MSc Program
Environmental Technology & International Affairs

Carbon dioxide Emissions of coal fired Steam Locomotives on Austrian Railways and Fuel Adaptations in times of Energy Crisis and Climate Policy

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Ao.Univ.Prof.i.R. Dipl.-Ing. Dr.techn. Hans Puxbaum

Leonhard Hartinger MEd

01472056

Vienna, 01.06.2023

Affidavit

I, **LEONHARD HARTINGER MED**, hereby declare

1. that I am the sole author of the present Master's Thesis, "CARBON DIOXIDE EMISSIONS OF COAL FIRED STEAM LOCOMOTIVES ON AUSTRIAN RAILWAYS AND FUEL ADAPTATIONS IN TIMES OF ENERGY CRISIS AND CLIMATE POLICY", 86 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 the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 01.06.2023

Signature

Abstract

This Master's thesis examines the carbon dioxide emissions of coal-fired steam operations on Austrian heritage and touristic railways, discusses problems in procurement, storage, and quality of coal, and gives an overview of the status of experience, current operation, and plans of alternative firing methods. The shift away from coal as an energy source due to climate change mitigation efforts and the global energy crisis are making bituminous coal more difficult to procure. This results in poor quality and high prices, putting pressure on steam operators, and creating challenges for the future. Two possible alternative firing methods to provide similar performance discussed in this thesis are oil firing and the use of biomass-based coal substitutions with similar energy density. While conversion to oil firing involves a high financial outlay and does not immediately solve the emissions problem, biomass-based coal substitutions require further development until they are ready for large scale production. The data was collected for all 25 Austrian heritage and touristic railways operating with steam locomotives and was divided into a quantitative and qualitative part. Missing data were compensated by research and an extrapolation includes railways, where the steam operation was cancelled in the year 2022 due to irregularities. The total carbon dioxide emissions from coal-fired steam locomotive operations in Austria are approximately 3,000 tons per year. Problems in procurement, storage and quality of coal were experienced by a majority of the organizations, while only a minority had experimental or operational experience with alternative firing methods or plans for conversion.

Preface

It was the last Sunday in November 2022. The atmospheric chemistry exam with our programme director Professor Puxbaum was scheduled for the following day. My brother Johannes and two of my friends from the ETIA programme, Rupert and Émile, were sitting in the first wagon behind a steam locomotive on the *Steyrtalbahn* in Upper Austria. Instead of spending the weekend in the library for exam preparation, we decided, with our study materials at least stowed away in our backpacks, to take this first weekend of Advent for a trip to the Christmas markets of the festively decorated town of Steyr and to the *Steyrtalbahn*. The steam locomotive driver Gerry, whom I already knew from previous encounters, allowed us to ride along in the driver's cab for a few kilometers each and explained the function of his class U locomotive from 1898 in detail. In our childlike enthusiasm for the fascinating archaic technology, thoughts of tomorrow's exam caught up with us for a moment. Thinking about atmospheric chemistry and standing in front of the smoking steam locomotive, we started to think about the scope of carbon dioxide emissions from steam locomotives. The result of the exam the next day was rather moderate and corresponded to our cultural- and culinary preparation weekend. Although my decision to study the ETIA programme at the Diplomatic Academy and the Technical University was based more on my political interest, and the professor of the first exam at TU certified that although I had a basic understanding of natural sciences, I should intensively improve my poor analytical approach, this experience at the *Steyrtalbahn* motivated me to take on the personal challenge of a thesis with a technological focus. The confrontation with my inner conflict between the cultural heritage of steam locomotives, for which my deceased father had inspired me since my early childhood, and my conviction of the need for rapid and radical greenhouse gas reductions turned out to be a good motivation. I would like to express the gratitude I owe to my always helpful supervisor Professor Puxbaum, to my unconditionally supportive mother and to many other people in my circle of friends and family, in a more personal way. All in all, I am very grateful to be in the privileged position of being able to complete a second master's degree in my mid-twenties without any financial worries and will give my best to use the knowledge acquired in the last two years to make a small contribution to the preservation of our planet.

