two main factors of gross domestic

[2] World Commission on Environment and Development, *Our Common Future.*
[3] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance).
[4] Bouazza and Kavazanjian Jr., 'Construction on Former Landfills'.
[5] 'Glossary of Environment Statistics'.
[6] Laurent et al., 'Review of LCA Studies of Solid Waste Management Systems – Part II'.

product growth and population growth. A trend subsequently linking higher income with increased generation of waste per capita can thus be observed (see Figure 1). The World Bank found that a share of 34 percent of the global waste is generated by rich countries (accounting for 16% of the world's poputlation), whereas low-income nations accounting for 9 percent of the world's population only generate 5 percent of global waste.[7]

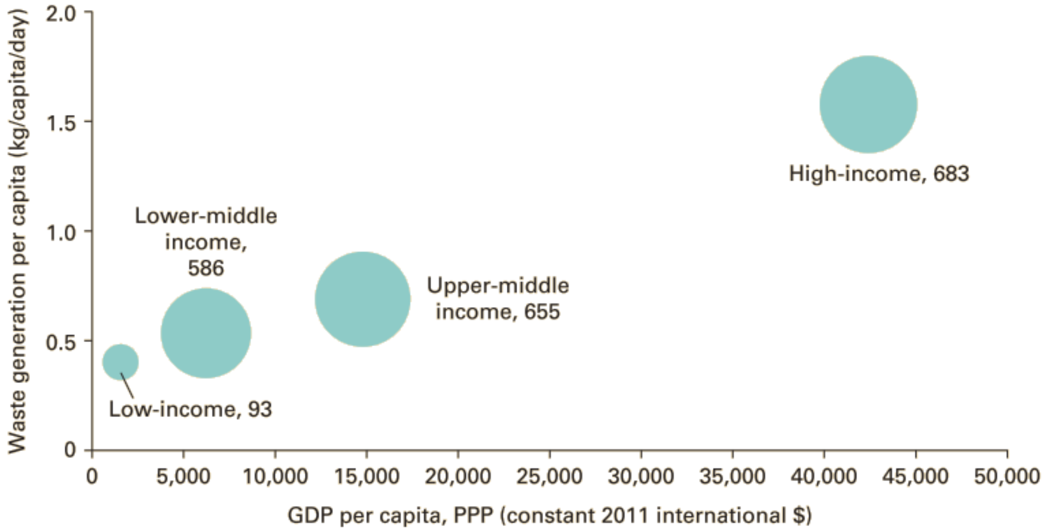


Figure 1: Waste generation by income group shows a positive dependence on the level of income. The circle diameter is proportional to the annual waste generation measured in million tons.[8]

Moreover, the waste composition greatly differs, as waste generated in developed countries is dominated by packing material, whereas the organic waste component makes up to 50% of municipal solid waste in low-income countries.[9] Therefore, instead of urging for an archetype of an ideal waste management system of global validity, the establishment of general guidelines with the possibility for optimal adaptation on national levels seems to be the more promising path.

The international community follows this apporach and recognizes the importance of integrated waste management. With an increasing sensibility towards environmental issues, the waste management sector is supposed to decrease its impacts and alter its perception of waste as a source of pollution to that of waste as a viable resource.[10,11]

Several parts of the Sustainable Development Goals, a global action plan which has been adopted by more than 150 nations, are dedicated to this issue. SDG 12, for example, urges to "make cities and human settlements inclusive, safe, resilient and

[7] Kaua et al., *What A Waste 2.0, A Global Snapshot of Solid Waste Management to 2050*.
[8] Kaua et al.
[9] Khatib, 'Municipal Solid Waste Management in Developing Countries'.
[10] Hoornweg and Bhada-Tata, 'What a Waste, A Global Review of Solid Waste Management'.
[11] Graedel et al., 'Recycling Rates of Metals, A Status Report of the Working Group on the Global Metal Flows to the International Resource Panel.'

sustainable deal with waste managements".[12,13] Furthermore, waste management is dealt with in SDG 11.6 which describes sustainable consumption and production patterns.

Further actions taken on a supranational scale include the adoption of legislation to steer the "waste development" into a sustainable direction. Several directives and regulations, comprising general frameworks and regulating waste management operations and specific waste streams, govern the European waste management. An overview of the legislative instruments which protect the environment and human health and manage the waste streams in Europe is given in Figure 2. The following explains several relevant regulations for the general understanding of waste management in Austria.

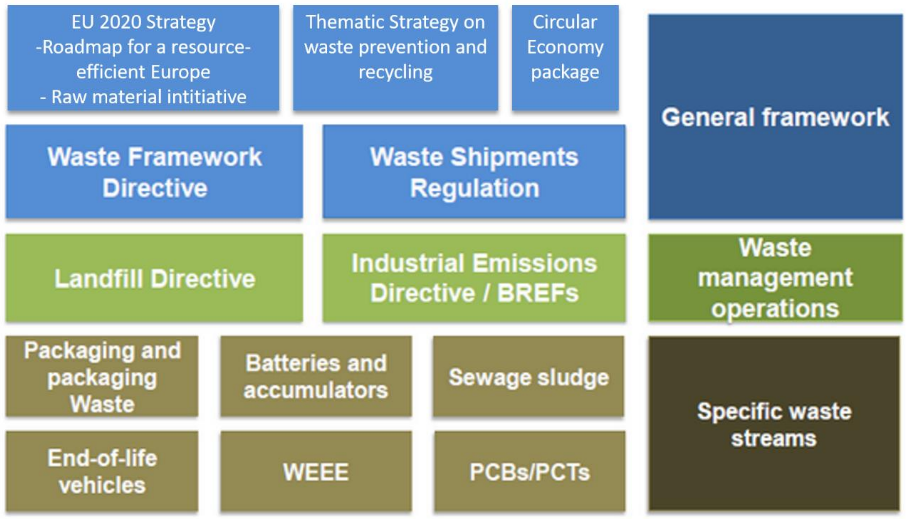
The 7th Environment Action Programme, also called EU 2020 Strategy, forms an environmental guideline for Europe until 2020 and beyond. Therefore, the Europen Comission identifies three main goals: "to protect, conserve and enhance the Union's natural capital, to turn the Union into a resource-efficient, green, and competitive low-carbon economy" and "to safeguard the Union's citizens from environment-related pressures and risks to health and wellbeing".[14]

Additionaly, the European Waste Framework Directive (Directive 2008/98/EC on waste) lays down the Europen Union's waste management definitions and goals. Its principles illustrate how waste should be treated within the EU and form the basis for the Waste Hierarchy, which sets priority objectives for waste policy as depicted in Figure 1. The prevention of waste forms the best environmental option for waste management, followed by the preparation for re-use. A mundane, albeit highly relevant example would be the diligent handling of food. The daily quantity of bread consumed in Austria's second largest city, Graz, equals the daily amount of bread thrown away in the Austrian capital, Vienna. Furhtermore, approximately 15% of food that is disposed of in Vienna, would be edible.[15] These numbers clearly demonstrate the paramount importance that reevaluating business models, goods and packaging bears in enhancing producer responsibility and changing consumer behaviour in order to mitigate waste creation. Simple measures, such as reparing a product instead of replacing it by a new one, would increase the product's lifespan and therefore minimise waste. Preparing for re-use is thus prioritized over recycling, in which material or energy is recovered form the discarded product in order to protect natural resources. Seperately collected waste

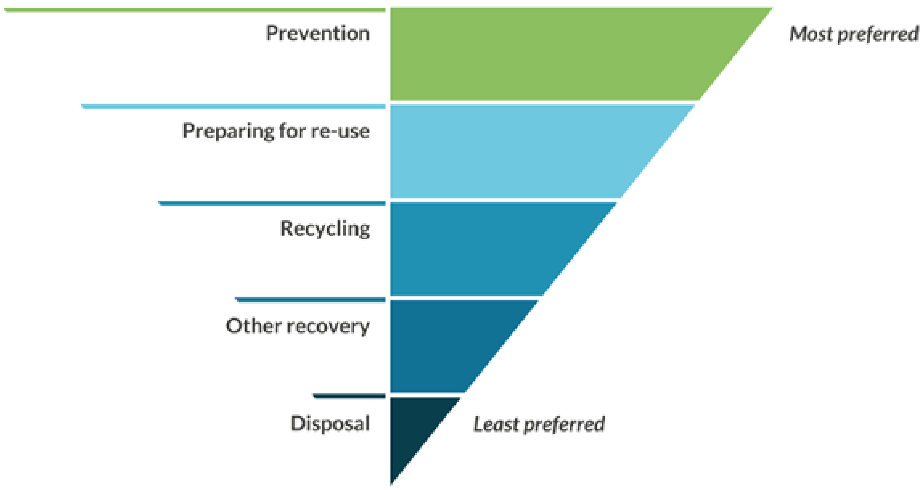
[12] 'World Leaders Adopt Sustainable Development Goals'.
[13] United Nations, Transforming our world, the 2030 Agenda for Sustainable Development, Sustainable Development Knowledge Platform.
[14] European Comission, *General Union Environment Action Programme to 2020, Living Well, within the Limits of Our Planet*.
[15] 'Gegen Achtlosigkeit und Unmäßigkeit'.

streams form a prerequisite for the high-quality recycling. Any operation other than recovery is regarded as waste disposal, including landfill. [16]

The European Circular Economy Package and the implementation of the Landfill Directive into the Austrian legislature and their effects on the environment are discussed in section 2.3.



(A)



(B)

Figure 2: Overview of the waste management legislative framework of the European Union (A) and their underlying principle of Waste Hierarchy (B). (A) Several policy tools cover different aspects of waste management in Europe.[17] (B) Within EU legislation the prevention of waste is the most preferred option. Preparing for re-use extends the lifetime of a product. Only if this is not possible, the object is regarded as waste. Waste should be recycled or energy recovered in an Waste to Energy Plant for example in order to protect resources. The least preferred option includes the final disposal to landslides.[18]

[16] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance).
[17] Table was adopted by author based on 'Legislation, FEAD'. and Fellner, 'Waste Management'.
[18] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance).

2.2 Waste Management: locally implemented

The “Abfallwirtschaftsgesetz”, the federal law for sustainable solid waste management (AWG 2002), provides the major legal basis for waste management in Austria. The AWG 2002 mainly governs the prevention, preparation for reuse, recycling, disposal and other use of waste, responisbilities of people working in waste management sector and legal requirements for waste treatment plants.

Being a member of the European Union, Austria’s legal framework is extended by supranational legislations such as regulations, which have to be implemented directly, and directives of the EU which have to be transposed into national law (see Figure 2 (A)).[19] Every six years, a Federal Waste Management Plan is established by the Federal Minister for Agriculture, Forestry, Environment and Water Management. The latter publication aims to contribute to achieving the targets set by the AWG 2002.[20] The waste strategy objectives, as established by the AWG 2002, are based on the precautionary and the sustainability principles, and include the protection of human beings, animals and plants, minimization of GHG emissions, conservation of resources through reduced consumption of primary raw material, energy, landscape and area and through the reduction of landfill volume for example, the risk potential of substances from recycling stating that it should not exceed that one of primary substances and products, and that the disposal of waste shall not pose a risk for future generations.[21]

Administrative organisation and responsibilites of waste management are divided into national, federal and municipal law. The financial apsects of waste collection and disposal, such as organising and defining waste collection and disposal fees, as well as the physical organisation of waste collection are not regulated on a national level. However, the collection of municipal solid waste, which is commonly organised on a municipial level, is administered by the respective provincial law.[22]

As this work focuses on a subfraction of municipal solid waste, namely residual waste, a general definition in accordance with Austrian waste legislature shall be provided.

Paragraph 4 of the “Steiermärkisches Abfallwirtschaftsgesetz 2004”, the provincal law for waste management (StAWG 2014), classifies municipal solid waste into the following five segments, with residual waste or mixed solid waste being defined through the principle of exclusion at last:

[19] ‘Allgemeines Zur Abfallwirtschaft’.
[20] Bundesministerium Nachhaltigkeit und Tourismus, ‘Bundes-Abfallwirtschaftsplan 2017, Teil 1’.
[21] Bundesgesetz über eine nachhaltige Abfallwirtschaft (Abfallwirtschaftsgesetz 2002 – AWG 2002).
[22] ‘Allgemeines Zur Abfallwirtschaft’.

1. Recycling materials, seperate collection: waste materials such as textiles, paper, metal, glass except packaging
2. Biodegradable waste, separate collection: kitchen waste, garden waste, market waste, or waste from cemetery
3. Bulky waste
4. Municipal solid waste arising from public streets, parking spaces and parks
5. Mixed solid waste: Residual waste: non-hazardous fraction which cannot be assigned to waste 1. to 4.[23]

Hence, residual waste is indirectly defined by not being allocable to other municipal solid waste categories. In other words, residual waste is related to waste left from household sources containing materials that have not been separated out or treated differently.

The provincial government of Styria provides some tangible guidance on what should be dispatched as residual waste, and what must not be disposed of in the residual waste bin. Residual waste includes diapers, sanitary towels, light bulbs, mirror and crystal glass, perfume bottles made from glass, kitty litter, hygiene products, rubber, vacuum bag, ash, toys, leather, household items, flowerpots, etc. On the other hand, problematic and hazardous materials, building rubble, construction timber, bulky waste, old electrical equipment, used cooking oil, bitumen, thermometers etc. are not constituent elements of residual waste.[24]

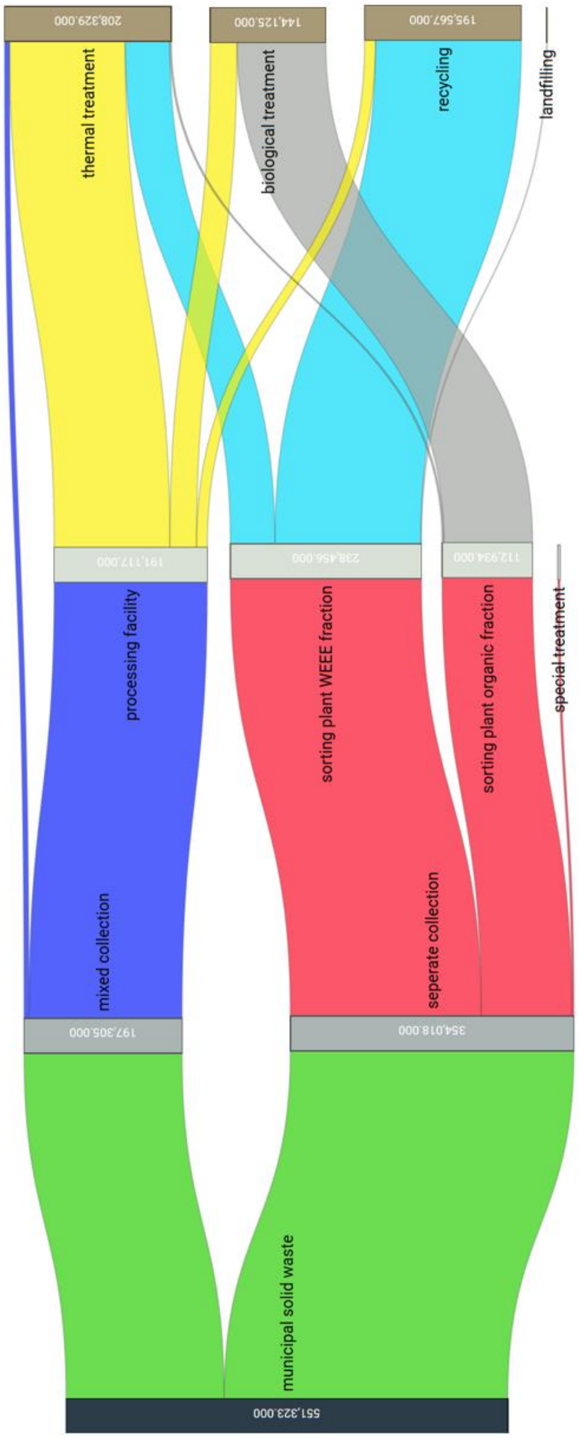
Despite having a "well-established" waste management system, Austria produced with 570 kg residual waste per capita in 2016 approximately 80 kg more than the EU-28 average.[25]

In Styria, around 28% of municipal waste is disposed as residual waste, accounting for a residual waste generation of approximately 155 800 t.[26] In order to provide an up-to-date picture of municipal waste generation and its treatment in Styria, a Sankey diagram was established based on the numbers published in the status report for 2019 by the Federal Minestry of Sustainability and Tourism.[27] The underlying numbers as well as the mass flow diagram are depicted in Figure 3. Each Styrian inhabitant produces more than 120 kg residual waste per year, around 2/3 of which are incorrectly disposed.[28,29] The incorrectly disposed waste accounts for up to 40% of recycable material and 35% of

[23] Steiermärkisches Abfallwirtschaftsgesetz 2004, Landesrecht konsolidiert Steiermark.
[24] Land Steiermark, 'Restmüll'.
[25] Data available only for 2016 'Municipal Waste Statistics, Statistics Explained'.
[26] 'Restmüll - gemischte Siedlungsabfälle'.
[27] Bundesministerium Nachhaltigkeit und Tourismus, 'Statusbericht 2019'.
[28] Land Steiermark, 'Restmüll'.
[29] ARGE Ingenieurgemeinschaft Innovative Umwelttechnik GmbH and Saubermacher Dienstleistungs AG, 'Sortieranalyse Für Restmüll Aus Der Steiermark 2013'.

organic material of total residual waste.[30] Despite high recycling rates already being achieved, this erroneous disposal causes significant financial and environmental burdens, as recyclable material is lost and the efficacy of post-treatment is substantially undermined. Annual economic damage due to incorrect disposal is well over 10 Million Euros in Styria.[31] These numbers clearly demonstrate that there is still room for improvement.

[30] Opelt, 'Sind Wir Smart Genug?'
[31] Land Steiermark, 'Restmüll'.



	biological treatment		recycling of waste material		treatment of hazardous materials + batteries	thermal treatment of processed fractions				biological treatment	landfilling	total [t]
	organic waste from seperate collection	organic waste from mixed collection	waste material + WEE from seperate collection	sorted waste material of processed fraction from mixed collection	hazardous materials from seperated collection	municipal solid waste + bulky waste, directly transferred	high calorific value waste of processed fraction from mixed municipal waste + bulky waste	waste material +WEEE from seperated collection	organci waste from seperate collection	low calorific value waste from mixed collection of municipal solid waste + bulky waste	WEEE of processed fraction from seperate collection + sorting residues	
Styria	66,710	44,161	182,189	13,378	2,628	6,188	144,485	55,593	2,063	33,254	674	551,323
mass [t]	110,871		195,567		2,628	208,329				33,254		
mass [%]	20.11%		35.47%		0.48%	37.79%				6.03%		
Austria	509,979	476,552	1,226,906	24,920	18,365	1,175,222	293,916	374,378	15,772	201,414	4,540	4,321,964
mass [t]	986,531		1,251,826		18,365	1,859,288				201,414	4,540	
mass [%]	22.80%		29.00%		0.40%	43.00%				4.70%	0.10%	100%

Figure 3: Treatment and disposal of municipal solid waste in 2017. The sankey-diagramm illustrates Styria's waste generation in tons and the subsequent waste treatment in sorting or processing plants. The table below lists the underlying database for the diagram based on numbers published by the Federal Minestry of Sustainability and Tourism in the status report for 2019.[32] The mass flow of landfilling is not representative, as also inert waste from thermal and biological treatment plants contribute to this fraction[33]. The table allows a comparison of different waste fractions generated by Austria and its federal province Styria.

[32] Bundesministerium Nachhaltigkeit und Tourismus, 'Statusbericht 2019'.

[33] The contributions of inert waste resulting from thermal and biological treatment towards the landfilling fraction are not shown as no data was publicly available for Styria.

2.3 Waste management: an environmental context

Waste management has changed drastically over the course of time, shifting from landfilling of untreated waste to a more environmental friendly approach. The ternary diagram of Figure 4 illustrates the development of Austria's waste sector during the last decades. Despite high prevalent standards in Austria, more stringent policies are necessary in order to develop a sustainable way of living for current as well as future generations.

The Circular Economy Package, for example, stipulates a transition from a linear to circular economy and is praised as "the first serious attempt to align products and waste related policies at the EU level". This agreement requires an increase of recycling rates to 60% for 2025 and additional 5% for 2030. A glance at the ternary diagram demonstrates that Austria has to amend its waste business model to meet such targets. Many are convinced that, despite exacerbating challenges such as the paradigmatic changes within labour markets and data security, the burgeoning digital transformation has the potential to boost eco-intelligent solutions.[34,35,36,37]

This work examines among others the potential of digital disruptions in driving waste management towards an even "greener" way. For this reason, the following subsections are dedicated to a short insight into waste and its effect on the environmnet.

2.3.1 Protection of resources

The EU Waste Framework Directive sets clear targets which have to be reached by the EU member states by 2020: 50 % of municipal waste from households and other origins similar to households are to be prepared for reuse and recycling. A higher target of 70% for preparation for re-use, recycling and other recovery is set for construction and demolition waste. The Waste Hierarchy is one of the main elements of the Waste Framework Directive, and prioritizes, as illustrated in Figure 2 (B), the prevention of waste over preparing for reuse, preparing for reuse over recycling, and recycling over disposal. Consequently, landfilling constitutes the least preferred measure. Waste management in accordance to this directive therefore entails the protection of primary resources and is accompanied by higher recycling rates.[38]

However, data shows that Member States' recycling rates differ greatly. Whereas some countries have already achieved high recycling rates or show a strong improvement,

[34] 'Österreich Auf Dem Weg in Die Kreislaufwirtschaft, Chancen, Herausforderungen, Strategien, AkteurInnen'.
[35] 'Digitale Abfallwirtschaft: Mehrwert Entlang Der Gesamten Wertschöpfungskette'.
[36] Büchele and Andrä, 'Die Digitalisierung in der GreenTech-Branche'.
[37] UNIDO, 'Accelerating Clean Energy through Industry 4.0'.
[38] 'Recycling of Municipal Waste, European Environment Agency'.

others may not reach the Waste Framework Directive target. Over the period from 2004 to 2016 Germany, Austria, Belgium, Switzerland, the Netherlands and Slovenia recycled a minimum of 50% of their municipal waste.. Another very positive example was provided by the Member State Lithuania, which demonstrated the strongest improvement by increasing its recycling rate by 46% during the examined time period. On the other hand, no significant development in the already low municipal waste recycling rates was achieved in some other countries, such as, Estonia, Malta, and the accession canditates to the EU, Bosnia and Herzogovina, and Serbia.[39] An overview over the municipal waste treatment in the EU-28 Member states is provided in Figure 4.

In 2015, the European Union agreed on the adoption of new and even more ambitious targets that shall foster the transition from a linear to a circular economy. The Circular Economy Package, published by the European Comission under the title “Closing the loop – An EU action plan for the circular economy”, requires the recyling and preparation for reuse of 55% of municipal waste by 2025.[40] The rate shall be increased step by step, to a minimum of 60% by 2030 and 65% by 2035.[41]

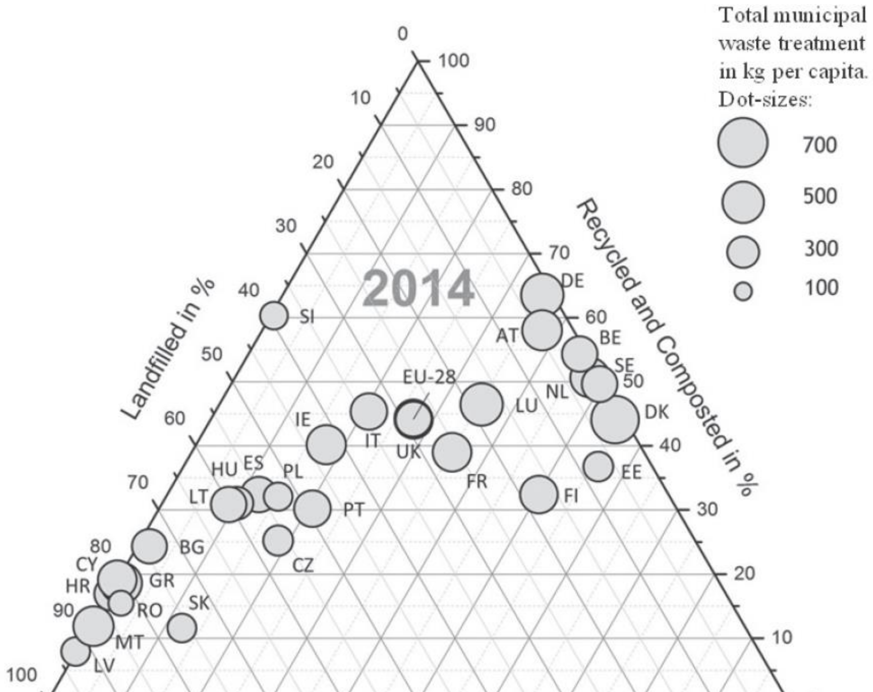


Figure 4: The treatment of municipal waste among EU-20 member states varies greatly. Austria ranks among the “top-performers” with already high recycling rates.[42]

[39] ‘Recycling of Municipal Waste, European Environment Agency’.
[40] Closing the loop, An EU action plan for the Circular Economy.
[41] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance).
[42] Pomberger, Sarc, and Lorber, ‘Dynamische Darstellung Der Leistungsfähigkeit Der Siedlungsabfallwirtschaft in Der EU Mittels Der Ternärdiagrammmethode’.

Pre-treatment plants are gaining more ground and extract further reycables from mixed municipal waste. However, the quality of the recycables are generally lower in comparison to seperately collected material and the risk of injecting contamination via the path of recyclables into the material and environmental cycle is higher.[43] For this and other reasons, separate collection by citizens is identified as a prerequisite for circular economy, as cleaner, seperated fractions of municipal waste clearly facilitates recycling.[44]

2.3.2 Sinks as limited resources

The anthropogenic metabolism as depicted in Figure 5 is embedded within the environmental sphere: natural resources are harvested and the obtained material is processed into consumer and investment goods. However, sooner or later all material will reenter the environmental system. An adequate sink protects humans and the environment and is in line with the waste targets described in section 2.1.

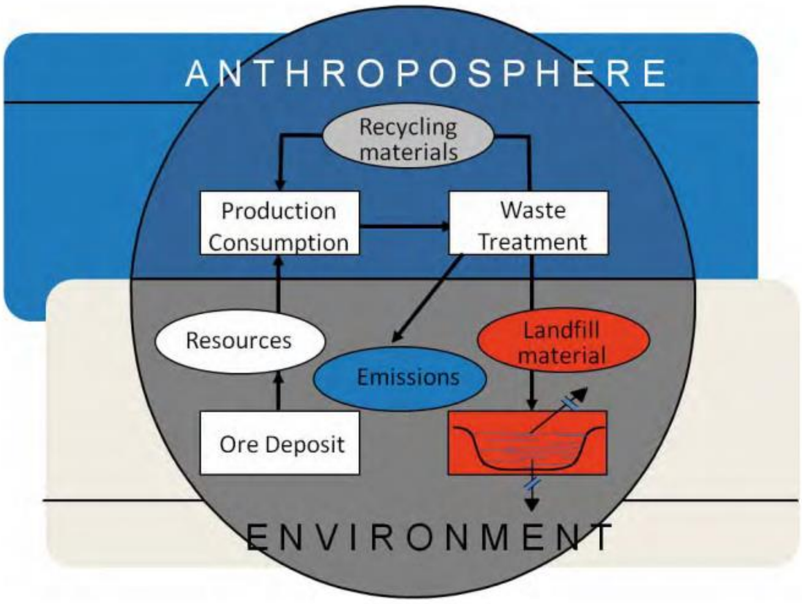


Figure 5: The anthropogenic metabolism results in a material and energy turnover by human society.Natural resources are being exploited and processed into consumer and investment goods to satisfy human needs. For this reason man-made material flows from the environmental to the anthoprogenic sphere have been created. The products enter the economic cycle where they are either consumed or stored. At the end of their life cycle, material is discarded and either recycled or disposed in sinks. A backwards directing flow of recycled material helps to protect resources. However, this only forms an intermediate backflow, as recycled material will finally also end up as waste. Discarded after use, material is burned and its residues are stored in landfills. Energy in form of electricity and heat can be collected during the waste treatment process and redirected to households and industries.In this Waste to Energy process, waste substitutes primary fuels.[45]

[43] 'Recycling of Municipal Waste, European Environment Agency'.
[44] Wielenga, 'Separate Waste Collection in the Context of a Circular Economy in Europe'.
[45] Fellner, 'Waste Management'.

One main final sink which plays an increasingly important role for waste management shall be briefly discussed in this subsection: the atmosphere. A quote from Schnoor (2013) in which the Professor for Civil and Environmental Engineering of the University of Iowa highlights the constraining storage capacity of this sink, intends to give food for thought, “I do not worry about peak oil whatsoever. We have plenty of oil, gas, and coal to last for hundreds of years, and we are not running out. But we are running out of room in the atmosphere to store our exhaust.” Therefore, a holistic approach for waste management also includes the question of final sinks and their storage.

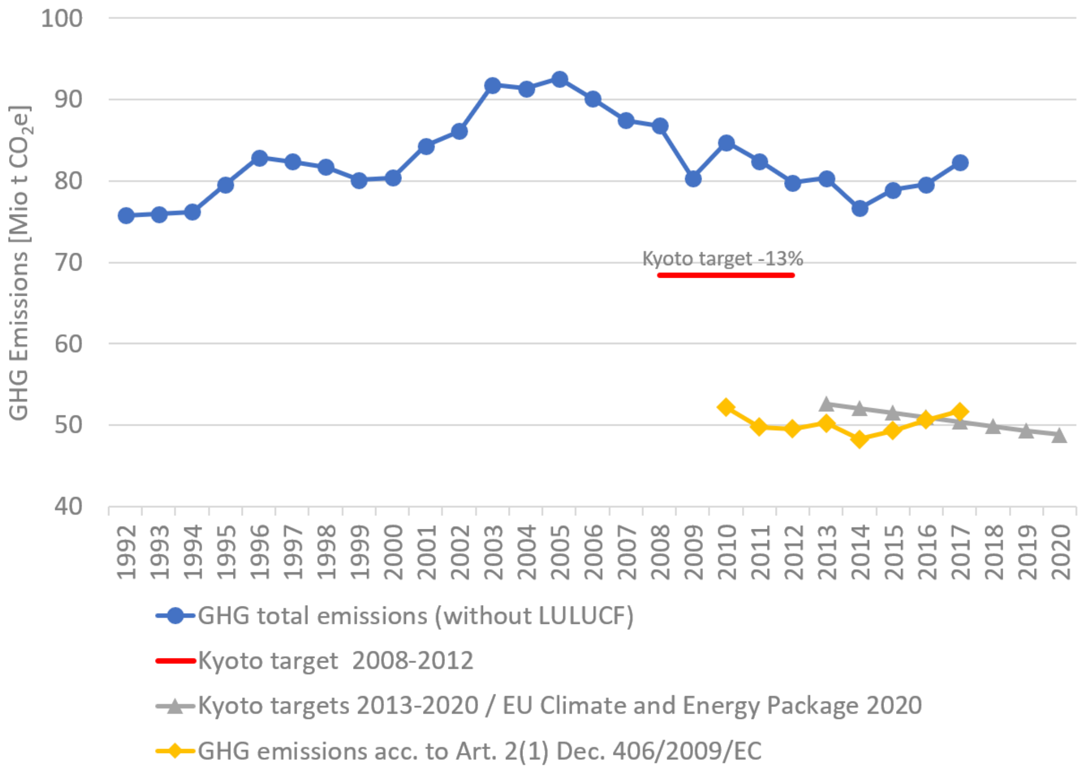


Figure 7: Greenhouse Gas emissions in Austria and diverse target requirements. Austria’s total emissions rose to 82.3 million tonnes of CO_2 equivalent in 2017. According to the Environment Agency Austria this increase was partly due to economic growth as well as an upsurge of emissions from the traffic, industry and energy production and the building sectors. For the first year, emissions in 2017 exceeded the national limit set by the EU Climate and Energy Package 2020. Eventhough credits are still at disposal, it is unsure whether the climate goals 2020 can be achieved. Moreover, the Environment Agency Austria urges for the implementation of comprehensive actions to reduce the use of fossil fuels, otherwise Austria is at risk to fail the energy and climate targets 2030.[46]

Austria signed the Kyoto Protocol in 1997 and thereby committed to reduce greenhouse gas emissions to combat climate change. Besides legally binding constraints, Member States can make use of the so-called ‘flexible mechanisms’ consisting of Emission

[46] Figure 7 created by author based on data retrieved from Anderl et al., ‘Austria’s National Inventory Report 2019, Submission under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol’., Änderungen des Protokolls von Kyoto zum Rahmenübereinkommen der Vereinten Nationen über Klimaänderungen, die in Doha beschlossen wurden., and Umweltausschuss, ‘Fortschrittsbericht 2017 Nach § 6 Klimaschutzgesetz’.

Trading, Joint Implementation and the Clean Development Mechanism to meet their obligations and to cut the costs of curbing emissions. Due to the EU burden-sharing system, Austria pledged to reduce the emissions of the 6 GHGs to minus 13% based on the 1990-level within the first commitment period of the Kyoto Protocol which comprised the years from 2008 to 2012. In order to converge with the Kyoto target, Austria had to buy emission certificates from abroad.[47] The Doha Amendment, which has yet to be ratified, forms the extention of the Kyoto Protocol until 2020.

Austria, which is among those countries that have already deposited their instrument of acceptance, is also required to meet the EU Climate and Energy package 2020 targets. Regardless of whether the Doha Amendment will enter into force or not, the fixed goal set by the European Union of minus 16% related to 2005 has to be met till 2020.[48] The EU Climate and Energy package 2030 constrains emissions to minus 40% till 2030 based on 1990.[49,50]

As party to the Kyoto Protocol, Austria is requested to regularly submit national GHG inventories.[51] Figure 6 illustrates the total GHG emissions (without land use, land-use change and forestry, (LULUCF)), numbers retrieved from this report among others. Although emissions decreased in 2005 and the following years, an increase in GHG emissions had to be recorded from 2014 till 2017. This corresponds to additional emissions in the range of 5.6 Million tons compared to the previously recorded low of 2014. A comparison to the targets set by the Kyoto Protocol or the EU Climate and Energy Package 2020 with Austria's actual total GHG emissions clearly indicates that a substantial improvement is required if targets are to be met. The change in emissions originates from developments in certain sectors, some of which evince an amelioration in while others face deterioration of their emission levels. A deeper insight is offered by Figure 7 which shows the GHG emissions by sectors as published in Austria's latest inventory report of the year 2019. Whereas emissions from energy and industry sector increased from 2014 onwards, the developments of the waste sector, amounting to 1,484 kt CO_2e in 2017, indicate a positive climate-relevant emission trend for the category 'waste'. Policy measures, like the Landfill Ordinance seem to take effect.[52]

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47 Niedertscheider, Haas, and Görg, 'Austrian Climate Policies and GHG-Emissions since 1990'.
48 The EU Climate and Energy Package 2020 is in line with the Doha Ammendment.
49 'Das Übereinkommen von Paris'.
50 '20-20-20 Ziele'.
51 'Reporting Requirements, UNFCCC'.
52 Anderl et al., 'Austria's National Inventory Report 2019, Submission under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol'.