Table of Contents

Abstract i

Preface ii

Table of Contents iii

1. Introduction 1

2. State of the art and literature review 3
   - 2.1 The cultural heritage of steam railways in Austria 3
   - 2.2 Technical Principles 10
   - 2.3 Emissions of coal combustion in steam locomotives 15
   - 2.4 Coal market in times of geopolitical tensions and climate policy 20
   - 2.5 Oil and Biocoal as alternative fuels for steam locomotives 23

3. Methodology 31

4. Research Chapter 35
   - 4.1 Field of Research 35
   - 4.2 Individual Results 37
   - 4.3 Emission Results 55
   - 4.4 Fuel management results 62

5. Summary and Conclusion 64

References 69

List of tables 78

List of figures 79

Annex A1

1. Introduction

No technical construction is as closely associated with the age of industrialization as the steam railway. From the middle of the 19th century until into the 20th century, steam locomotives shaped the transport of goods and passengers, connecting not only economic centers but also remote regions with reliable means of transport. Today, with a few exceptions, steam locomotives are only in nostalgic operation but enjoy great popularity as a tourist attraction. In Austria, 25 institutions operate steam locomotives in heritage and touristic traffic and thus contribute to the operational preservation of the technical cultural heritage. Due to the dominant coal firing, steam locomotives are in the focus of climate debates. The aim of this thesis is to determine the magnitude of the resulting carbon dioxide emissions, which leads to the following main research question: What are the carbon dioxide emissions of steam traction on Austrian heritage and touristic railways?

The economic upheavals in the fuel market caused by the Corona crisis and the Ukraine war have also affected the prices and commodity chains of coal. In order to assess the impact of these events on the steam operations of Austrian heritage and touristic railways, the following supplementary question arises: Which problems in procurement, storage and quality of coal did steam powered Austrian heritage and touristic railways face between spring 2021 and spring 2023?

To limit the impact of anthropogenic climate change to a manageable level, a radical global reduction of carbon dioxide emissions is necessary. The resulting climate policies will continue to restrict the use of fossil fuels and favor climate-friendly adaptations. In order to get an overview of experience, current operation, and plans of steam-powered Austrian heritage and touristic railways to coal alternatives, the following research question is posed as a further supplementary one: What is the status of alternative firing methods in the experience, current operation, and plans of steam-powered Austrian heritage and touristic railways?

The motivation for this thesis comes from the discussion potential that the use of steam locomotives raises in times of climate protection. The data generated will be made available to the institutions concerned in order to contribute to a factual basis for discussions, considerations and decisions on the subject of steam operation. The author's personal conviction is that steam locomotives, as an important testimony to an industrial society, should be able to transmit the technical, economic, and cultural significance of this key technology to future generations.

Figure 1 Two historic monuments: Trestle bridge from 1898 and steam locomotive class Uv from 1902 on the Ybbstal Railway Mountain line (Own work, 2015)

2. State of the art and literature review

2.1 The cultural heritage of steam railways in Austria

When the first section of the horse-drawn railway Gmunden-Linz-Budweis, built and operated by the *k. k. priv. erste Eisenbahngesellschaft*, went into operation in southern Bohemia between *Trojerhof* near Zartelsdorf and Budweis on 7 September 1827 (Sachslehner, 2014, pp. 26-27), the first steam engines had already been moving on the rails of industrial and mining companies in Great Britain for almost 25 years (Maedel, 1965, pp. 10-11). While in the year of 1829, it was decided to extend the horse-drawn railway in Austria to Gmunden (Sachslehner, 2014, p. 27), a historical event was taking place in Great Britain. At the famous *Race of Rainhill*, George Stephenson's steam locomotive *Rocket* prevailed in a competition for the future steam locomotive operation of the *Liverpool and Manchester Railway* (Giesl-Gieslingen, 1986, p. 13), thus giving the starting signal for an era of railway-driven industrialization based on James Watt's steam engine.

George Stephenson himself supplied four of the first locomotives, including instruction personnel, for the first Austrian steam railway, the *Nordbahn*, which is closely associated with the geologist *Xaver Riepl* and the banker *Salomon Freiherr von Rothschild* (Sachslehner, 2014, pp. 32-33). A trial run in November 1837 marked the first trips on the Vienna-Brno railway line, which was fully opened in 1839. In addition to the expansion of traffic in a northerly direction and thus the development of important cities and valuable sources of raw materials such as coal fields, construction work also began in a southerly direction in 1839, which in 1840 already allowed operation as far as Baden but ended in 1842 in Gloggnitz at the foot of the Semmering (Sachslehner, 2014, pp. 50-55). In 1853, after five years of construction, the Semmering Railway was opened as the first mountain railway in the world, although at the beginning of construction five years earlier there was no locomotive that met the requirements of gradient and curve radius (Maedel, 1965, pp. 44-45). The *Bavaria* of the Munich based *Maffei* company won a competition held by the bold builder of the line, Carl Ritter von Ghega, but the other three participating locomotives also proved to be very relevant in terms of construction history (Maedel, 1965, pp. 44-45). The technical conquest of the Semmering by railway opened the door to Styria, where the iron industry was booming, and subsequently to the economically very important port of Trieste, which was reached in 1857 (Sachslehner, 2014, p. 72). The pioneering period of the railways in Austria marked an epoch of a process of expansion of the railway network, driven by its own technical achievements, combined with constructive innovation at an unprecedented speed.