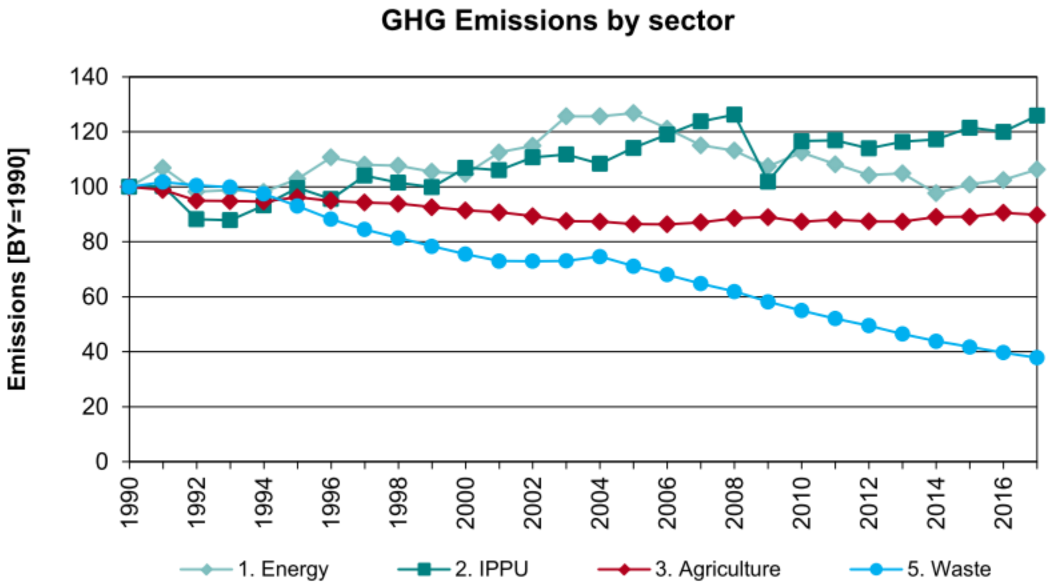

Figure 8: Emissions from Industrial Processes and Other Product Use (IPPU) along with the energy sector emissions are the main sources of GHGs in Austria. Emissions form the IPPU sector increased by 26% from 1990 to 2017 due to developments in the metal and mineral industry. Fuel combustion activities in road traffic contributes to the emissions from the energy sector. The increase in GHGs of this sector by 6.3% during the same period can mainly be attributed to the rise in CO2 emissions originating from traffic. The agriculture sector shows a decrease of 10% in GHG emissions. This positive trend is driven by decreasing stock numbers of cattle and a decrease in the usage of Nitrogen containing fertilizers. GHGs emissions originating form the waste sector could be reduced by 62% form 1990 to 2017, contributing only 1.8% of total national emissions in 2017. Drivers of this positive trend are the implementation of certain waste management policies, such as the Landfill Ordinance in 1996 to name one. Improved waste seperation, higher reuse and recycling rates resulting in a decrease of disposed waste, along with landfill gas recovery led to a reduction of the emission of GHGs.[53]

In accordance to the Europen Union's Waste Hierarchy, landfilling is the least preferable option as it imposes great negative enivronmental impacts. The Landfill Ordinance of 1996 brought about a rebound for Austria's waste sector emissions. Waste management companies had to search for other alternatives, as the transition time for total compliance expired in 2004. From then onwards, certain categories, such as untreated waste (with more than 5 mass-% of organic carbon) were not allowed to be disposed of in landfills anymore. [54,55] The positive trend mainly results from a strong decrease of methane as seen in Figure 8, with this GHG amounting to roughly 82% of all emissions from the waste sector.

[53] Anderl et al.
[54] Ban regulated by Landfill Ordinacne 1996.
[55] Pomberger, Curtis, and Scherübl, 'Klimarelevanz Der Abfallwirtschaft Aus Sicht Eines Sammlers'.

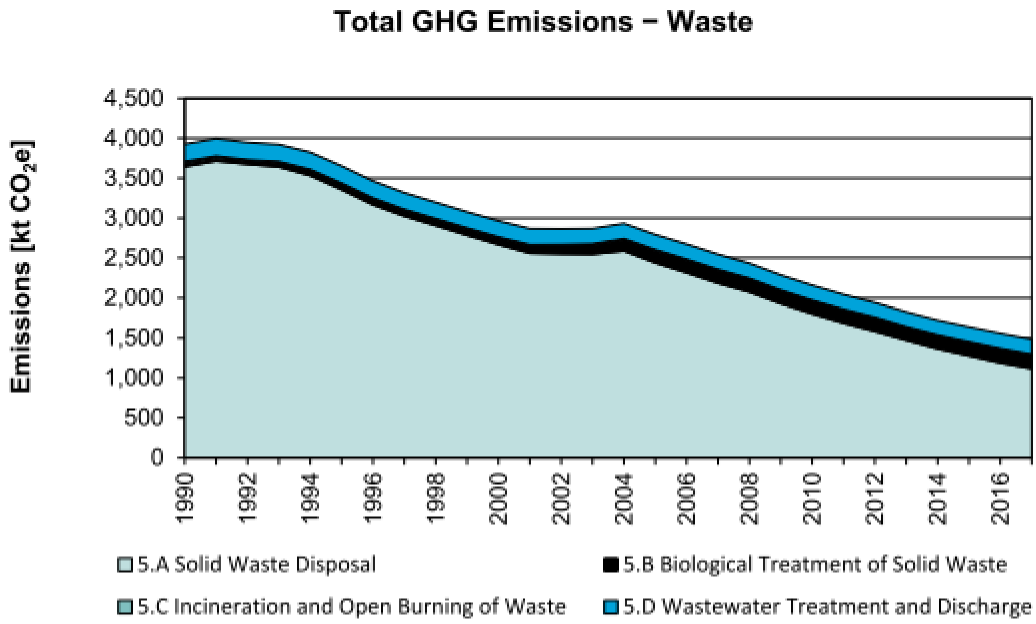

Figure 9: GHG emissions from waste management and treatment activities which are source of methane CH_4, cabron dioxide CO_2 and nitrous oxide N_2O emissions.[56]

The reduction of methane emissions from landfills by approximately 68% during the examined period from 1990 to 2017 was achieved due to several developments: an overall decrease in the amount of landfilled waste, along with a reduction of the organic fraction resulting in less generation of methane, as well as more methane recovery systems prohibiting methane being released into the atmosphere.[57] In addition to the Landfill Ordinance's positive effects on GHGs, the reduction of landfilling also stimulated an increase in recycling rates.[58]

Waste management companies are increasingly looking for a climate friendly way of how to provide their services. Nevertheless, measures undertaken are often not credited to the waste sector. Route optimisation resulting in reduced fuel consumption leads is accounted as road traffic and credited to the energy sector for example. Similarly, the usage of waste as a substitute fuel is allocated as credits to the IPPU sector. Additionally, Pomberger et al. (2008) demonstrated that recycling of materials also leads to an often overlooked positive contribution towards energy saving. They assume a GHG saving for Austria similar to Germany, meaning that the recycling of residual waste allows a reduction of GHG emissions of up to 47% in comparison to a primary production of the same materials.

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[56] Anderl et al., 'Austria's National Inventory Report 2019, Submission under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol'.
[57] Anderl et al.
[58] Wielenga, 'Separate Waste Collection in the Context of a Circular Economy in Europe'.

The steel industry is one of Austria's most important exporteurs, accounting for over €2.8 billion of the foreign trade surplus in 2017.[59] As previously mentioned, overall emissions form the IPPU sector increased by 26% from 1990 to 2017 and amounts for 21% of total national emissions. This development is largely driven by an increase in metal production. The substitution of pig iron with recycled iron would lead to an enormous GHG saving: one ton recycled scrap steel saves 1.5 t ore and 0.5 t fuel like coal or oil which would have been needed to fuel the furnance. In total, one ton of recycled iron saves 2.400 kg CO_2e when subsituted for a primary material.[60]
However, as pointed out by Pomberger et al. (2008), recycling rates have already been high in both countries for a long time, therefore it would be erroneous to assume extensive future improvements.[61]

59 Wolf, 'Branchenbericht, Metallsektor Mit Detailberichten: Stahlindustrie, Metallverarbeitung'.
60 Broadbent, 'Steel's Recyclability: Demonstrating the Benefits of Recycling Steel to Achieve a Circular Economy'.
61 Pomberger, Curtis, and Scherübl, 'Klimarelevanz Der Abfallwirtschaft Aus Sicht Eines Sammlers'.

3 Industry 4.0

3.1 Industry 4.0: a general context

Ever since the beginning of industrialisation, technological progress has engendered profound effects in all areas of life. Historically, three major technological revolutions have led to dramatic shifts in economic, social and political paradigms. As already indicated by the name, Industry 4.0 represents the fourth ongoing wave of technological advancement, the Fourth Industrial Revolution.

The First Industrial Revolution, which originated in Great Britain around 1750 and subsequently spread across the rest of the world, was characterised by the introduction of mechanization and marked a major turning point in history. People moved to cities to work in big water and steam powered manufacturing facilities. This transformation was therefore marked by a movement of labour away from the production of primary products to manufacturing goods and services. A newly divided society categorized people into two new classes, namely factory owners and factory workers.[62] Improved transport systems made it easier to provide food and clothing to the people. Along with higher productivity due to innovations in machine technology, industrialisation helped curb hunger. [63] However, a negative corrolary development was the dubious reputation for its exploitation of the working class, as well as child labour.[64]

What iron and coal represented during the First Industrial Revolution, was echoed by electricity, steel and the rise of the chemical industry during the second industrial transformation.[65] At the end of the 19th century, the widespread and intensive use of electricity and other new technologies triggered division of labour, mass production based on assembly line running on electricity and facilitated mass transportation.[66]

Further automatization brought about by a transition from mechanical and analogue to digital systems characterised the Third Industrial Revolution during the second half of the 20th century. Important innovations in the IT sector, such as Modicon 084, the first programmable logic controller[67] or increasingly powerful microprocessors, as well as in the transmission technology and later on the Internet marked the Digital Revolution.

The Fourth Industrial Revolution is expected to be similarily promising to fundamentally alter our current system. The term "Industry 4.0" became known during the Hannover

[62] Deane, *The First Industrial Revolution*.
[63] Bauernhansl, 'Die Vierte Industrielle Revolution, Der Weg in ein wertschaffendes Produktionsparadigma'.
[64] Honeyman, *Child Workers in England, 1780–1820*.
[65] Horn, *The Industrial Revolution*.
[66] MacDonald, 'Future Trends in Engineering'.
[67] Bonciu, 'Evaluation of the Impact of the 4th Industrial Revolution on the Labor Market'.

Messe, one of the world's largest trade fairs, taking place in Germany, when a working group elaborated on the shift of paradigm within the industry, leading to new business models and driven by cyber-physical systems.[68] In 2011 Kagermann, Lukas and Wahlster who coined the phrase of Industry 4.0, explained in an interview that, "…This will lead to a shift in paradigm in the industry, it will be the first time that the product itself will take on an active role: the product itself and not a central control unit will "say" how it should be manufactured in the individual production steps."[69] Two years later, the final report of the working group, headed by Siegfried Dais and Henning Kagermann and on behalf of the Federal Ministry for Education and Research Germany, advised preparing Germany's industrial infrastructure for the 4th Industrial Revolution.[70]

The causes of industrial revolutions are often complicated and topic of debate. Nevertheless, it is undeniable that technological leaps, such as those illustrated in Figure 9, formed a favourable climate for radical changes in each of the four Industrial Revolutions.

The invention of the steam engine by James Watt, or the first power loom built by Edmund Cartwright, certainly contributed towards the First Industrial Revolution, much the same way as the assembly line did in the second one. [71] The introduction of programmable logic controllers greatly influenced the development of the third transition phase. In the same manner, one might search for technological advances leading to the 4th Industrial Revolution.[72]

Bauernhansl argues that sooner or later production will not be able to keep up with the demand side, giving the energy sector as an example. If energy efficiency remains unchanged, energy demand is likely to double until 2050. However, humans annually consume the same amount of fossil fuel that was formed in one million years. Consequently, if things remain the same, we will reach a point in time, where we will run out of this source of energy, creating a growth problem on the supply side. Therefore, we are in desperate need for an adequate substitute for fossil fuel, as moreover, climate as well as biodiversity are already under tremendous threat. This supply sided dilemma will make mandatory transformations necessary in the energy and human resource sectors, as well as in capital. According to Bauernhansl innovations in the information

[68] Kagermann, Lukas, and Wahlster, 'Industrie 4.0'.
[69] Kagermann, Lukas, and Wahlster.
[70] Kagermann, Wahlster, and Helbig, 'Umsetzungsempfehlungen Für Das Zukunftsprojekt Industrie 4.0'.
[71] Brezina, *The Industrial Revolution in America*.
[72] MacDonald, 'Future Trends in Engineering'.

and communication technology will be key enabler for the alteration of the factors of production mentioned before. These pave the way for the Fourth Industrial Revolution.[73]

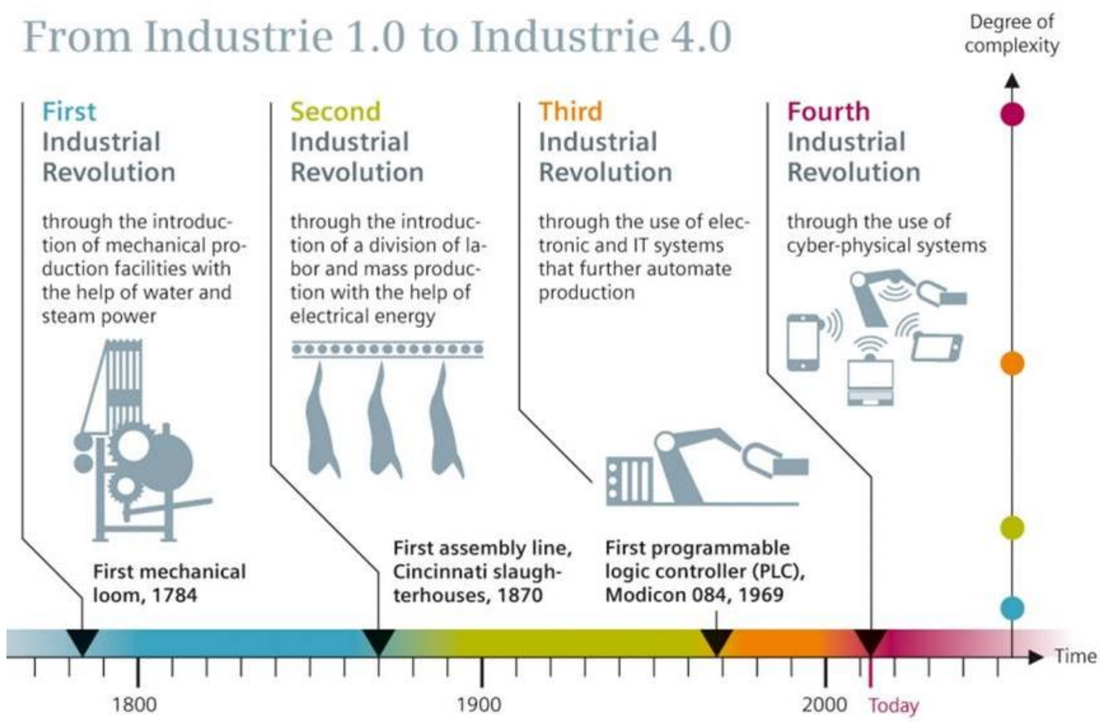


Figure 10: Industry has constantly been subject to revolutionary changes. Paradigm shifts were encompassed by different innovations in technology and engineering and complexity increased over time. Hence, each revolution standardised an even higher industrial level in technology. In today's transition period to the Fourth Industrial Revolution, industrial operations are increasingly making use of cyber-physical systems.

However, due to the rather short time of existence no universal definition of the term "Industry 4.0" can be given.

Nevertheless, Kagermann et al. (2013) interpretated this term as following, "Industry 4.0 addresses the fast technological transition which is based on the confluence of modern technologies of the information technologies with classical industrial processes in order to form cyber-physical systems."[74] UNIDO (2017) describes these novel systems as a state "where the physical world of industrial production merges with the digital world of information technology", creating a "digitised and interconnected industrial production".[75] The international community hopes that the Fourth Industrial Revolution will mitigate the global social, economic and environmental challenges, as well as encourage inclusive and sustainable industrial development. Sustainable solutions associated with high

[73] Bauernhansl, 'Die Vierte Industrielle Revolution, Der Weg in ein wertschaffendes Produktionsparadigma'.
[74] Kagermann, Wahlster, and Helbig, 'Umsetzungsempfehlungen Für Das Zukunftsprojekt Industrie 4.0'.
[75] UNIDO, 'Accelerating Clean Energy through Industry 4.0'.

economic and energy saving potential are thought to contribute in meeting the 17 Sustainable Development Goals set by United Nations General Assembly.[76]

3.2 Industry 4.0: in the context of waste management

According to a report by Berger (2016), digitalisation possesses a great potential to stimulate green developments: The report established under the authority of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany expects that until 2025, 50 Million tons of CO_2 will be saved per year due to the digital transformation of the environmental technology sector. Following markets of the Green Tech group are considered to contribute: energy generation, conservation and distribution, energy[77] efficiency, resource and materiel efficiency, sustainable mobility, water management and circular economy.

However, the waste management sector seems to be reluctant: when it comes down to the "digitalisation wave", only 30% of German-speaking waste management companies feel ready for the digital transformation. Foregoing this inevitable modernisation process is a surprising choice, as the AMCS study reported that more than 80% of their participating municipality and private sector waste management companies regard digital modernisations as essential to guaranteeing bussiness prosperity.[78] Moreover, the market of cirular economy has the greatest potential of additional market growth induced by digitalisation, with approximately 6% in comparison to the other six markets mentioned before.[79]

The digital transformation will influence and bring fundamental changes to all aspects of waste management, no matter whether it comes to logistics and waste collection, engines and plants, business ideas and models or data processing.[80] Frost & Sullivan (2018) identifies four major areas of the waste management system which are and will be subject to digital disruptive innovations.[81] As depicted in Figure 10 and

Figure 11 collection and logistic systems will be revolutionised by digital solutions such as smart waste bins and route optimisation.[82,83] For more information on the latter solution, a reference is made to subsection 3.2.1. Waste bins will be equiped with sensor

[76] UNIDO.
[77] 'Digitale Abfallwirtschaft: Mehrwert Entlang Der Gesamten Wertschöpfungskette'.
[78] 'The Waste Management Industry Is Critical of Its Own Digital Transformation Progress, the Survey Finds.'
[79] Büchele and Andrä, 'Die Digitalisierung in der GreenTech-Branche'.
[80] 'Digitale Abfallwirtschaft: Mehrwert Entlang Der Gesamten Wertschöpfungskette'.
[81] 'The Impact of Digital Transformation on the Waste Recycling Industry, Capitalizing on Opportunities in the Emerging Digital Economy'.
[82] 'The Impact of Digital Transformation on the Waste Recycling Industry, Capitalizing on Opportunities in the Emerging Digital Economy'.
[83] 'Digitale Abfallwirtschaft: Mehrwert Entlang Der Gesamten Wertschöpfungskette'.

nodes, enabling data collection such as the level of the waste bin or its content. In conjunction with data transmission and communication modules, companies in tandem with the customers can adjust the waste collection shedule to decrease inefficencies.[84] Bonino et al. (2016) claim that personalised solutions placing the user at its focus can help to improve recycling rates. Supporting tools such as “Waste Apps” are hoped to provide customised assistance in order to overcome waste recycling struggles. More details and an outlook of the results obtained by the Smart Waste solution by Saubermacher involving such a communication platform is given in subsection 3.2.2.

Figure 11: Digitalisation pillars of the waste recycling industry.[85]

Figure 11 arranges the innovations of the beforementioned sectors brought about by the digital transformtation of the waste and recycling industry in accordance to their predicted year of market maturity and relevance, the greater the sphere, the more important this technology is expected to be. Two projects, their innovations are highlighted in red, will be presented in the following sections 3.2.1 and 3.2.2 in order to assess their potential to drive economical as well as ecological changes within the waste management system of rural municipalities. The route optimisation project led to a redesign of the collection route. Digital platforms as well as a material scanner built into the waste truck form the base of the Smart Waste project undertaken by Saubermacher AG. The latter therefore can be seen as an overarching project combining the areas collection/logistics with new business ideas/models of Figure 11.

[84] Wijaya, Zainuddin, and Niswar, ‘Design a Smart Waste Bin for Smart Waste Management’.
[85] ‘The Impact of Digital Transformation on the Waste Recycling Industry, Capitalizing on Opportunities in the Emerging Digital Economy’.

All in all, digital transformation undeniably spurs new innovations. The fact that these developments have not taken place as of yet makes a literature review rather difficult. For this reason, a different approach is used in this thesis. In combination with insight into existing literature, the aforementioned real-life projects are examined.

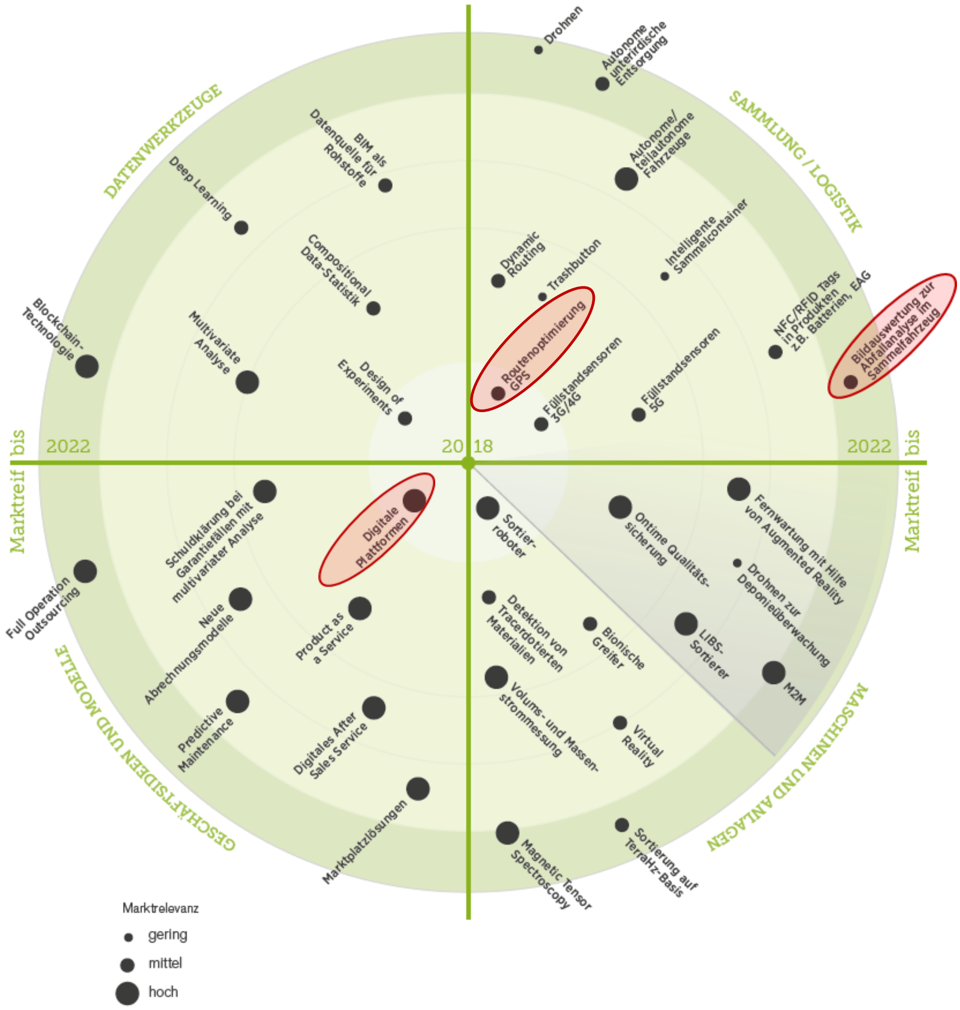


Figure 12: Digitalized Waste Management: time of market launch and estimated relevance for the market for various innovations. The graphic shows diverse innovations brought about by the digital transformation at its expected year of market maturity. The relevance to the market is proportional to the size of the spherical indicator. The Route Optimisation and the Smart Waste project which makes use of a digital platform and an imaging system are marked in red.[86]

3.2.1 Route Optimisation

In 2015 a route optimisation project was undertaken in Birkfeld, a market town located in the northeast of Styria, in order to improve the residual waste collection system. Figure 12 depicts the urban-rural topology of Styria, a federal province of Austria with the small inlet showing Austria's pattern. The region of Birkfeld is highlighted by a black

[86] 'Digitale Abfallwirtschaft: Mehrwert Entlang Der Gesamten Wertschöpfungskette'.

frame in this Figure and is considered as rural area according to Statistics Austria's Topology classification.[87] Futhermore, the map shows that rural areas dominate, comprising over two thirds of Styria's landscape. For this reason, research and innovations for rural areas should not be underestimated in their significance despite the progressively increasing trend towards urbanisation.

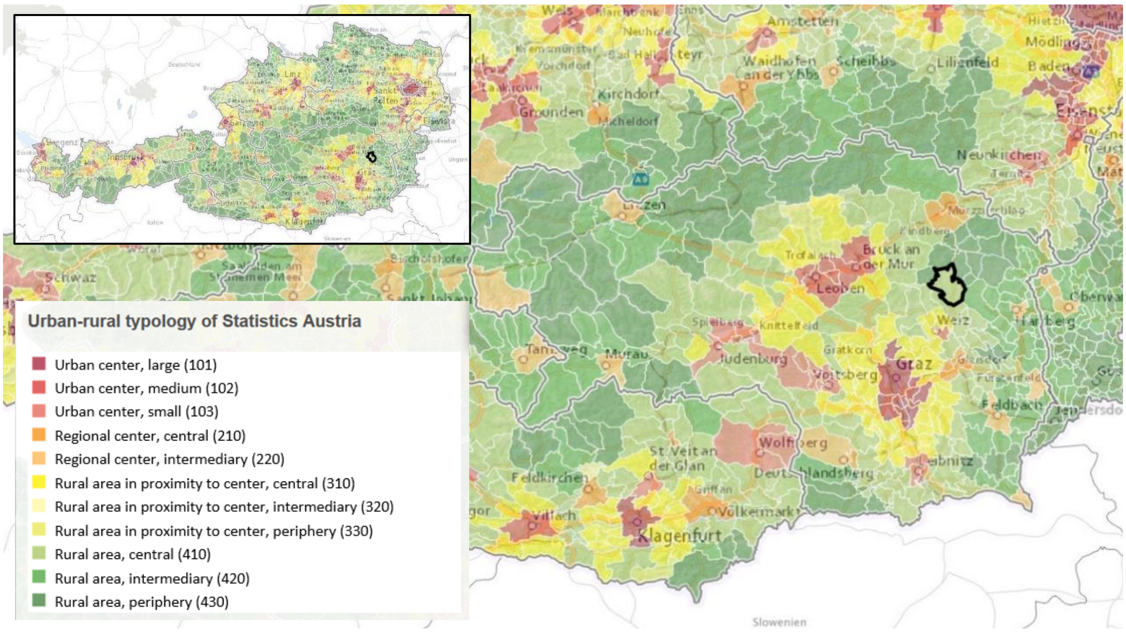


Figure 13: Classification of urban-rural areas: According to Statistics Austria Birkfeld (black frame) is a rural central area (classification number 401). The inlet in the upper corner shows Austria's topology according to this classification.[88]

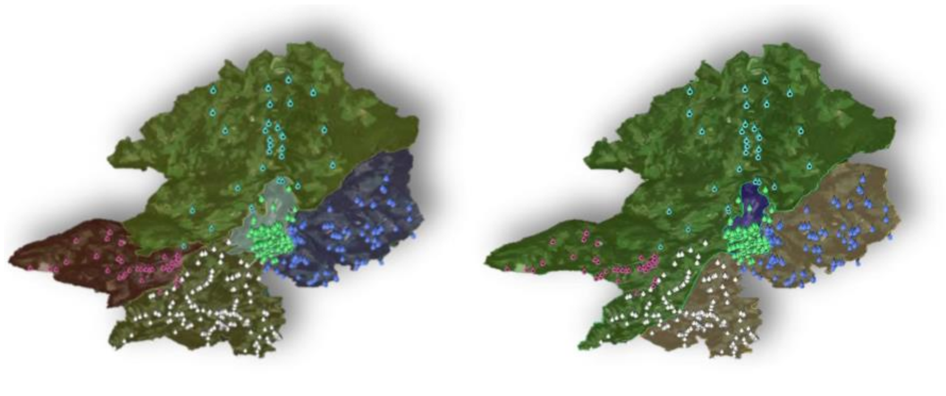
Birkfeld was enlarged as part of the Structural Reform of communities in Styria in 2015: In addition to the original community of Birkfeld, the four communties of Gschaid, Haslau, Koglhof and Waisenegg were merged together and are now part of Birkfeld. The municipality of Birfkeld is now home to 4992 people.[89] Over the course of this restructuring, existing systems, processes and tariffs of waste collection of the latter community were reviewed. Adenso, an environmental consulting firm, was assigned to optimise the collection route for solid waste within Birkfeld. A diverse team was assembled with members form various backgrounds: Abfallwirtschaftsverband-Weiz (sector association for waste management), market community Birkfeld, University of Graz as well as the state government of Styria were involved in addition to Adenso.[90]
Residual waste was collected over the course of 5 tours. Each collection tour was accompanied twice to gather filling rates, quality of the residual waste (indicating the

[87] For more information on the different categories of the topology see Annex 1.
[88] Figure adopted by author based on 'Urban-Rural Typology of Statistics Austria'.
[89] counting on 1.1.2018
[90] For detailed information on the project team see Weltin and Fischer, 'Projektbericht Version 1.0 Restmüll-Gebietsoptimierung Gemeinde Birkfeld'.

quality of waste separation), size and number of bins as well as geolocation of the bin. The characteristics of the collection drive, such as distance and elevation, were recorded via GPS.[91]

In order to gain a comprehensive picture and additional understanding independently from literature, extensive discussions and meetings with relevant project partners were arranged. DI Dr. Himmel Wilhelm, in his function of Sustainability Coordinator of the Province of Styria, provided an overview of the route optimisation project, and established a first contact to other stakeholders. On the municipal side, Dipl.-Päd. Bianca Moser-Bauernhofer and Mr. Reitbauer Robert, representing the Abfallwirtschaftsverband Weiz, were available as interview partners. Additional valuable insight and background information regarding route length and fuel consumption of waste trucks were provided by Prok. König Manfred (Saubermacher), Dr. Fischer (University of Graz), Danko Simic, BSc (University of Graz) and by Dr. Weltin, Managing Director of Adenso. Subsequently, a summary of the main for this paper relevant aspects shall be provided:

- **Route optimisation**
  With the help of the geo-based information, a new system was developed wherein the vehicles' starting location was placed in closer proximity to the municipality. In addition, a different discharging station was chosen in order to reduce the length of the route. This led to a reduction of the number of routes necessary to collect and discharge the residual waste of Birkfeld from 5 to 3 tours as indicated by the coloring of Figure 13.[92] The total number of kilometers could thereby be minimized from initially 993 km to 556 km.[93]



(A) *(B)*

Figure 14: The Route Optimisation project led to a reduction of the number of routes necessary for the residual waste collection from 5 (picture (A) illustrating situation before) to 3 (picture (B) depicting the actual situation).[94]

[91] Weltin and Fischer.
[92] Weltin and Fischer.
[93] According to Dr. Weltin.
[94] Weltin and Fischer, 'Projektbericht Version 1.0 Restmüll-Gebietsoptimierung Gemeinde Birkfeld'.

Consequently, the time needed to collect the residual waste of the whole catchement was reduced. As the waste collection service is calculated on basis of hours needed, this also led to a reduction of costs. The following will discuss the economic effects of the route optimisation project in more detail.

- **Economical Aspect: Increased transparency & reduction of costs**

  As mentioned at the beginning of this chapter, Birkfeld was merged with four other neighbouring municipalities under the Structural Reform of communities in Styria in 2015. This enlargement of Birkfeld brought about a new award of the waste collection contract.

  An essential prerequisite for negotiation is detailed knowledge about the operational systems of waste management forms. Most communities do not provide the service of waste collection themselves. Due to its increasingly complex nature, which is among others exacerbated by separated waste collection, this service is often outsourced to waste disposal companies relying on routine collection of trash. Consequently, communities lose track of the waste collection system development within their region over the course of time. Based on the know-how gained and the data collected throughout the course of the Route Optimisation project the community of Birkfeld drastically improved its negotiating power vis-à-vis waste disposal enterprises. The outcome of these new negotiations was that hours charged for residual waste collection could be adapted to the optimised routes. The following specifications concern hours charged for the compacting vehicle, including the district Koglhof. For the sake of completeness, it should be mentioned that the service for Birfkeld also includes five hours with a flatbed vehicle. As those hours could not be reduced via the route optimisation process, they will be omitted in the subsequent sections.

  According to Saubermacher, 36 hours of waste collection by a compacting vehilce, including Koglhof, were charged for the total of five tours. Adenso calculated a reduction to 26.5 hours for the optimised scenario based on the tour reduction. The implementation of this route proposed by Adenso had to be adjusted to several constraints on the part of the waste disposal company.

  Legal restrictions allow a maximum tour of 8.5 hours per driver (time for breaks not included in this time allowance). In addition, each driver must undertake a statutory driver intermission of 45 minutes. Furthermore, waste collection routes are adapted to special demands of certain areas. For example, one avoids driving by specific sensitive locations during busy times to minimise the risk of accidents.

Routes are adjusted to protect school children by collecting waste in that area outside of school time.[95]

These and other practical constraints led to a less pronounced decrease of working hours. Nevertheless, the initial situation of 36 hours for the total of 5 routes could be reduced to 32 hours for 3 routes by optimising the collection tours.[96]

The collection of residual waste is undertaken every fourth weeks, in total 13 times a year.[97] In total this adds up to a reduction of 52 hours per year. Due to the cutback in hours charged, a decrease in costs on the part of the municipality of Birkfeld could be achieved. Prior to the project, a fee of €43.269 per year had to be paid for residual waste collection. The costs which had to be covered after the route optimisation process amounted only to €35.312 in 2016.[98] Hence, a reduction of expenses of approximately 18.4% on the part of the community could be achieved.

Around one third of the project costs were covered by the municipality itself. During an interview performed as part of this thesis, representatives of the municipality of Birkfeld expected the pay-back period of the route optimisation project to approximately two years.[99]

- **Ecological aspect: Reduction of CO_2 emissions**

  Ecological issues were also investigated by a study of Fischer and Simic (2016) which estimates the waste truck emissions. The researchers of the University of Graz established a 3D-CO_2 model that depends on certain route characteristics. Besides taking into account typical parameters such as tour lenght, specific data such as petrol consumption and increasing loading weight, and consequent CO_2 production of the initial collection tour were considered in dependence of the geographical height profile. The outcome of those calculations are depicted in Figure 14.[100] Several parameters drastically influence the fuel consumption and the consequent CO_2 emissions of waste trucks:

  1. The fuel consumption reference in the case of a diesel engined truck of approximately 25 t was assessed with 70 to 85 l per 100 km.

[95] Information provided by Saubermacher, König.
[96] König, 'Marktgemeinde Birkfeld, Tourenoptimierung Bzw. Evaluierung'.
[97] Interview Marktgemeinde Birkfeld
[98] Disposal fees are not included.
[99] Interview Marktgemeinde Birkfeld
[100] Fischer and Simic, '3D-CO2-Modelling for Waste Management in Styria/Austria'.

2. The altitude travelled greatly alters fuel consumption.
3. The waste load increases along the collection route and increases fuel consumption.
4. Waste trucks frequently stop-and-go and therefore consume more fuel in the course of their tour.
5. The amount of fuel consumed per stop-and-go greatly depends on topography. A truck drive continuing uphill leads to higher fuel consumption, whereas a downhill stretch could result in a consequent reduction.

Taking these considerations into account, a multiplying factor of 3.6 was introduced. With 2.65 kg CO_2 generated per burned liter of diesel fuel, the emission reduction by the route optimisation can be deduced from the above parameters as following:[101]

$$CO_{2,red} = 3.6 * 85 \frac{l}{100\,km} * (953 - 556)\,km * 2.65 \frac{kg\,CO_2}{l} = 3.22\,t\,CO_2 \qquad (1)$$

Therefore, it shall be assumed that a waste truck emits 8 kg CO_2 per km and thereby consumes more than triple the amount of fuel during its collection tour in hilly areas.[102]

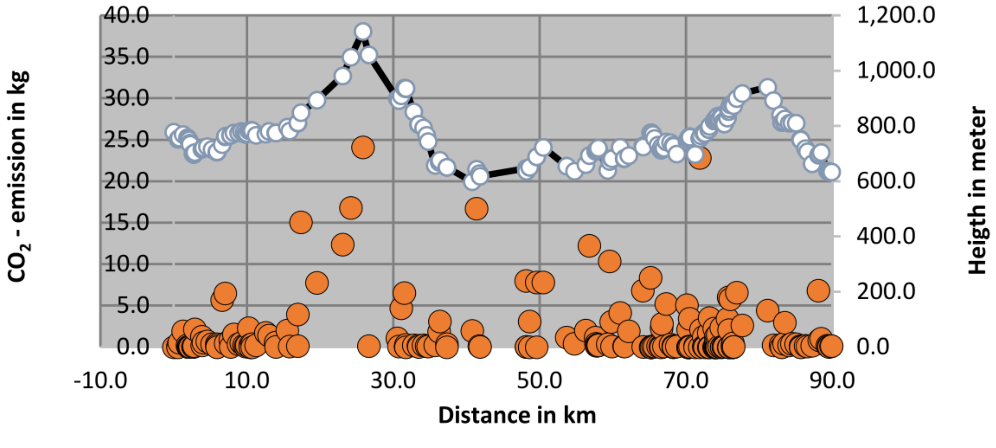


Figure 15: The 3D-CO_2 of a waste collection tour.The topography of the collection tour is illustrated by the black solid line. Stops for loading waste containers is marked by white dots. The ecological load in form of CO_2 produced by the waste collection truck on the way to an individual household is depicted by red dots. As expected, it follows that the longer the distance and the more height meters a collection tour have the higher the ecological load.[103]

[101] Emse, 'CO2-Rechner, CO2-Emissionen Berechnen'.
[102] According to Dr. Weltin.
[103] Fischer and Simic, '3D-CO2-Modelling for Waste Management in Styria/Austria'.