The steam-powered railway not only shaped the economic and social development of the central regions, but also increasingly opened up more remote regions of the Monarchy in the second half of the 19th century. Already in the revolution year of 1848 (Sachslehner, 2014, pp. 41-46) and a year later during Radetzky's warfare in Italy (Schiendl, 2015, p. 8), the railway demonstrated its great military importance, which increased as a result of the expanding network. The track gauge of 1435 millimeters chosen by George Stephenson for his railway projects and the successful export of his designs to the European continent laid the foundation for a continuous European railway network from the Arctic Circle to the Bosporus and beyond, which today still has the track gauge chosen by him. Wider gauges were developed on the Iberian Peninsula and in the Russian sphere of influence. The beginning construction of branch lines towards the end of the 19th century was based on a changed economic policy approach of building railways not for the expectation of profit but to open up areas in need of development (Österreichische Raumkonferenz, 1980, pp. 9-10). In addition to the usual standard gauge, after good experiences with the development of the military occupied Bosnia and Herzegovina (Schiendl, 2015), narrow-gauge railways with a gauge of 760 millimeters were built more and more frequently. The various uses in passenger, freight and shunting services with different loads and speeds, as well as the different line characteristics in terms of topography, curve radii, water supply and track gauge, required a variety of different steam locomotive designs from the industry. Of particular relevance to the Austrian history of technology are the 47 locomotive types developed between 1893 and 1916 by Karl Gölsdorf, who was head of the design office of the Austrian State Railways (Giesl-Gieslingen, 1981, pp. 7-8). His designs produced up to 3.6 times the output of their predecessors (Giesl-Gieslingen, 1981, p. 7), were successfully exported and shaped railway traffic in Europe, especially in the countries of the former imperial and royal monarchy, until the second half of the 20th century. His designs were manufactured in the machine factory of the *Austro-Hungarian State Railway Company*, the locomotive factories of *Wien Floridsdorf*, *Sigl Wiener Neustadt*, *Krauss Linz*, and the *Bohemian-*

Moravian machine factory in Prague (Giesl-Gieslingen, 1981, p. 7). Some of Gölsdorf's designs, such as the large express steam locomotive class 310 from 1911, which combined the technical innovations of superheated steam technology and compound engines with an output of 1800 horse powers (Sachslehner, 2014, p. 141), can still be experienced in museum operation today.

Figure 2 Gölsdorf's construction later ÖBB class 92 operated by the Heritage Local Railway Association Zwettl at a guest excursion on the Ampflwang Railway (Own work, 2023)

After the First World War and the Treaty of Saint-Germain, which sealed the end of the great multi-ethnic state of Austria-Hungary, the national territory and the economic area were significantly reduced. Due to the lack of own large coal deposits and problems with coal supplies from the new foreign countries, electrification was pushed politically, starting with the topographically demanding and thus energy-intensive Alpine routes, together with the construction of hydroelectric power plants (Kraus, 1992, pp. 23-26). However, as there was still a need for modern powerful steam locomotives due to the sluggish electrification, especially in the east of the country, eleven more successful steam locomotive designs (Giesl-Gieslingen, 1981, p. 8) were built, mainly for the BBÖ, the Federal Railways of the First Republic. The culmination of the history of Austrian steam locomotive construction was the class 214 from 1928, which caused a worldwide sensation (Giesl-Gieslingen, 1981, p. 8) and with an output of around 2700 horse powers had the reputation of being one of the most powerful European steam locomotives (Schröpfer, 2002, p. 84).

In the course of the annexation of Austria to the German Reich in 1938, the Austrian Federal Railways were incorporated into the German *Reichsbahn* and the *Wiener Lokomotivfabrik* into the *Henschel Werke*, which put an end to the almost 100-year Austrian tradition of locomotive construction, since from then on mainly German standard designs, mostly war locomotives, were produced in a considerable number of 2112 locomotives until March 1945 (Schröpfer, 2002, p. 252). After the last post-serial war locomotives were delivered to the Austrian State Railways two years later under Soviet occupation, the construction of steam locomotives in Austria came to an end (Schröpfer, 2002, pp. 254-255).

In addition to the focus on electric traction, petrol and diesel-powered railcars and locomotives entered Austrian railway service from the end of the 1920s. However, due to their poor performance, these could only be used for isolated tasks (Doleschal, et al., 1999). Light diesel railcars proved to be successful in rapid transit between cities with limited seating capacity because attractive trips times could be achieved due to the absence of frequent fuel supply stops and their high speeds.

After the Second World War it was not possible that diesel locomotives and diesel railcars were able to take over the tasks of steam locomotives to a serious extent, although there was support of US engineers, but the increasing electrification of main lines such as the *Westbahn* and the *Südbahn* led to a greater replacement by more efficient and economical electric locomotives. On many branch lines, however, steam locomotives could still not be replaced. Post-war technical innovations in the steam locomotive sector, such as the *Giesl ejector* named after its inventor Adolph Giesl-Gieslingen, were able to increase performance (Giesl-Gieslingen, 1981, pp. 279-283), but the near end of steam locomotives prevented far reaching effects. While the majority of the 180 diesel units delivered in the 1950s were still smaller shunting locomotives and railcars, the 290 diesel units delivered in the 1960s included many heavy shunting machines, mainline locomotives and rail buses (Doleschal, et al., 1999, p. 30). It was not until the delivery of 154 standard diesel locomotives (Doleschal, et al., 1999, p. 30) of the classes 2043 and

2143 in the 1970s that steam traction could be replaced, as a large part of main lines had also been electrified in recent years. The official end of scheduled steam traction for Austrian steam locomotives came on 31 December 1976 with four units of class 52 (Giesl-Gieslingen, 1981, p. 283), which were actually only intended for war service in the Second World War, but ironically played a major part in the reconstruction of Austria. Even after the official end, standard gauge steam locomotives of the class 93 were kept as operational reserve until 1982 (Schröpfer, 2002, p. 197) and the narrow-gauge Steyrtalbahn line was till its decommissioning in 1982 completely served by steam locomotives. On the narrow-gauge *Waldviertelbahn*, all six machines of the class 399 had to be kept in reserve for freight traffic until the end of the 1980s, which led to a smooth transition from scheduled operation to touristic operation through an initiative of the staff to haul some passenger trains on weekends with steam locomotives (Straka, et al., 2012, p. 6).

Over the last decades, some steam locomotives were restored for heritage and touristic service. Figures from 2004 show a number of 208 steam locomotives preserved in Austria at more than 30 different locations (Zoubek, 2004, pp. 56-69), of which only a small number were kept in operational condition. The author of this thesis is aware of a few exports abroad, but also of additions, so that even in 2023 we can speak of a number of around 200 preserved steam locomotives in Austria. Surveys carried out in the course of this thesis (Chapter 4), came to the conclusion that there are 43 steam locomotives in operation in Austria, whereby the trend is generally downwards. The largest collections are those of the Republic of Austria in the *Collection Technisches Museum Wien* and the *Collection Österreichische Bundesbahnen*. Many of the preserved steam locomotives are listed as protected historical monument. According to a list compiled by Bernhard Graf, an expert in the Association of Austrian Heritage and Tourist Railways *ÖMT* (Graf, 2022), as well as to the book *Dampflokomotiven in und aus Österreich 2004* (Zoubek, 2004), 77 steam locomotives in Austria are listed as protected historical monument, of which only a small number is in operation. The majority is exhibited in museums like the museum *Das Heizhaus* in Strasshof in the province of Lower Austria.

Figure 3 ÖBB Class 93 steam locomotive on the Zayatal railway: These locomotives ran until the end of the steam era at Austrian Federal Railways (Own work, 2014)

Steam locomotives in operation are generally used on three different categories of lines in the course of nostalgic operation. These are according to Austrian law public railways with main and branch lines (§ 4 Eisenbahngesetz – EisbG), on connection lines (§ 7 Eisenbahngesetz – EisbG) as well as on lines that do not fall under the railway act and are authorized by provincial event laws. On public railways, since the liberalization of the network, free access to the network is guaranteed for main lines and interconnected branch lines for all railway companies established in the EU and Switzerland (§ 57 Eisenbahngesetz – EisbG), which fulfil the technical requirements to operate on the specific network. Track access charges (§ 67 Eisenbahngesetz – EisbG) are based on the principle of equality and have no legal basis for exceptions for historical services. Narrow-gauge railways do not fulfil the character of networked branch lines due to the different track gauges. The legal form used on connecting lines is that of a limited public service, which does not have the scope of a general service but corresponds to a public railway in terms of safety (§ 17 Eisenbahngesetz – EisbG). For operation under provincial event laws, the vehicle and track safety requirements of regular railway operation are usually applied.