Moreover, Fischer and Simic (2016) compared the optimised area collections to the former system. From this, recommendations for CO2 emission reductions were deducted. Table 1 sums up the main suggestions for improvement.

Table 1: Recommendations to reduce emissions of a waste truck generated in the course of a collection cycle.[104]

Opportunities	Description	Considerations for implementation
Improved routing	Sub-optimal routing of waste bin collection generates unnecessary tonne-kms	Use more advanced logistics planning and vehicle routing tools Cost implications
Improve vehicle operation (eco-efficient driving)	The operation of a vehicle can be improved by driver training. Driver training can be supported by intelligent electronic systems that monitor driving behaviour and fuel-consumption.	Cost-benefit of different measures. Potential impact on service levels.
Make use of energy sources with a lower carbon intensity	Increase use of alternative fuels with lower carbon intensity (e.g. bio-fuel)	Sufficient cost advantage. Availability of technology and suitable equipment.

In summary, an adequately designed route with the objective of reducing the distance of the waste collection under the consideration of route topology offers an opportunity for a more sustainable waste collection management.

In this context, the question arises if the outcome of Route Optimisation project can be transferred to to other municipalities in a “copy and paste” like manner and whether or not this effort might lead to viable solutions. The underlying assumption is that similar results can only be expected for comparable communities. Thus, in order to gain some insight into what might happen, comparable criteria need to be established, as no municipality is identical with regard to settlement structure and number of inhabitants.
During the interview with the representatives of Birkfeld, Moser-Bauernhofer and Reitbauer, the following became clear: Although the number of inhabitants constitute a decisive parameter for the number of waste bins and hence the number of stops necessary, the settlement structure is likely to be the most influential value in determining the characteristics of waste collection tours. The length and extent of tours in rural areas, regardless of whether measured in hours or kilometers are highly dependent on settlement structure as this defines the total route length and distance to local recycling centers. Figure 15 explains this train of thought in an illustrative way. An artifical scenario involving the collection of 4 bins in close proximity to each other one additional remote garbage can is created. A young family builds a house along the Neudörfl street and their

[104] Fischer and Simic.

waste, as indicated by the bin symbol framed in red, shall be collected as well. This additional stop does not increase the total route length in a pronounced way, as the waste truck would have to drive to Koglhof anyways. The result is that for waste management in rural areas, the settlement structure rather than the size of the municipality should be used as a point of comparison.

Whether this experience can be transposed to urban areas is questionable, as the time needed for the number of stops might outweigh the time necessary for the distance travelled. Therefore, a more valid comparabilty criteria for cities could be the number of inhabitants or waste bins.

It shall be noted that this waste collection setting was created by the author only for explanatory reasons and does not represent the real-life situation of the municipality of Birkfeld.

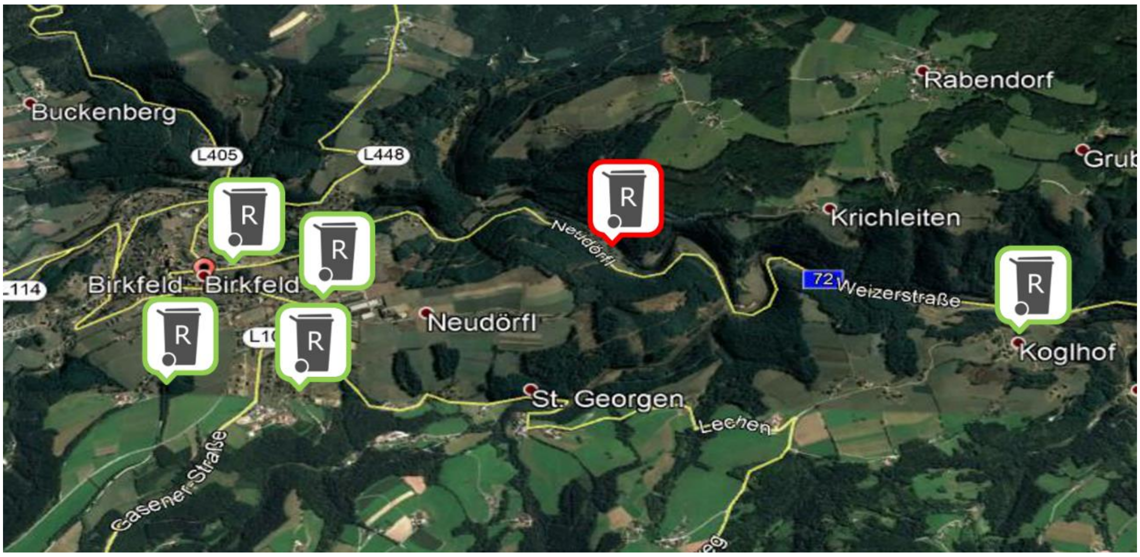


Figure 16: Examplary presentation of a waste collection tour in Birkfeld. In this scenario, Birkfeld including Koglhof shows a relatively elongated structure consisting of an agglomeration around the city center and the remote settlement of Koglhof. On the basis of this experience it seems to follow that a projection of the outcome of a route optimisation process from one municipality to another one should rather be done on the bases of similar settlement structures than comparable numbers of inhabitants. This example involves 5 residual waste bins marked in green, 4 of which are located in close proximity to the city center and one in Koglhof, in approximately 6 km distance to the center. Experience has shown that the collection of one additional waste bin along the connecting line does not drastically influence the tour length in terms of time. This supplementary stop is indicated by the red garbage can. A strong direct dependence between number of wate bins and number of inhabitants can be assumed. The time necessary is rather influenced by the settlement structure.[105]

Already at this point a reference to section 4 is made, as it elaborates on possible results in case a route optimisation process would be undertaken in all rural areas. It is assumed that the element of rural-urban topology can be used as an indicator for the settlement structure, as the accesibilty of the municipality as well as proximity to the next town

[105] Picture adapted by author on base of 'Satellite image, Birkfeld'.

center were used as a classification characteristic.[106] For the sake of clarity it is stated, that an elaborate investigation of the potential of the route optimisation process of municipalities on the basis of similar settlement structures rather than comperable indicators would be a worthwile focus for future research.
Nevertheless, for a first estimate, the optimisation potential of municipalities ranging from 3001 to 5000 inhabitants is assessed in this section.
Research on Styria's municipalities revealed that around 18% of Styrian people live in a municipality comparable to Birkfeld with regard to number of inhabitants (3001-5000 inhabitants) and 20% of Styrian's municipalities have a similar size (58 out of 287 municipalities). An optimisation of waste collection tours in those communities can, as demonstrated by Birkfeld, reduce the costs for residual waste management in addition to providing ecological benefits. From this, it can be derived that in the best case, up to one out of five Styrian inhabitants could possibly profit from a reduction of waste charges and therefore gain from a reduction in the financial burden[107].

It can be concluded that route optimisation provides a tool for economic improvements. In recent years, more and more waste companies have made use of such optimisation tools themselves in order to reduce operating costs and stay competitive, along with providing an even more environmental friendly solution. If not developed by themselves, improving IT solutions are offered on the market by manifold software providers such as the consulting firm Route Optimization Consultants and the platform company AMCS to name some.[108,109] Efficient routes entail savings in time and hence, salaries. Eventhough an ideal collection tour might also result in a reduced consumption of fuel, and consequently leads to less environment-damaging emissions, the ecological effect might not be of primary importance. In order to adequately assess the ecological significance of optimised logistics, their contribution towards the total waste management system including collection, mechanical pretreatment and thermal processing has to be taken into account as well. Curtis et al. demonstrated that only 4% of the total CO_2 emissions of the waste management system originate from its logistic and processing sector.[110]
Nevertheless, route optimisation should be undertaken for economic reasons especially, albeit not exclusively, in rural areas demonstrating high topographical variance. If conducted properly and with special regard to the CO_2 dependency also on topography,

[106] For further information on the classiciation criteria please see Annex 1.
[107] For source and further information a reference is made to Annex 2.
[108] 'Route Optimization for Solid Waste Collection'.
[109] 'Waste'.
[110] Curtis et al., 'Klimaschutzbeitrag Der Saubermacher Dienstleistungs AG Update 2006'. out of Pomberger, Curtis, and Scherübl, 'Klimarelevanz Der Abfallwirtschaft Aus Sicht Eines Sammlers'.

ecological GHG savings contribute towards a climate-friendly waste mangament and form an additional benefit.[111]

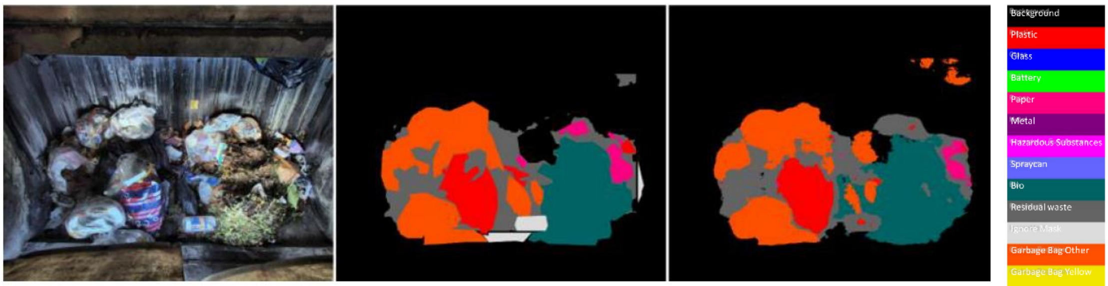
3.2.2 Smart Waste

Saubermacher AG examines innovative ways introduced by digitalistion tools to further increase high recycling rates.
Seperating waste leads to less residual waste as more material is recycled. This has mutual benefits, as on the one hand recycables form a valuable economic fraction and can be resold on the market. On the other hand, primary resources are conserved and their substition leads to verifiable GHG savings.[112] Data show that there is still room for improvement, because around ¾ of the residual waste should have been disposed of differently.[113] In order to meet the environmental targets set by the EU Energy and Climate Package 2020, the Circular Economy Package and others, new strategies have to be found to further increase recycling rates. For more information on waste management and climate targets see section 2.3.
Saubermacher developed and is currently testing a device to collect and analyse the waste stream and report back to the "waste producer" in order to improve their waste behaviour where necessary. Therefore the concept of the Smart Waste project, as understood by this thesis, is based on two pillars: a qualitative analysis of the composition of residual waste and the coordinated communication of the respective outcome.

The first pillar involves a scanner developed by Saubermacher AG which is integrated into the garbage truck. This device records the different types of material being disposed of by using multi-spectral imaging. A Convolutional Neural Network (CNN) is trained to distinguish between the different types of recyclable material. Iteration of the network's parameters ensures that results derived by the CNN are continuously improved and become successively more accurate. The classification device which generates images based on the CNN outcome as illustrated in Figure 16 works, with an achieved accuracy of around 15% (at the time of this thesis, further increasing with more training data and optimized technology). In comparison, results of different experts show variations of around 50%. Despite the error that a machine algorithm will always have, reproducible and comparable results are measured around any time, which is an essential prerequisite for any optimisation problem. From the surface composition image of the

[111] Fischer and Simic, '3D-CO2-Modelling for Waste Management in Styria/Austria'.
[112] For further information a reference is made to subsection 2.3.1.
[113] Opelt, 'Sind Wir Smart Genug?'

waste sample conclusions can be drawn for the whole content. This approach is justified due to the fact that the target set is to provide an incentive for residents to modify their separate waste collection behaviour rather than to deliver composition data with the highest accuracy possible.[114]



(A) *(B)* *(C)*

Figure 17: The "Wertstoffscanner" by Saubermacher. The classification device analyses the material components of a waste sample: Picture (A) showing the typical content of a residual waste bin, whereas Image (B) illustrates different contents labelled manually according to their material, and image (C) was generated automatically by the CNN.[115]

The second pillar is formed by a communication tool: results obtained through the classification device are stored in an access-protected platform and can be monitored geographically. A wide range of other editing options allow a customized presentation of the data collected, results can be interpreted for a whole community down to a single waste bin.[116]

This tool closes the cycle of the information flow. Data which had initially been gathered by the "Wertstoffscanner" are reported back to the respective target group through the establishment of a feedback channel: Results visualised graphically or numerically can be transmitted by different media, via mail, sms, app or print media, such as the municipal newspaper, for example. The automated feedback to the waste generator plays a key role, the better this is done, the more likely it is that the right incentive will be provided. Following, this shall be elaborated in more detail. [117]

In contrast to previous waste analyses, the two pillars together allow for an approximation of real time feedback, and therefore drastically reduce the time between waste disposal and response. A simple example can illustrate the potential of this system: Let's consider an unaware resident named John Doe. Chances are high that John's residual waste consist of up to 10% paper. He assumably produces 120 kg residual waste per year, just

[114] Kornthaler, 'Wertstoffscanner, Smart Waste'.
[115] Kornthaler.
[116] Kornthaler.
[117] Kornthaler.

as much as the average Styrian person.[118] Within five years, the resident therefore generates an incorrectly disposed fraction of residual waste of 60 kg, the. same amount of waste paper was disposed of per person in Styria in 1997.[119]But in contrast to the latter, of which all is recycled and thereby helps conserve resources, John Doe's wrondoing creates environmental as well as economic burdens. Paper that, if he would have been informed ab initio, might have been recycled as well, is lost. Moreover, the more anonymous a person feels, the more likely the resident is to act erroneously. In general, a resident living in a large apartment building generates a higher incorrectly disposed fraction than others.[120] The logical conclusion is that a report pointing out the malpractice averaged over a large amount of people, is less likely to change individual behaviour because one dos not feel personally responsible.

In the end, it is the fast processing nexus between the scanner and the communication tool which enables a more frequent monitoring of the cause-effect relationship and allows for an individualised feedback as illustrated in Figure 17. Therefore, it can be expected that the closed information loop provides a strong incentive to change the waste behaviour of all still unaware John and Jane Does.

Figure 18: Closed loop system: From the Werkstoffscanner to the resident via a customized feedback channel. This information flow creates an incentive to the target group's waste behavior and reduce the incorrectly disposed fraction of residual waste.[121]

[118] Land Steiermark, 'Restmüll'.
[119] 'Jahresbericht zur Abfallwirtschaft, Daten 2017'.
[120] Müller, 'Abfallberater des Jahres 2014, Großer Erfolg für unsere beiden Abfallberater!'
[121] Figure adopted by author based on Opelt, 'Sind Wir Smart Genug?'

This assumption had been tested by Saubermacher. Pioneer Smart Waste projects involving Werstoffscanner and Communication Tool were undertaken in small test regions. All initial results were positive, meaning that a reduction of incorrectly disposed residual waste could be achieved. This paper will focus on one test region only, as the outcome of each area shows similar patterns. The respective region was chosen due to its longest test period of 8.5 months at the time of the thesis, as the test is still ongoing. The test area included 35 households. If a region-specific average household size of around 2.24 people per home is assumed, the residual waste of approximately 78 people was collected by press vehicles equipped with waste scanners. The incorrectly disposed fraction of residual waste was recorded over the course of the test period with the help of the "Wertstoffscanner" as described before. Data, as illustrated in Figure 18, evinced a pronounced relative decline of this fraction by approximately 53% over the period of 8.5 months. The development depicts a sinusoidal pattern, during the first months a distinct decrease from 55% to 17% could be recorded, followed by an increase of this share of 15% during winter months of December and January.

The grey boxes in Figure 18 explain special "events". In September the start of the Smart Waste project and the first introduction of waste collection tours with trucks equiped with a scanner were announced. Interestingly, even the mere announcement that the residents' waste behaviour would be monitored already led to a significant improvement. A phenomenon that might be explained by the Hawthorne effect which has been tested by Schwartz et al. (2013) in the energy sector. The researchers found evidence that households which felt observed (by believing that their electricity use would be recorded during the experiment) responded by adapting their behaviour to what they perceived as socially desirable. The effect was that their average energy consumtion reduced by 2.7%.[122] The same effect might explain the improvements in the waste behaviour at the beginning of the test phase.

Shortly after the start of the testing phase, communicating via SMS posed some problems. Saubermacher estimated that, once the communiction problems were corrected, a significant improvement in waste seperation was recorded in October. As the quality communication seems to be an indispensable prerequisite for the successes. Therefore, this shall be elaborated on in more detail.

Besides traditional print media, feedback was also provided via an app as well as sms. Saubermacher created customized app, known as "Daheim", which is freely available for all municipalities in which Saubermacher is responsible for the waste collection. The initial idea was to set up a digital reminder informing residents of upcoming waste

[122] Schwartz et al., 'The Hawthorne Effect and Energy Awareness'.

collection dates. Over time the app was equipped with more and more useful features, such as tipps on how to separate waste correctly.[123] During the Smart Waste project this app was used as part of the communication channel. Averaged municipality results were reported back to the residents with the help of this app. Additionally, customized feedback was given via sms. After each waste collection tour, the individual resident was informed on the household's own fraction of incorrectly disposed residual waste. Communications were adapted with respect to good, average or bad waste seperation. In case of a good result the message may have been as follows, “Dear Mr John Doe! Great news, you are an expert in separate waste collection! Only a small fraction of XX% did not belong to residual waste. The main undesirable material was XXX. Thank you very much for your help and please, just continue this way. All the best, your Saubermacher! P.s.: More informations are available in your App “Daheim”!”

Saubermacher assumes that the relapse of some residents into worse waste seperation behaviour might be partially explained by the unvarying stimuli set by the communication tool.

In addition to the uniform feedback communication, the Christmas festival along with New Year holidays seem to have played a role. Improved communications is considered to have brought the development on the right track again towards the beginning of spring. For the sake of completeness, it is noted that the first data point is based on an analysis of residual waste undertaken by the federal state of Styria in 2013. It represents a residual waste fraction incorrectly disposed of, which remains typical for urban areas and not a discrete measurement. For this reason, this set of data is not included in Figure 19 which shows the components measured by the Wertstoffscanner.

[123] Saubermacher, ‘Leistungen, Digitale Services’.