In general, a distinction must be made between lines on which heritage or touristic operations exclusively and lines on which scheduled passenger and/or freight services are carried out. On lines with purely nostalgic service, the technical and operational requirements are lower than on the network with regular service. Steam trips on the network of the Austrian Federal Railways are tending to decline, as the Austrian Federal Railways no longer carry out or support nostalgic trips themselves after the discontinuation of their heritage and nostalgic division *ÖBB Erlebnisbahn* in 2014 (Anon., 2015). In principle, nostalgic trips are possible under the management of a railway company. The registration of the vehicles required in Austria with the main network operator *ÖBB Infrastruktur* is carried out according to a separate scheme. The characteristics of nostalgic vehicles are defined by the features worthy of preservation for cultural-historical interest, nostalgic museum function, no fundamental use in regular service and a high age (ÖBB, 2021). Providers such as the Austrian Society for Railway History *ÖGEG* have also reduced their numbers of trips on the ÖBB network in recent years. While *ÖGEG* operated 27 steam trips on its own museum railway as well as on the lines of the *Linzer Lokalbahn* and the *Salzburger Lokalbahn* in 1998, 15 trips of its steam locomotives were operated on the *ÖBB* network (Österreichische Gesellschaft für Eisenbahngeschichte, 1997). In 2022 ÖGEG only offered five of such trips (ÖGEG, 2023, personal communication, 6 May). The reasons for this development are the overall higher frequency on the *ÖBB* network, high access fees and increased technical and operational requirements (Ziegler, 2018). In recent months, additional complicating factors have included higher train safety requirements and a certification obligation for rail vehicle maintenance (Eisenbahntechnische Rundschau, 2019).

2.2 Technical Principles

The steam locomotive developed in a wide variety of o gauge, size, speed, firing and operation, depending on the intended use and the topography, climate, and available fuels, but was based on the same mode of operation and basic design. Adolph Giesl-Gieslingen himself, a former chief designer and optimizer of steam traction in the late stage (Slezak, 1967, pp. 3-24) saw as an outstanding technical characteristic that the entire construction of a steam locomotive, compared to its successors, could be planned by one competent person (Giesl-Gieslingen, 1986, p. 8). The basic technical type of steam locomotives, which became internationally accepted in the history of railways, is based on the first constructions of George Stephenson in Newcastle around the year 1829 and found its mature proportions in the middle of the 20th century (Giesl-Gieslingen, 1986, p. 8).

Three main features of Stephenson's locomotive, namely a steam boiler with a number of heating tubes through which combustion gases from a firebox flow, a fire ventilation through an ejector effect caused by the exhaust steam, and a direct power transmission from the piston of the steam cylinder through a main rod to the wheel, were already found in the world-famous *Rocket* (Giesl-Gieslingen, 1986, p. 13). All locomotives used on Austrian heritage and touristic railways are based on this principle. The fuel for the *Rocket* was coke, of which 250 kilogram were carried on the locomotive (Schwarze, et al., 1964, p. 27). In principle, wood, peat, lignite briquettes, bituminous coal and fuel oil can be used to fire steam locomotives, but bituminous coal has become the most widely used fuel (Schwarze, et al., 1964, pp. 882-883). In English and Central European practice, coal with a size between 50 and 150 millimeters is preferably used, whereby it must be taken into account that ideally larger pieces are broken up manually and smaller unavoidable pieces of grit and coarse dust are prevented from being immediately carried away by the air flow by means of wetting (Giesl-Gieslingen, 1986, p. 45). The firing is usually carried out manually by the heater, whose main task is additional to the water management in the boiler, the correct charging of the grate adapted to the prevailing operating situation, which requires consideration of the line characteristics (Schwarze, et al., 1964, pp. 801-802).

Mechanical methods of grate charging, so-called *stokers*, which made it possible to efficiently fire smaller grain sizes as well as low-grade coal, were developed in the USA at the beginning of the 20th century and became more widespread in single European countries such as France or Czechoslovakia, but not in Austria (Giesl-Gieslingen, 1986, pp. 113-125). Since stoker firing systems are not used on Austrian heritage and touristic railways and are not to be expected, they will not be considered in the further course of this work.

Figure 4 Czechoslovakian construction class 556: 1950s design with stoker firing at a guest operation in Austria (Own work, 2014)

Due to oil discoveries in Galicia, oil firing systems were already tested in Austria on the threshold from the 19th to the 20th century and were installed in high numbers, but their significance remained low throughout Europe due to the often higher fuel costs compared to coal (Giesl-Gieslingen, 1986, pp. 128-134). In the context of modern approaches to the environmental improvement of steam traction, oil firing with the use of light oil has also received attention in Austria in the present, which was noticeable in the procurement of four oil-fired modern steam locomotives from the Swiss manufacturer *SLM* for the S*chafbergbahn* as well as the oil firing adaptation of a steam locomotive of the

Zillertalbahn, which meanwhile has been dismantled again (Serchinger, 2018). A more detailed technical description of modern oil-fired systems is given in *Chapter 2.5*.

Figure 5 Coal, as here on the Steyrtal Heritage Railway, is with a few exceptions the most common fuel type for steam locomotives in Austria (Own work, 2022)

Since Austrian heritage and touristic railways are manually fired with coal, apart from the exception just mentioned, the rest of the technical description deals with the conventional procedure. The combustion process during operation of a steam locomotive begins with the removal of the coal from the tender by shovel and its introduction through the firedoor into the firebox, which is closed off at the bottom by a grate. The grate, through which air is supplied from below and which also serves to remove slag, has a grate width which ideally depends on the structure of the fuel. Austrian grates had a standard gap width of 21–26 centimeters, which was big by international standards and prevented the efficient combustion of small-sized or crumbly coal, so that the grate was usually covered with a fist-sized layer of slag residue (Giesl-Gieslingen, 1986, pp. 98-99). In Germany, a gap of 10 millimeters was used for Upper Silesian coal and 13 millimeters for Westphalian coal (Igel, 1990, p. 114). Under the grate is the ash pan, which, in addition to collecting the combustion residues, also regulates the air flowing into the firebox. In the history of steam locomotive construction, a decent air supply through the ventilation inlets of the ash pan, which should be appropriate to the oxygen demand of the fire, has often been neglected (Giesl-Gieslingen, 1986, p. 104). The theoretical requirement of around 11 kg or 9 cubic meters of air for the combustion of one kilogram of coal must in practice be calculated at 15-16 kilogram or around 13 cubic meters (Igel, 1990, p. 114). The air from the air inlets is called primary air, while secondary air enters the firebox through the fire hole (British Transport Comission, 1957, p. 25) and the firedoor. In addition to the dimensions of the grate and the heating surfaces, a precisely adjusted blast pipe system consisting of a blast pipe and the furnace is elementary for the performance, as in it the outflowing exhaust steam from the cylinders with a sog triggers a negative pressure in the firebox and thus regulates the air flowing in (Giesl-Gieslingen, 1986, p. 139). Perfect matching and control of the fuel and air supply is therefore elementary for complete combustion, economical operation, and the flue gas balance.

Within the scope of the very low thermal efficiency of 6 to 9 percent of steam locomotives (Giesl-Gieslingen, 1986, p. 10), coal wastage can be prevented by adequate firing. It should also be mentioned, that in the course of its technical development, the steam locomotive has not only been able to save 25 percent fuel through technical adaptations to the drive unit, such as the compound cylinder technology but also through changes in the area of exhaust gas flow and the emitted steam, leading to significant fuel savings and increases in performance (Giesl-Gieslingen, 1986, pp. 286-287). Worth mentioning in this context are superheaters, which achieved fuel savings of up to 24 percent (Giesl-Gieslingen, 1986, pp. 186-189), devices for preheating the boiler water by means of exhaust steam and exhaust gases, which were able to achieve fuel savings of up to 8 and 9 percent respectively (Giesl-Gieslingen, 1986, pp. 174-185). The revolutionary Giesl ejector was at the time of its late series production in the second half of the 20th century (Giesl-Gieslingen, 1981, pp. 280-283) able to save around 9 percent of fuel with increased performance. The introduction of so-called brick arches inserted into the firebox, which were made of firebricks or concrete, further improved the combustion properties (Schwarze, et al., 1964, pp. 136-138).