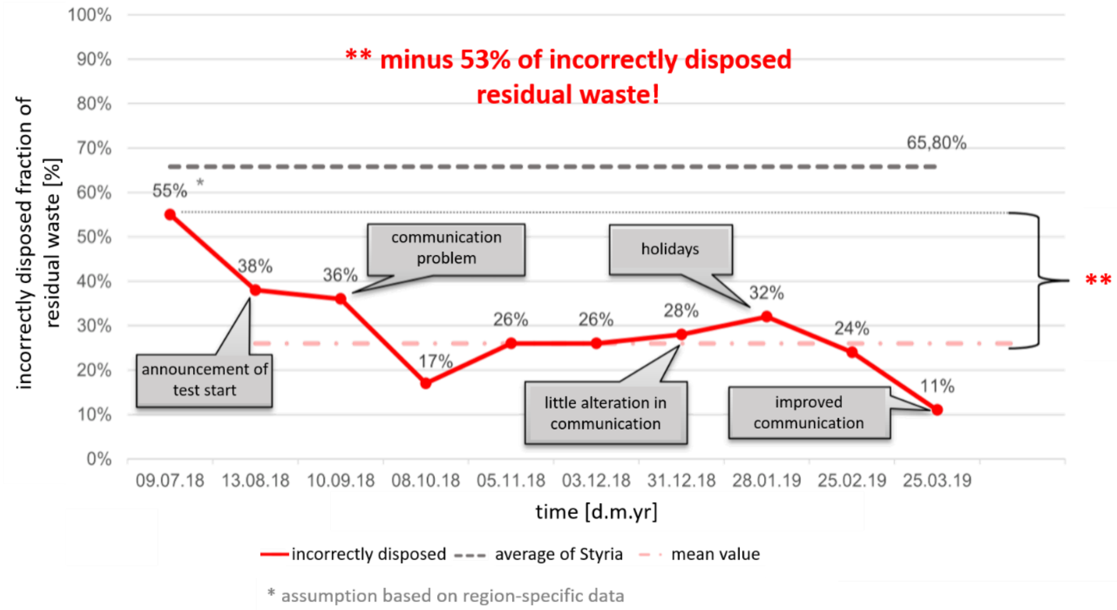


Figure 19: Incorrectly disposed fraction of residual waste over the course of the test period of the Smart Waste project. A reduction of this fraction of around 53% could be observed during the period of 8.5 months. The data shows a sinusoidal behaviour with a strong first decrease of minus 38% succeeded by a less pronounced increase. It can be assumed that the relapse of some into the original behaviour is due to the unvarying stimuli, followed by holidays. Improved communications is considered have improved this situation.[124]

The wave-like oscillating development of the incorrectly disposed residual waste fraction of Figure 18 results from variations of its components. The measured variations in compositions over time can be seen in Figure 19. As previously mentioned, the sum of all components shows two distinct extrema: a minimum during October and a maximum in January. The pronounced decrease in autumn can be mainly attributed to the drop in the paper fraction by 5%. In the same manner a doubling in that fraction from one month to the next led to a local maximum at the end of January. A reconciliation of the explanation of specific events marked by gray boxes in Figure 18 makes clear that these variation fits well to the stimuli provided via the communication tool. This might allow the cautious assumption that people seem to be more likely to incorporate the incentive provided by Smart Waste information flow into their waste paper behaviour, relative to their behaviour with other waste component fractions.

The variations in the fraction of light packaging run approximately parallel to those of paper, albeit in a slightly less pronounced pattern. Organic waste, for example, is practically not existant in the last test month. In contrast to paper and light packaging, the metal fraction's time dependent development seems to be rather stable, as already its initial amount in residual waste makes only up for 3%. At the beginning of December, the amount of organic waste found in residual waste ascends to a value only slightly

[124]Figure adopted by author based on Kornthaler, 'Wertstoffscanner, Smart Waste'.

below its original amont. This incline is not mirrored by the red curve symbolising the total amount, as it is compensated by the decline of the fractions light packagings, paper and metal waste.

Figure 20 was generated on numbers provided by Saubermacher. For detailed numeric information please see Annex 3.

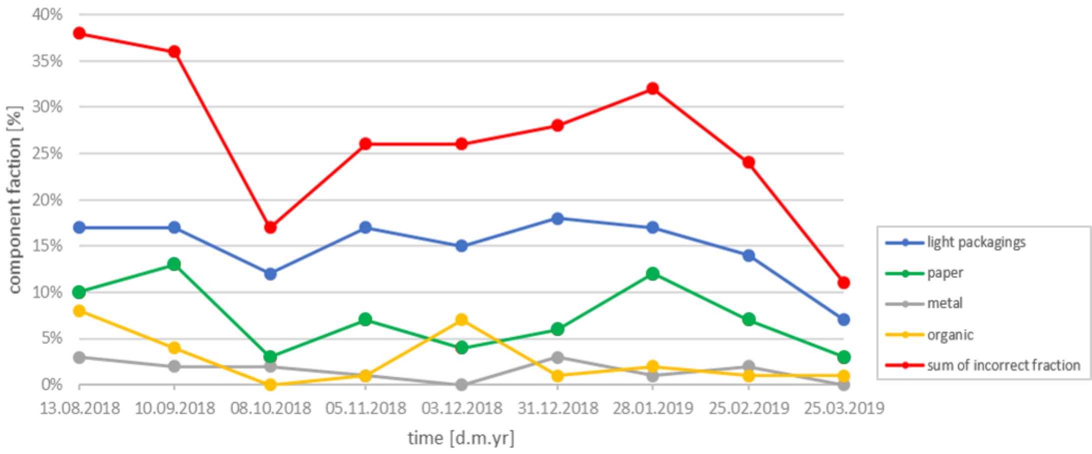


Figure 20: Composition of incorrectly disposed fraction of residual waste over the course of the actual measuring time. A decrease of the sum of all components to 11% could be achieved. The average incorrect fraction amounted to 26%. All waste segments found in residual waste show a sinusoidal pattern. Reasons for this behaviour might be the uniform feedback and the occurance of holidays during the winter months.[125]

To conclude, as waste generation is prompted by diverse reasons, further investigations would be needed in order to facilitate precise and reliable conclusions. Nevertheless, new technologies provided by Industry 4.0 enables the waste managemetn sector to motivate and give feedback in a very different manner than the decacdes before.The outcome of the Smart Waste project reflects this positive development as it highlights that the quality of waste seperation can be positively influenced.

[125]The diagram was created by the author based on a table provided by Kornthaler. For more information a reference is made to Annex 3.

4 Utopian Model

The primary idea of this work is to assess the potential effects that certain Industry 4.0-innovations in waste management can have on an economical as well as ecological level. This thesis centers its focus on a special aspect of waste management, namely residual waste management in rural areas. To translate this idea from theory to practical reality, two projects, one dealing with route optimisation and the other one with Smart Waste systems incuding digital platforms and tech in trucks, have been investigated and are presented in sections 3.2.1 and 3.2.2, respectively.

The goal of the following section is to develop a model which allows an estimation of certain budgetary as well as environmental consequences of the beforementioned digital developments, especially in case of large-scale implementation. The Utopian Model therefore describes a hypothetical situation of Styria in which all rural areas would be transformed by the Route Optimisation and Smart Waste project. The name "utopia" seems appropriate, as it describes an desirable state of society.[126] The concept of the utopian Styria is depicted in

Figure 20.

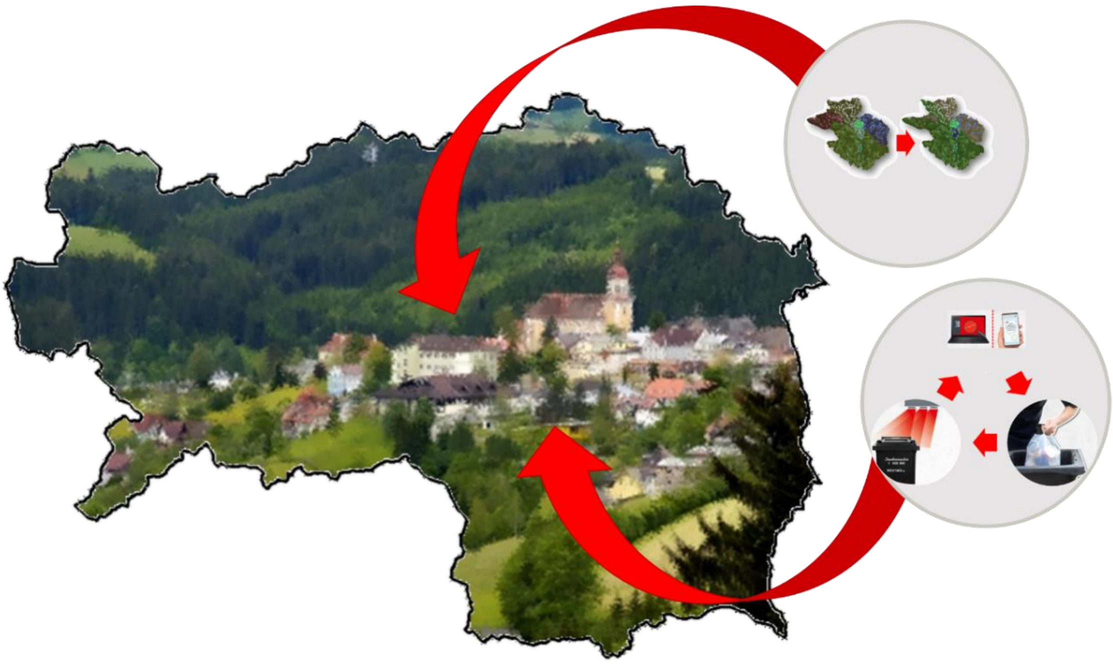


Figure 21: Upscalling Model Utopia.

[126] Giroux, 'Utopian Thinking Under the Sign of Neoliberalism: Towards a Critical Pedagogy of Educated Hope'.

4.1 Model Design and Outcome

Models mirror real-world problems in such a simplified manner that it is possible to make predictions based on a set of input parameters.

On the one hand, simplifying assumptions are therefore necessary to reduce the complexity of the system to the extent that predictions within can be made certain system boundaries. On the other hand, to quote the french physicist and economist Maurice Allais "a theory can only be as good as its assumptions. If the premises are false, the theory has no real scientific value."[127] Initial conditions, system boundaries and assumptions form essential parts in every modelling. Because of their strong interlinkage with the model design, they are elaborated in this section rather than in a separate discussion. The final passage examines the results of the Utopian Model.

According to the report on municipal waste generation of 2017, each person generates approximately 126 kg residual waste per year, of which a weight share of 60% should have been collected seperately.[128] This creates an economic burden of over €10 million only for the region of Styria.[129]

The regional boundaries of the Utopian model are predefined by the rural areas of the Austrian province of Styria. The aforementioned report revealed that people living in rural areas tend to dispose of less residual waste and separate better. In average, around 113 kg of residual waste is generated per inhabitant of rural areas, incorrectly disposing around 55% and therefore 18% less than the average Styrian person.[130,131] The rural annual contribution towards the incorrectly disposed fraction can be estimated to be 62 kg per capita, with economic consequences amounting to around €4 million per year. These numbers demonstrate that cost effectiveness alone provides a suitable reason to increase efforts adressing the quality of separate waste collection. For more detailed information on municipal residual waste in Austria or Styria respectively, please see section 2.2.

Additionaly, negative ecological consequences, with the "loss" of recyclable material being the most apparent one, are contributing factors. This is closely linked to the question of climate protection, as recycled material substitutes primary material, and thereby not only contributes towards the protection of primary resources but also reduces the emission of carbon dioxide. An elaborate study developed, among others, a scenario

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[127] Allais, *L'Anisotropie de l'espace*.
[128] 'Jahresbericht zur Abfallwirtschaft, Daten 2017'.
[129] Land Steiermark, 'Restmüll'.
[130] Kornthaler, 'Wertstoffscanner, Smart Waste'.
[131] Kornthaler.

based on resource optimisation. Brunner et al. (2015) found that the implementation of several parallel measures such as material recycling, and increased recovery of scrap metal from incineration plants as well as prolonged landfill aftercare would lead to the optimal outcome with regard to the targets defined by the AWG 2002. A prerequisite for such an optimised scenario would be an increase in separate waste collection rates to facilitate high quality recycling.[132]

The climate potential of recycling has already been discussed in section 2.3, therefore only a short example shall demonstrate the importance of recycling at this point: The Federal Environment Agency of Germany assigns a GHG saving potential of 217 kg CO_2 equivalent and approximately 3,23 GJ energy for one ton of paper waste redirected from residual waste to waste paper.[133]

The Route Optimisation project, as described in detail in subsection 3.2.1, considers indirect environmental stress created by residual waste collection. Parallel to the primary task of reducing the length of the collection tour necessary for Birkfeld's cachement area, Fischer and Simic (2016) investigated how much carbon dioxide a press tuck emits over the course of its waste collection tour. Among others, it is the goal of the Utopian Model to provide an estimate on carbon dioxide savings in case each rural municipality optimises its collection route.[134]

As already discussed in subsection 3.2.1, specific community characteristics such as the geographical structure play an influential role on waste truck emissions. Subsequently, a scientific valid deduction of the outcome of one municipality to another one can only be done in case of similar characteristics. As already explained in subsection 3.2.1. Statistics Austria classified 11 types of ural-urban typology. For reasons of simplicity, classes (101) to (220) are considered as urban, whereas classes (310) to (430) as rural areas. A comparison of different sources allowed an approximation of the population living in rural areas in 2017 to 620 380 people, accounting for approximately half of Styria's inhabitants. For further information on the classifcation, a reference is made to subsection 3.2.1 and Annex 4.

The outcome of both digitalisation projects was extrapolated to the total amount of people living in rural areas.

The Route Optimisation project resulted in a reduction of the residual waste collection tour by400 km. The minimised collection routelength entailed a cost reduction due to less labour hours in addition to a decrease in CO_2 emissions generated by the waste

[132] Brunner et al., 'Benchmarking Für Die Österreichische Abfallwirtschaft'.
[133] Dehoust et al., 'Statusbericht Zum Beitrag Der Abfallwirtschaft Zum Klimaschutz Und Mögliche Potentiale'.
[134] Fischer and Simic, '3D-CO2-Modelling for Waste Management in Styria/Austria'.

truck, which was calculated with formula The latter traffic emissions are approximated by forumla (1) in dependence on the route length. Consequently, a route reduction of minus 42% saves emissions of the same magnitude. In the event that collection tours of all rural areas of Styria were to be optimised, the Utopian model would provide an economical as well as ecological change as presented in Table 2.

Table 2: The Utopian Route Optimisation Model's consequences on ecomomical as well ecological aspects.

	economical change [€]	economic relief [%]	ecological change [kg CO2]	ecologic relief [%]
test region	-7,957	-18	-3,219	-42
utopian Styria	-988,855	-	-400,075	$-88*10^{-4}$

In total, rural municipalities would experience a financial relief of approximately €1 Mio. This economsation could lead to a yearly reduction of waste collection fees of rural citizens by around €2. The relative reduction of the economic burden for Utopian Styria cannot be assessed, as reference values of the municipal residual waste services for the entirety of Styria are not available. Nevertheless, a reduction of 18% similar to the test region may be taken as a benchmark for the rural areas of Styria as well, but keeping in mind that the potential for optimisation clearly depends on the initial situation of each municipality and whether the initially implemented collection tour can still be improved or not.

In recent years, emissions resulting from the energy sector were steadily rising, as an increase by more than 6% from 1990 to 2017 had been recorded. With this development mainly resulted from escalating traffic emissions, countermeasures have to be introduced. The contribution in form of emission savings obtainable from Route Optimisation projects in rural areas amounts for up to 400 t CO_2 per year. In order to interpret the ecological outcome in a wider context, emission savings calculated for Styria's rural areas are compared to the total of 32.234 kt CO_2 resulting from liquid fuel combustion activities in Austria.[135] To do so, the latter emissions are downscaled by a factor of 0.14 which reflects the proportionality of number of inhabitants of Styria with regard to Austria's approximately 8.77 Mio people.[136] Through this approach the impact of Utopian Styria can be calculated to slightly reduce Styria's emissions resulting from

[135] Emission share generated by liquid fuel combustion activities amounting of Styrian rural areas were estimated with 2,279,452 t CO_2. Input values for this calculation were taken from Anderl et al., 'Austria's National Inventory Report 2019, Submission under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol'.

[136] According to Oschischnig, 'Statistisches Jahrbuch 2017', Austria's population amounted to 8,772,865 in 2017.

liquid fuel combustion activities by 0.0088%. Nevertheless, emission reduction due to route optimisation within the waste management sector might make a small but important contribution especially in light of steadily rising traffic emissions.[137]

The outcome of the Smart Waste project was calculatedas following: Based on the results of the latest provincial sorting analysis in 2013, the residual waste generation for the 620 380 rural residents was estimated at approximately 70 000 t.[138] This assumption could be drawn because the waste generation per capita in rural areas was reported at around 113 kg per year. Saubermacher assumes in its Smart Waste Project that an average rural/semi-rural inhabitant incorrectly disposes of 55% of his/her residual waste (for further information please see section 4.1).[139]

According to this, and the fraction specific data presented in section 3.2.2, waste fractions for rural areas would experience a change as presented in Figure 21. A relative decrease of incorrectly disposed residual waste of minus 48% would redirect this fraction towards more valuable and climate friendlier frations of recycables. The wide scale implementation of this project would therefore reduce the most cost intensive section of residual waste by approximately 27 000 t with light packaging showing the most pronounced changes of minus 15%, and metal the least with minus 2%. These individual changes of incorrectly disposed residual waste fractions are described in subsection 3.2.2, Figure 18.

To be complete, the following train of thought shall be mentioned: This model assumes that a decrease of residual waste by one unit results in an increase of a recycables by one unit. With regard to organic waste, this might not be transferrable to rural areas. Especially in the countryside, people still tend to compost organic waste.[140] The redirected organic waste stream might therefore be finally disposed of as compost, rather than in the organic waste bin. Hence, improving separate collection might lead to an increased waste quality, yet would not be a mandatory prerequisite to a proportional quantitiave improvement. Further research would be needed, to better understand the dynamic of waste streams.

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[137] Anderl et al., 'Austria's National Inventory Report 2019, Submission under the United Nations Framework Convention on Climate Change and under the Kyoto Protocol'.
[138] ARGE Ingenieurgemeinschaft Innovative Umwelttechnik GmbH and Saubermacher Dienstleistungs AG, 'Sortieranalyse Für Restmüll Aus Der Steiermark 2013'.
[139] Kornthaler, 'Wertstoffscanner, Smart Waste'.
[140] Felsberger, 'Bioabfall (biogene Siedlungsabfälle), Abfallaufkommen und Mengenentwicklung'.