The locomotive crew is an important factor in the operation of steam locomotives that should not be underestimated. This crew usually consists of a driver and a heater. The locomotive driver is responsible for the movement and thus for transferring the power via the cylinders to the running gear. Steam-saving methods can increase economic efficiency (Schwarze, et al., 1964, pp. 798-799), which is possible due to lower coal consumption. The heater is responsible for providing the necessary steam pressure and thus for the water supply and the firing. He must constantly adapt his fire to the line conditions, the train load, the timetable and, among other things, ensure perfect combustion, control the formation of slag and feed the boiler optimally with water (Schwarze, et al., 1964, pp. 801-806). Poor combustion technology can result in a lack of air and a drop in temperature, which causes hydrocarbon compounds to escape as smoke and fumes as well as unnecessary soot formation, which also leads to energy losses (Schwarze, et al., 1964, p. 872). In order to ensure the most effective, economical, and low-emission operation of a steam locomotive, close coordination between the locomotive personnel is necessary in addition to expert knowledge of the machine and the track as well as personal experience.

2.3 Emissions of coal combustion in steam locomotives

Coal is a solid fuel suitable for firing the boiler of a steam locomotive. It is a complex mixture consisting mainly of organic components such as carbon, hydrogen, oxygen, nitrogen, sulfur, and inorganic components (Schweinfurth, 2009, p. 7). The most common inorganic components are minerals such as quartz, clay minerals, pyrites, calcites, and siderites (Schweinfurth, 2009, p. 8). In total, coal can contain up to 76 of the 90 elements found in the periodic table, most of which occur only as traces, but have the potential to be hazardous (Schweinfurth, 2009, p. 7). The chemical complexity of coal is based on the transformed plants and other organisms, biological and chemical processes, geometry and location, introduction of minerals, and coalification (Schweinfurth, 2009, p. 13). The process of coalification after burial, caused by increased pressure and temperature, affects organic matter, resulting in a loss of water, oxygen and hydrogen and a relative enrichment of carbon (Schweinfurth, 2009, p. 14). From an international perspective, the different geological processes result in different coal reserves in terms of quality and quantity. Today's coal reserves vary internationally but are mainly spread over a few countries such as the USA with a share of 23 percent, Russia with a share of 15 percent, Australia with a share of 14 percent or China having 13 percent (BP, 2021, p. 47).

Table 1 Variance of heating values of different solid fuels (derived from: Stockholm Convention on persistent organic pollutants, 2013)

Type of Fuel	**Heating Value**
Anthracite	27–35 MJ/kg
Bituminous coal	20.5–34 MJ/kg
Sub-bituminous coal	12–17 MJ/kg
Lignite / brown coal	4–12 MJ/kg
Peat	1–7 MJ/kg
Spruce, air dry	14–17 MJ/kg
Beech, air dry	13–16 MJ/kg

In the history of steam locomotives, bituminous coal was generally used to obtain the highest possible calorific value and thus a high output. However, the properties and quality of bituminous coal also differ greatly in the proportion of moisture, volatile matter, ash, carbon, hydrogen, sulfur, oxygen, and nitrogen, which together define the calorific value. The calorific value is normally between 24 and 32 MJ/kg (Schwarze, et al., 1964, p. 885) and thus shows a high variance. Historically, the quality of the coal, as well as the grain size, which was extremely relevant for the burning in the firebox, depended on the geographical location. This is reflected in the different constructions of the fireboxes and grates (Giesl-Gieslingen, 1986, pp. 99-103). In addition, the political and economic situation played an equally important role. In Austria, the fact that after the Treaty of Saint-Germain the majority of all coal mines were suddenly located abroad and the supply against foreign exchange functioned very unreliably meant that the entire economy suffered from the shortage of high-quality locomotive coal and an electrification program was given top priority (Kraus, 1992). The connector railway of the *Wolfsegg-Traunthaler Kohlenwerks-AG*, where pit-moist lignite with a water content of around 50 percent was used for steam locomotives (Giesl-Gieslingen, 1981, pp. 197-199) marks the worst of the coals ever used in Austria.

Figure 6 Polish bituminous coal for firing on steam locomotives (Own work, 2023)