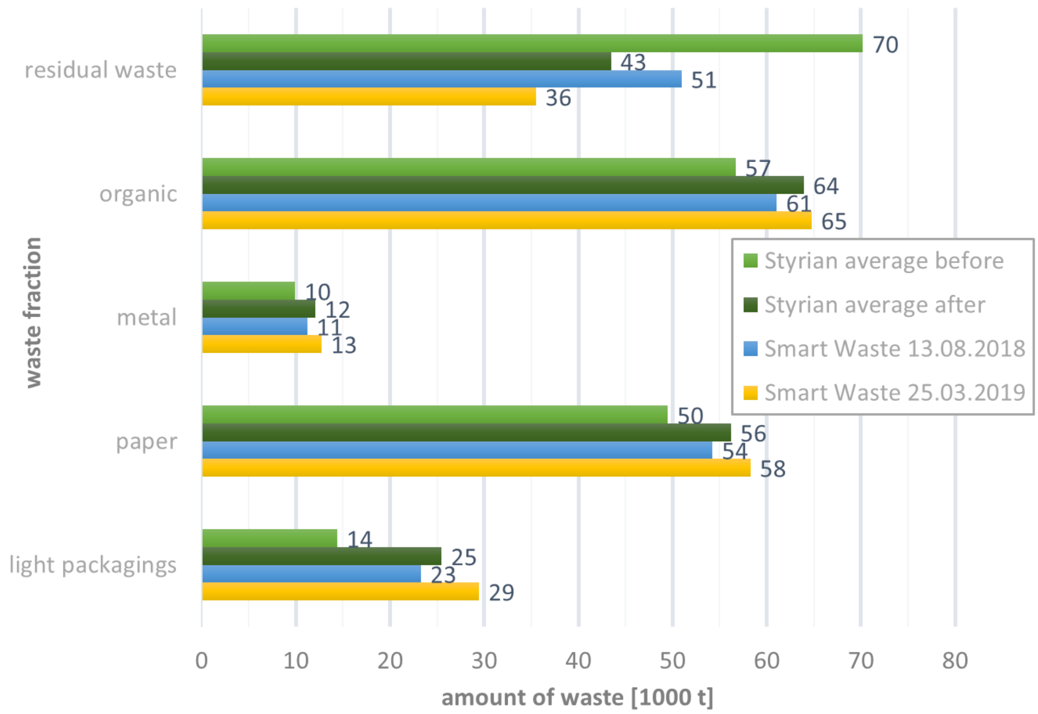

Figure 22: The Utopian Smart Waste Model's impact on waste fractions. Improved separate waste collection lead to a waste stream away from residual waste towards other recyclable fractions. The total waste generated by the utopian rural settlements remains constant, as a decrease in the residual fraction results in an increase of the same amount in the respective recyclable fraction.

For the financial outlook a reference is made to the background information provided in section 2.2. With assumptions laid down therein the costs of 1 kg incorrectly disposed residual waste amounts to €0.1. As a result, a decrease of residual waste in all rural areas of Styria resulting from a reduction in incorrectly disposed waste would result in a financial alleviation of €2.7 Mio, and thereby reduce Styria's annual burden for incorrectly disposed residual waste by more than 30%. It shall be noted that this work focuses on residual mixed waste costs only and does not add the revenues or costs for the resulting separately collected materials. The outcome of the financial aspects is presented in Table 3.

Table 3: The Utopian Smart Waste Model's impact on residual waste, its incorrect fraction and its economical consequences. The relative economic relief for utopian Styria is obtained through a comparison with the economic burden for residual waste of all Styrian rural municiaplities. As the latter describes the situation before the large-scale implementation of the Smart Waste project, the relative relief obtained by the project is noted as zero for rural Styria.

	residual waste [t]	incorrrectly disposed fraction [%]	economical burden [€]	economic relief [%]
rural Styria	70,215	55	3,861,803	0
Utopian Styria	43,469	27	1,187,254	-31

Austria, being a member of the European Union has agreed to fullfill climate targets by curtailing the yearly amount of GHG as already discussed in sector 2.3. Though the waste sector has already successfully reduced its share, Austria's total emissions have been rising by 3.3% from 2016 to 2017.[141] Therefore, as temperatures are rising due to increasing emissions, a further reduction brought about by the waste management sector can only be welcomed irrespective of its actual point of origin.

A positive contribution to climate change can be quantified by emission credits. Directly generated CO_2e emissions from fossil carbon, methane emissions or others result in emission units. The difference between emissions generated and emission units saved from processes, such as substituting fossil fuel with waste to produce energy or recycling metal to protect primary resources, results in emission credits.

The Montanuniversität Leoben developed an online tool on behalf of the province of Styria allowing municipalities to monitor their "climate-footprint" resulting from waste management. If the annual communal quantities of organic waste, paper, glas, metal, residual waste, packaging materials and bulky waste are known, the "Klimabilanz-Tool" calculates the amount of CO_2e emissions as sum of GHGs relevant for waste management.[142] Moreover, it also takes the previously mentioned emissions savings into account when analysing the waste streams. This tool was used to assess the climate-relevant potential of the Smart Waste project, its outcome is presented in Table 4.

Table 4: Emission quantity change througout the Smart Waste project. Category rural Styria describes the situation before the wide-scale implementation of this project, whereas the utopian Styria demonstrates the average effects after its implementation. For the last category, namely Styrian best scenario, the best results of the project, recorded on the 25th of March 2019 were upscaled for the rural areas. This scenario should provide an outlook for the potential of this project.

	rural Styria	utopian Styria	Styrian best scenario
residual waste [t]	70,215	43,469	35,502
emission generation [t CO_2e]	54,176	51,728	51,587
emission saving [t CO_2e]	144,527	142,981	143,613
emission credits [t CO_2e]	-90,351	-91,253	-92,026

The input data for the climate tool is based, on the one hand, on the results obtained by the Smart Waste project as presented in subsection 3.2.2, Table 1. On the other hand, as waste quantities of bulky waste, glas, waste wood, old textiles were not recorded, reference data from the latest yearly report of communal waste generation in Styria was upscaled, and included.[143] As the latter waste streams were not subject of change induced by the investigated project, the same values were used as input data for rural

[141] Data not yet available for the years 2018 and 2019.
[142] For the "Klimabilanztool 2.0" visit klima.unileoben.ac.at or www.klimabilanz.steiermark.at.
[143] 'Jahresbericht zur Abfallwirtschaft, Daten 2017'.

Styria, utopian Styria and Styrian best scenario which is equivalent to the upscaled outcome of Smart Waste measured at the 25th of March 2019. It is for this reason, that a qualitative rather than a quantitative disussion of the Utopian Smart Waste Model outcome seems appropriate.

The changes in emissions arise from a shift within the fractions residual waste, organic waste, metal, paper and light packaging due to an improved seperation of waste. The ecological effect of the utopian Styria scenario based on improved waste seperation would be a decrease of directly emitted GHGs by approximately 5%. Already the announcement of the test start for the 13th of September 2018 showed verifiable effects. The increase in emission credits is mainly due a reduction in generated emissions. The unexpected slight decrease of emission savings cannot be explained and would need further investigation of the underlying mathematical model of the climate tool. In summary, emission credits changed by 1% and 2%, creating a positive contribution in case of transition from rural Styria to utopian Styria or Styrian best scenario respectively. The latter gives an outlook of the possible extent achievable with improved waste seperation.

However, conclusions on the scale of impact with regard to climate targets can only be drawn with reservations, as a detailed comparison of the underlying calculations of the “Klimabilanztool” and the model regulated under the Kyoto Protocol or EU Climate and Energy Package would be necessary, but are not the subject of this thesis. On the assumption of equality, a decrease of emissions generated comparable to the outcome of the utopian scenario would decrease GHG emissions of Austria by more than 34,000 t CO_2e attributable solely to improved seperation in rural areas. Due to reasons mentioned above, this counclusion is to be viewed cautiously.

As this thesis focuses exclusively on rural areas, an emission reduction in these areas, as examined in the course of this model, would lower the greenhouse gas level of the entirety of Styria by $3 \cdot 10^{-3}$%. It shall be noted that the total amount of CO_2e attributed to the waste sector was approximated by the climate tool already mentioned, under consideration of waste volumes reported in 2017. Again, this contribution seems rather negligible, thus prompting a suggestion to investigate the possible effect of implementation, regardless of whether in a rural or urban setting. Moreover, as already requested by Pomberger (2008), emission savings should be taken into account when analysing emissions of the waste sector. [144] This would provide a more holistic picture of the climate-potential of waste management.

[144] Pomberger, Curtis, and Scherübl, ‘Klimarelevanz Der Abfallwirtschaft Aus Sicht Eines Sammlers’.

A presentation by Dr. Opelt during Austria's largest waste management and recycling conference, the Recy&Depotech, demonstrated that despite already high recycling rates, further improvements are needed to comply with the the 65% recycling target for municipal waste set by the Circular Economy Package for 2035. In case of implementation of the new method of calculation, the status quo is unsatisfactory, as 10% are still pending.[145] The utopian Styria could devise a way of how to make further progress. According to this model, a theoretical average increase of the fractions light packaging, metal and paper of 76%, 21% and 13% would be within reach in case of improved separate waste collection. However, a prolonged test time and further investigations would be needed, to clearly understand underlying effects and to demonstrate whether this progress is sustainable or not.

[145] Opelt, 'Sind Wir Smart Genug?'

5 Summary

The current work closely inspects potential economic and ecological improvements within the framework of municipal residual waste management. Waste generation greatly differs between urban and rural settlements, thereby requiring different approaches in its management.[146]

This Thesis places its focus on the rural areas of Styria, a federal province of Austria. For this reason, two digital technology projects, assigned to the collection and logistics, as well as the business ideas and models segment of waste management are examined.[147] To investigate the effects of their wide-scale implementation, a mathematical model was developed within this discourse: Starting point of the Utopian Model was the categorization and characterisation of Styria's rural areas. It was found that approximately half of Styria's population lives in rural sites. Then, the outcome of the previously mentioned projects was extrapolated to all rural municipalities of Styria. The financial relief as well as the carbon emission reduction was evaluated in a wider context through comparison with existing data.

The Route Optimisation project was conducted in the municipality of Birkfeld, under the supervision of Adenso, and included an assessment of the initial waste collection route and its redesign. The reduced tour length led to a cost reduction for the collection service. Furthermore, route characteristics such as length, altitude and loading weight were researched from an ecological perspective. The Utopian Model suggests that route optimisation measures in Styria's municipalities could lead to savings up to €1 Million. In light of the threat that Austria's steadily rising traffic emissions pose to achieving international environment targets, route optimisation projects seem rather promising. However, research by Saubermacher showed that CO_2 emissions originating from waste logistics and processing only amounts to 4% of the total emissions arising from the waste management processes. In case of the Utopian Model a decrease of 400 t CO_2 was calculated. When faced with national emission levels, the economic relief of minus 10% seems the more promising argument for route optimisation projects in rural areas of Styria.

The Smart Waste project demonstrates that it is possible to further reduce the cost-intensive fraction of incorrectly disposed residual waste. Improvements in separate waste collection were achievable due to a closed information loop. The "Wertstoffscanner", a digital imaging device developed by Saubermacher AG, scans the residual waste collected by a waste truck. This data contains, among others, information

[146] Vergara and Tchobanoglous, 'Municipal Solid Waste and the Environment'.
[147] Classification according to 'Digitale Abfallwirtschaft: Mehrwert Entlang Der Gesamten Wertschöpfungskette'.

on the quantity and nature of the incorrectly disposed residual waste. After processing the data collected, information is reported back to the respective target group with the help of diverse feedback channels, such as a municipal newspaper or the customized waste app "Daheim". The outcome demonstrated a relative waste separation improvement of 53% as a result of incentivised citizens. Consequently, the incorrect fraction of residual waste decreased significantly. A transition to the utopian Styria would yield a decrease of 27,000 t of residual waste due to the redirection of former incorrectly disposed waste to recycable fractions. As the costs of for residual waste disposal is covered by municipal waste fees, a decrease of €4 per person, or minus €2.7 Mio in total would be attainable. This would lead to a reduction of Styria's economic burden arising from incorrectly disposed residual waste by more than one quarter. The ecological effect in terms of GHG emission savings was simulated with the help of the "Klimabilanztool 2.0", an online tool developed by the Montanuniversität Leoben. The expected change of communal quantities of organic waste, paper, glas, metal, residual waste, packagings and bulky waste were upscaled for all rural areas and used as its input parameters. It was calculated that a quantitative redistribution of the aforementioned fractions would decrease emissions generation by 2,447 t CO_2e. A decrease of such magnitude would lower the emissions generated by the waste treatment of Styria's rural municipalities by 5%. In order to provide an outlook for what is possible, the best obtained outcome of the Smart Waste project was extrapolated. The best scenario would yield an additional reduction of emisions by 141 t CO_2e.

Table 5 presents the outcome of the Route Optimisation and Smart Waste project for the Utopian model. A comparison of both projects additionally demonstrates, that an environmentally friendly and cost saving management of waste starts at the waste producer and greatly depends on the qualitiy of the separate collection system, and that the digital transition has the potential to support a sustainable development.

Table 5: The numerical outcome of the Utopian Model. The Route Optimisation and Smart Waste projects were extrapolated to the rural municipalities of Styria. Their economical outcome in terms of financial relief for municipalities as well as their ecological impact measured in direct emissions generated were calculated.

	economical outcome		ecological outcome	
	[€/yr]	[%]	[kg CO2e]	[%]
Route Optimisation	-988,854	-	-400,075	$-88*10^{-4}$
Smart Waste	-2,674,549	-27	-2,588,033	-5

6 Conclusions and Recommendations

The outcome of the Utpian Model should be undestood as a generalised conclusion.
The potential for route optimisation greatly depends on the quality of the initial situation and specific characteristics of the individual municipality. In case of Birkfeld, a substantial decrease in distance travelled was possible as a result of access route optimisation and the emergent possibility of waste disposal in a waste treatment plant situated in closer proximity to the municipality.[148] Furthermore, different types of collection and delivery services could be tested. As illustrated in Figure 15 of subsection 3.2.1, the waste collection tour is extensively prolonged by households further away from the city center. The implementation of a delivery and collection service requiring the resident to deposit the waste in a centralized collection station could further decrease the collection tour. If such an unreasonable burden is unacceptable, community workers could pick up the waste directly with flatbed vehicles, for example. The prior scenarios shall be undestood as a rather loose train of thought. Its real-world implementation would require further investigation.
A detailed numerical simulation should also take the different topographical situations into account. Upper Styria is dominated by a mountainous landscape, whereas Eastern Austria is rather hilly. Thus, average fuel consumption and the consequent generation of emissions of waste trucks may vary greatly. However, extensive research based on simulations of waste collection tours requires a digitalisation of the waste collection system of the municipalities. As most municipalties have not yet implemented this process, upscale models similar to the Utopian Model will always imply great simplifications.
The ecological potential of a route optimisation for the entirety of logistic companies should be, from the author's point of view, object of further investigations: Municipal waste collection tours in urban areas are, for example, characterised by very frequent stop-and-go patterns, as the distance between waste bins is shorter due to the higher population density. Especially during this phase, emissions are expected to be above average. Technical innovations such as the emission reducing start/stop technology can help to reduce CO_2 emissions by more than 20%.[149] Therefore, the digitalisation potential to drive green waste management related developments should also be researched for urban areas. In case a significant outcome were to be achieved, other delivery or pick-up services with regular tours could profit from the knowledge already gained, and thereby accelerate the desperately needed decrease of vehicular exhaust.

[148] According to the invertview with Moser-Bauernhofer and Reitbauer.
[149] Fonseca, Casanova, and Valdés, 'Influence of the Stop/Start System on CO2 Emissions of a Diesel Vehicle in Urban Traffic'.

The Smart Waste project demonstrated that it is possible to further reduce the incorrectly disposed fraction of residual waste. This work assumes that a decrease of this fraction is due to an improved separate waste collection: The waste producer can be motivated to seperately collect packaging that was previously thrown into the residual waste bin, for example. However, more scenarios are conceivable. If residual waste would be charged directly according to weight and/or quality, the risk that residents might try to save money by redirecting parts of the residual waste to other waste fractions might rise. This would lead to an undesirable decrease in the quality of recycable material. Concequently one might think that "screening" all recycable waste fractions with a waste scanner similar to the one used in the Smart Waste project might improve the waste quality of those divisions. However, with rising waste fees charged directly and stricter monitoring, household may also have a stronger incentive to dump waste illegally. This would shift the waste stream from the municipal waste collection to fly tipping with tremendous undesirable environmental consequences. A study conducted for England underlines this assumption. Morris and Read (2001) found that if the opportunity costs for fly tipping exceed the costs for disposing rubbish, an increasing amount of individuals and business will dump waste illegally.[150] Only an elimination of avenues of illegal dumping would allow direct charges applied to citizens to provide an adequate incentive to improve their separate waste collection behaviour.[151]

A more sustainable approach would involve promoting social awareness. Although 85% of Austrians consider separate waste collection as an important ecological contribution, evidence shows that especially young people are often uninformed about correct waste separation procedures.[152] As already discussed in section 3.2.2, a closed information loop might provide the right household incentive. Additionally, changes in waste streams resulting from stimuli set by waste management companies or the municipalitiy itself become evident at an earlier stage. The close monitoring of impulse and reaction would enhance understanding of the underlying dynamics and would provide an interesting tool for research on municipal waste management. Especially in light of increasing migration, an increased effort to strengthen awareness and knowledge about separate waste collection becomes necessary.[153] The Austrian system may differ greatly and may seem too complex at first. New scientific findings could serve as a base to amend and improve

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[150] Morris and Read, 'The UK Landfill Tax and the Landfill Tax Credit Scheme'.
[151] Liu, Kong, and Santibanez Gonzalez, 'Dumping, Waste Management and Ecological Security'.
[152] Verband der österreichischen Entsorgungsbetriebe, '85 Prozent Der Österreicher Achten Auf Mülltrennung'.
[153] 'System Zu Komplex? Hohe Fehlwurfquote Beim Verpackungsmüll'.

waste related educational work in schools or other insitutions, thus sensitising the public to the issue.

The legal framework has the potential to become a trailblazer for Industry 4.0 developments. More stringent ecological and economical goals could become attainable with the help of innovations such as the route opimisation of waste collection tours or similar to the Smart Waste project. A bottom-down approach in legislation shall be illustrated from an environmental point of view, as the benefits of cost-saving measures are more aparent and easier to stimulate with the help of regulations on waste fees.
As already mentioned, several international agreements require an increase of recycling quotas and/or a reduction of GHG emissions. In order to assess the status quo of waste management with regard to recycling quotas, the use of a ternary diagramm similar to the waste diagramm developed by Pomberger et al. (2016) could be prescribed on a municipal level.[154] This would establish a municipal benchmark and thereby increase the ability to compare municipal actions and improvements which might accelerate their effort. As higher recycling quotas are closely associated with improved separate waste collections, projects of anologue format to the Smart Waste one can provide the right tool. Similarly, a nationwide usage of the "Klimabilanztool 2.0" would facilitate the monitoring and assessment of municipial climate footprints due to waste management actions. The Utopian Model demonstrated that CO_2 emission reduction can be expected to result from both investigated digitalisation projects.
Even if a bottom-up rahter than a paternalisitc apporach is prefered, politics shall not be relieved from its role to support municipal efforts. New measures developed to incentivise and encourage sustainable waste management on a municipial level can be promoted by programmes similar to the European Energy Award which attests innovative energy-saving projects of municipalities. Comparable scenarios are imaginable for waste management projects should therefore be promoted by politics.
Moreover, separate waste collection is aggrevated by the increasing complexity of the products itself, especially with regards to the packaging sector. The producer responsibility principle stimultated the development of free take-back instruments and is understood to incentivise the industry to contribute towards environmental friendly innovations. Yet, if intermediary actors, namely the citizens who separate the waste, are prevented from achieveing the desired expectations by increasingly complex products, recycables are likely to end up in the residual waste fraction. Furthermore, intelligent packaging of products should be in line with the Waste Hierarchy of the Europan Union.

[154] 'Digitale Abfallwirtschaft: Mehrwert Entlang Der Gesamten Wertschöpfungskette'.

Therefore, the legislative is increasingly required to enter into dialogue with the industry in order to foster sustainable developments.

In summary, it can be concluded from the Utopian Model that technological innovations within the waste management sector do have the power to drive sustainable developments and protect resources. Nevertheless, one must consider that every digital device requires raw materials for its original production. However, Uecker (2018) derived that Industry 4.0 also has the potenital to increase efficiencies of the production processes, which then in return would optimise the use of resources and help to protect them.

It can be seen, that Industry 4.0 entials highly interlinked effects. Hence, in order to assess the big picture of emerging trends, more research is needed.

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Annex 1

Urban Rural Typology as classified by Statistiks Austria according to accessibility[155]

		Zentral (Erreichbarkeit SR < 30 min)	**Intermediär** (Erreichbarkeit SR ≥ 30 min und RZ < 20 min)	**Peripher** (Erreichbarkeit SR ≥ 30 min und RZ ≥ 20 min)
Städtisch/ Urban	SR100 **Stadt-regionen**	**101** Urbane Großzentren		
		102 Urbane Mittelzentren		
		103 Urbane Kleinzentren		
Ländlich/ Rural	RZ200 **Regionale Zentren**	**210**	**220**	
	LR300 **Ländlicher Raum im Umland von Zentren**	**310**	**320**	**330**
	LR400 **Ländlicher Raum**	**410**	**420**	**430**

Annex 2

Size of Austrian communities along with inhabitants for 2018 [156]

Gemeindegrößenklassen mit Einwohnerzahl 2018

Größenklasse	Burgenland		Kärnten		Niederösterreich		Oberösterreich		Salzburg		Steiermark		Tirol		Vorarlberg		Wien		Österreich	
	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung	Anzahl der Gemeinden	Summe der Bevölkerung
-500	17	5.765	.	.	21	6.843	11	4.364	7	2.590	3	1.322	34	10.440	15	5.084	.	.	108	36.408
501- 1.000	39	31.287	13	10.700	83	64.773	75	57.067	14	10.144	14	10.722	60	43.949	18	13.069	.	.	316	241.711
1.001- 1.500	45	56.313	25	30.593	124	153.027	75	93.734	15	18.744	51	65.819	55	69.529	10	12.304	.	.	400	500.063
1.501- 2.000	25	44.239	26	45.193	103	175.898	68	115.181	10	16.897	46	79.251	32	55.031	8	14.282	.	.	318	545.972
2.001- 2.500	17	37.564	16	34.730	61	133.488	56	124.318	8	18.024	42	93.242	23	50.673	10	22.160	.	.	233	514.199
2.501- 3.000	10	27.778	12	32.348	45	124.664	38	104.861	11	30.308	26	72.050	17	46.017	4	10.431	.	.	163	448.457
3.001- 5.000	13	46.318	21	80.644	69	258.733	64	246.648	33	127.888	58	227.533	34	132.402	14	53.309	.	.	306	1.173.475
5.001- 10.000	4	28.935	12	86.303	41	282.045	40	259.463	14	91.453	34	233.151	16	111.852	7	47.831	.	.	168	1.141.033
10.001- 20.000	1	14.476	4	53.104	19	249.563	8	110.355	5	62.004	10	123.389	7	98.754	6	77.946			60	789.591
20.001- 30.000	.	.	1	25.035	5	122.165	2	53.175	1	21.150	2	47.443	.	.	2	52.627			13	321.595
30.001- 50.000	.	.	.	.	1	44.820	1	38.331	.	.	.	.	.	.	2	82.698			4	165.849
50.001-100.000	.	.	1	61.879	1	54.649	1	61.233	.	.	.	.	.	.	.	.			3	177.761
100.001-200.000	.	.	1	100.369	.	.	.	.	1	153.377	.	.	1	132.493	.	.			3	386.239
200.001-500.000	.	.	.	.	.	.	1	204.846	.	.	1	286.292	.	.	.	.			2	491.138
über 1 000.000	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1.888.776	1	1.888.776
Summe	171	292.675	132	560.898	573	1.670.668	440	1.473.576	119	552.579	287	1.240.214	279	751.140	96	391.741	1	1.888.776	2.098	8.822.267

Q: Statistik Austria

155 'Urban-Rural-Typologie'.
156 Statistik Austria, 'Gemeinden'.

Annex 3

Table illustrating composition of incorrectly disposed fraction of residual waste over the course of the test period of the Smart Waste project[157]

date	light packagings	paper	metal	organic
13.08.18	17%	10%	3%	8%
10.09.18	17%	13%	2%	4%
08.10.18	12%	3%	2%	0%
05.11.18	17%	7%	1%	1%
03.12.18	15%	4%	0%	7%
31.12.18	18%	6%	3%	1%
28.01.19	17%	12%	1%	2%
25.02.19	14%	7%	2%	1%
25.03.19	7%	3%	0%	1%

Annex 4

Inhabitants of municipalities sorted according to urban-rural topoloy for 2017. The table was created by the author with official municipal key, municipality as well as inhabitants based on Landesenwticklung Steiermark and urban rural topology based on Statistik Austria. [158,159]

official municipal key	municipality	urban-rural topology	inhabitants
60323	Pölfing-Brunn	430	1624
60345	Eibiswald	430	6495
60351	Wies	430	4433
61002	Arnfels	430	1013
61024	Oberhaag	430	2133
61112	Radmer	430	562
61204	Altaussee	430	1879
61205	Altenmarkt bei Sankt Gallen	430	821
61207	Bad Aussee	430	4830
61213	Gröbming	430	3011
61215	Grundlsee	430	1201
61251	Wildalpen	430	466
61253	Admont	430	5017
61255	Bad Mitterndorf	430	4966
61256	Gaishorn am See	430	1334
61257	Irdning-Donnersbachtal	430	4125

157 Table adopted by author based on Kornthaler, 'Wertstoffscanner, Smart Waste'.
158 Holzer, 'Wohnbevölkerung'.
159 'Urban-Rural-Typologie'.

61258	Landl	430	2719
61261	Mitterberg-Sankt Martin	430	1936
61262	Öblarn	430	2029
61264	Sankt Gallen	430	1832
61266	Sölk	430	1493
61410	Mühlen	430	880
61437	Krakau	430	1425
61439	Neumarkt in der Steiermark	430	4980
61440	Oberwölz	430	2970
61443	Sankt Lambrecht	430	1847
61708	Fischbach	430	1530
61711	Gasen	430	913
61728	Miesenbach bei Birkfeld	430	696
61741	Ratten	430	1126
61743	Rettenegg	430	747
61744	St. Kathrein am Hauenstein	430	635
61750	Strallegg	430	1933
61759	Gersdorf an der Feistritz	430	1703
62010	Hohentauern	430	406
62021	Pusterwald	430	450
62142	Mariazell	430	3819
62216	Großsteinbach	430	1246
62242	Sankt Jakob im Walde	430	1054
62245	Sankt Lorenzen am Wechsel	430	1493
62262	Wenigzell	430	1400
62274	Neudau	430	1487
62278	Vorau	430	4724
62279	Waldbach-Mönichwald	430	1530
62387	Sankt Anna am Aigen	430	2339
62388	Sankt Peter am Ottersbach	430	2956
62390	Straden	430	3598
60329	Sankt Peter im Sulmtal	420	1267
60349	Schwanberg	420	4573
61203	Aigen im Ennstal	420	2706
61206	Ardning	420	1228
61217	Haus	420	2428
61222	Lassing	420	1723
61236	Ramsau am Dachstein	420	2804
61243	Selzthal	420	1593
61247	Trieben	420	3393
61252	Wörschach	420	1128
61254	Aich	420	1283
61260	Michaelerberg-Pruggern	420	1178
61263	Rottenmann	420	5236
61267	Stainach-Pürgg	420	2861
61425	St. Peter am Kammersberg	420	2043

61428	Schöder	420	944
61441	Ranten	420	1160
61442	Sankt Georgen am Kreischberg	420	1774
61445	Stadl-Predlitz	420	1675
61446	Teufenbach-Katsch	420	1897
62144	Neuberg an der Mürz	420	2492
62202	Bad Blumau	420	1641
62205	Buch-St. Magdalena	420	2175
62206	Burgau	420	1048
62209	Ebersdorf	420	1272
62211	Friedberg	420	2604
62214	Greinbach	420	1793
62220	Hartberg Umgebung	420	2235
62226	Lafnitz	420	1464
62232	Ottendorf an der Rittschein	420	1555
62233	Pinggau	420	3175
62235	Pöllauberg	420	2059
62244	Sankt Johann in der Haide	420	2149
62252	Söchau	420	1421
62264	Bad Waltersdorf	420	3789
62265	Dechantskirchen	420	2041
62268	Grafendorf bei Hartberg	420	3080
62270	Hartl	420	2135
62272	Kaindorf	420	2938
62273	Loipersdorf bei Fürstenfeld	420	1880
62275	Pöllau	420	6066
62276	Rohr bei Hartberg	420	1458
62277	Rohrbach an der Lafnitz	420	2636
62311	Edelsbach bei Feldbach	420	1336
62326	Halbenrain	420	1748
62332	Kapfenstein	420	1563
62335	Klöch	420	1197
62368	Tieschen	420	1257
62372	Unterlamm	420	1254
62375	Bad Gleichenberg	420	5309
62377	Deutsch Goritz	420	1821
62378	Fehring	420	7323
62380	Gnas	420	6053
62384	Paldau	420	3112
62386	Riegersburg	420	4910
60346	Groß Sankt Florian	410	4178
60347	Sankt Martin im Sulmtal	410	3044
60348	Sankt Stefan ob Stainz	410	3566
60350	Stainz	410	8650
60651	Übelbach	410	2030

60663	Frohnleiten	410	6662
61008	Gabersdorf	410	1226
61013	Großklein	410	2293
61016	Heimschuh	410	1972
61019	Kitzeck im Sausal	410	1220
61030	Sankt Andrä-Höch	410	1730
61032	Sankt Johann im Saggautal	410	2020
61049	Ehrenhausen an der Weinstraße	410	2550
61050	Gamlitz	410	3250
61051	Gleinstätten	410	2812
61054	Leutschach an der Weinstraße	410	3723
61056	Sankt Veit in der Südsteiermark	410	4041
61057	Schwarzautal	410	2315
61058	Straß in Steiermark	410	4858
61101	Eisenerz	410	4060
61105	Kalwang	410	998
61106	Kammern im Liesingtal	410	1607
61107	Kraubath an der Mur	410	1274
61109	Mautern in Steiermark	410	1777
61119	Wald am Schoberpaß	410	587
61413	Niederwölz	410	596
61444	Scheifling	410	2140
61611	Krottendorf-Gaisfeld	410	2472
61627	Edelschrott	410	1744
61628	Geistthal-Södingberg	410	1538
61629	Hirschegg-Pack	410	1025
61710	Floing	410	1196
61716	Markt Hartmannsdorf	410	2942
61719	Hofstätten an der Raab	410	2254
61740	Puch bei Weiz	410	2098
61745	Sankt Kathrein am Offenegg	410	1085
61746	St. Margarethen an der Raab	410	4090
61748	Sinabelkirchen	410	4204
61756	Anger	410	4133
61757	Birkfeld	410	5002
61758	Fladnitz an der Teichalm	410	1789
61761	Gutenberg-Stenzengreith	410	1778
61762	Ilztal	410	2149
61763	Passail	410	4263
61764	Pischelsdorf am Kulm	410	3716
61765	Sankt Ruprecht an der Raab	410	5282
62008	Gaal	410	1372
62026	Sankt Georgen ob Judenburg	410	849

62034	Seckau	410	1279
62036	Unzmarkt-Frauenburg	410	1360
62042	Obdach	410	3813
62043	Pöls-Oberkurzheim	410	2976
62044	Pölstal	410	2685
62048	Weißkirchen in Steiermark	410	4883
62105	Breitenau am Hochlantsch	410	1707
62115	Krieglach	410	5294
62131	Spital am Semmering	410	1522
62132	Stanz im Mürztal	410	1829
62135	Turnau	410	1547
62138	Aflenz	410	2406
62141	Kindberg	410	8146
62145	Sankt Barbara im Mürztal	410	6612
62247	Schäffern	410	1375
62256	Stubenberg	410	2168
62266	Feistritztal	410	2416
62269	Großwilfersdorf	410	2063
62271	Ilz	410	3741
62314	Eichkögl	410	1309
62330	Jagerberg	410	1655
62343	Mettersdorf am Saßbach	410	1287
62347	Murfeld	410	1651
62382	Kirchberg an der Raab	410	4489
62383	Mureck	410	3566
62389	Sankt Stefan im Rosental	410	3954
60632	Peggau	330	2202
62148	Tragöß-Sankt Katharein	330	1902
60318	Lannach	310	3462
60324	Preding	310	1772
60326	Sankt Josef (Weststeiermark)	310	1587
60341	Wettmannstätten	310	1586
60613	Gratkorn	310	7880
60618	Haselsdorf-Tobelbad	310	1399
60623	Kainbach bei Graz	310	2802
60626	Kumberg	310	3854
60628	Laßnitzhöhe	310	2794
60629	Lieboch	310	5099
60639	Sankt Bartholomä	310	1434
60641	Sankt Oswald bei Plankenwarth	310	1238
60642	Sankt Radegund bei Graz	310	2164
60645	Semriach	310	3328
60647	Stiwoll	310	725
60648	Thal	310	2273

60654	Weinitzen	310	2613
60656	Wundschuh	310	1583
60659	Deutschfeistritz	310	4282
60660	Dobl-Zwaring	310	3539
60661	Eggersdorf bei Graz	310	6602
60664	Gratwein-Straßengel	310	12984
60665	Hitzendorf	310	7120
60666	Nestelbach bei Graz	310	2642
60668	Sankt Marein bei Graz	310	3657
61001	Allerheiligen bei Wildon	310	1465
61007	Empersdorf	310	1375
61017	Hengsberg	310	1443
61020	Lang	310	1317
61021	Lebring-Sankt Margarethen	310	2170
61027	Ragnitz	310	1463
61033	Sankt Nikolai im Sausal	310	2256
61052	Heiligenkreuz am Waasen	310	2778
61055	Sankt Georgen an der Stiefing	310	1480
61059	Wildon	310	5345
61113	Sankt Michael in Obersteiermark	310	3065
61115	Sankt Stefan ob Leoben	310	1936
61116	Traboch	310	1377
61118	Vordernberg	310	1057
61120	Trofaiach	310	11138
61612	Ligist	310	3265
61615	Mooskirchen	310	2195
61621	Sankt Martin am Wöllmißberg	310	797
61624	Stallhofen	310	3127
61630	Kainach bei Voitsberg	310	1624
61633	Söding-Sankt Johann	310	4086
61729	Mitterdorf an der Raab	310	2053
61730	Mortantsch	310	2164
61731	Naas	310	1379
61751	Thannhausen	310	2430
62014	Kobenz	310	1854
62032	Sankt Peter ob Judenburg	310	1109
62045	Sankt Marein-Feistritz	310	2006
62046	Sankt Margarethen bei Knittelfeld	310	2731
62125	Pernegg an der Mur	310	2355
62128	Sankt Lorenzen im Mürztal	310	3606
62146	Sankt Marein im Mürztal	310	2689
62147	Thörl	310	2318
62381	Kirchbach-Zerlach	310	3270

62385	Pirching am Traubenberg	310	2552
60344	Deutschlandsberg	220	11606
61259	Liezen	220	8211
61265	Schladming	220	6661
61438	Murau	220	3647
62219	Hartberg	220	6651
62267	Fürstenfeld	220	8539
62376	Bad Radkersburg	220	3172
62379	Feldbach	220	13356
60305	Frauental an der Laßnitz	210	2885
61701	Albersdorf-Prebuch	210	2038
61727	Ludersdorf-Wilfersdorf	210	2396
61760	Gleisdorf	210	10720
62116	Langenwang	210	3867
62143	Mürzzuschlag	210	8557
61012	Gralla	103	2385
61043	Tillmitsch	103	3273
61045	Wagna	103	5830
61053	Leibnitz	103	12232
61618	Rosental an der Kainach	103	1667
61625	Voitsberg	103	9463
61626	Bärnbach	103	5638
61631	Köflach	103	9906
61632	Maria Lankowitz	103	2861
61766	Weiz	103	11594
62007	Fohnsdorf	103	7706
62038	Zeltweg	103	7232
62039	Lobmingtal	103	1853
62040	Judenburg	103	9959
62041	Knittelfeld	103	12660
62047	Spielberg	103	5337
61108	Leoben	102	24762
61110	Niklasdorf	102	2525
61111	Proleb	102	1525
61114	Sankt Peter-Freienstein	102	2377
62139	Bruck an der Mur	102	15879
62140	Kapfenberg	102	22826
60101	Graz	101	285430
60608	Feldkirchen bei Graz	101	6315
60611	Gössendorf	101	3989
60617	Hart bei Graz	101	4960
60619	Hausmannstätten	101	3243
60624	Kalsdorf bei Graz	101	6860
60646	Stattegg	101	2911
60653	Vasoldsberg	101	4540
60655	Werndorf	101	2374

60662	Fernitz-Mellach	101	4765
60667	Raaba-Grambach	101	4402
60669	Seiersberg-Pirka	101	11136
60670	Premstätten	101	6052