The reaction that releases energy when coal is burnt in air is that of carbon with oxygen $C + O_2 = CO_2$. The energy content of coal is virtually completely sequestered in carbon, which means that coal has the highest carbon dioxide emissions per unit of energy (Breeze, 2015, p. 56). This makes coal combustion the largest contributor to total carbon dioxide emissions (Ritchie, et al., 2020) and thus drives global warming. In terms of direct environmental and health damage, other substances arise when coal is burned. Since coal usually has a sulfur content that can reach up to 10 percent (Breeze, 2015, p. 53), but is usually much lower in steam locomotive coal (Schwarze, et al., 1964, pp. 884-885), sulfur dioxide emissions play a serious role. The same applies to nitrogen oxide compounds NO_x, which are formed either from organic stock or from the ambient air at high combustion temperatures (Breeze, 2015, p. 53). The mineral components of coal can melt and fuse with other similar materials during combustion, which can escape in the flue gas (Breeze, 2015, pp. 53-54). Other serious pollutants that are relevant in the context of environmental degradation and human health are volatile organic compounds, which are present in large quantities in many types of coal, as well as carbon monoxide, which is produced during incomplete combustion (Breeze, 2015, p. 54). Other pollutants, such as heavy metals, which occur in small quantities, would have to be detected individually depending on the type of coal. The levels of chlorine, mercury and cadmium require special attention in this context. Extensive detailed research that goes beyond combustion properties would facilitate the identification of the origins, nature, and effects of coal quality (Schweinfurth, 2009, p. 15).

Another part of the emissions of a steam locomotive consists of soot particles, whose health relevance depends on their size. If these particles belong to the PM_{10} and $PM_{2.5}$ fractions, they are able to penetrate the thoracic region, leading to respiratory and cardiovascular morbidity and increasing mortality from cardiovascular diseases and lung cancer (World Health Organization Regional Office for Europe, 2013, p. 6). In the context of steam locomotive operation, there are different data. An American study based on historical data assumes the existence of a particulate matter fraction in coal-fired steam locomotives, particularly during start-up and uphill runs (Bond, et al., 2007, pp. 5-7), while current findings exclude a particulate matter fraction (Serchinger, 2018, p. 2). An experimental study at the Austrian *Achenseebahn* showed that all soot particles emitted by the steam locomotive were over 30 micrometers in size and thus cannot be classified as hazardous to health (Serchinger, 2017). Nevertheless, it is possible that steam locomotives contribute to fine dust pollution through the formation of secondary particles, which result from chemical reactions of sulfur dioxide and nitrogen oxides (World Health Organization Regional Office for Europe, 2013, p. 3). The conditions would be given on the one hand by the sulfur content of coal, and on the other hand by the temperatures required for the formation of nitrogen oxides. Temperatures at around 1500° Celsius (Meineke & Röhrs, 1949, p. 17), which prevail in the fireboxes of steam locomotives, fulfil the conditions for the formation of thermal NO_x (Joos, 2006, pp. 598-604) and the nitrogen content of the coal also enables the formation of fuel-bonded NO_x

(Joos, 2006, pp. 608-610). Studies of coal-fired thermal plants have shown that although annual secondary particulate pollution levels are very low, they can be associated with adverse health effects (Mangia, et al., 2015, pp. 7676-7677).

Figure 7 Typical smoke plume with high soot content in special operational situations of steam locomotives (Own work, 2015)

The much smaller scale of operation of steam locomotives on heritage and touristic railways compared to large power plants, the very limited timetables and the permanent movement of the pollutant source steam locomotive over several kilometers during operation do not allow an immediate comparison and exclude the risk of long-time exposure. In individual cases, a critical area could be the vicinity of railway depots, where exposure is possible over longer periods of time due to the heating up and shutting down of steam locomotives. However, it must be mentioned that railway facilities, depending on the type of traction, traffic volume and infrastructure condition, are also affected by exhaust and non-exhaust fine dust pollution without steam operation (Abbasi, et al., 2013, pp. 20-24). The emission calculation in *Chapter 4* of this thesis only calculates the climate-damaging carbon dioxide, as the analysis of sulfur oxides, nitrogen oxides and particulate matter would have to be carried out experimentally and based on individual case studies due to the high variance of coal qualities, steam locomotive types and firing techniques.

A not specifically differentiated but relevant phenomenon in the course of steam locomotive emissions is flying sparks. This issue is not directly harmful to health but is extremely relevant in the context of steam operation, especially under climatically arid conditions. Glowing particles from the chimney have the potential to trigger wildfires in the immediate vicinity of railway installations. In the case of a densely overgrown railway embankment, even glowing particles from the ash box are sufficient to start a fire. Immediate technical specifications such as a spark arrester can mitigate this problem and prevent damage (Giesl-Gieslingen, 1981, pp. 202-203). To reduce smoke and spark emissions in general, a low cost standard conversion procedure for classic coal-fired steam locomotives includes adaptations to the firebox by a steel or brick arch as well as a deflector plate and additional air inlets through the fire door and the ash pan, fire protection by mesh in all air openings, a spark arrestor between blast pipe and chimney and a modified front end, such as a *Giesl ejector* (Serchinger, 2018, p. 8).

2.4 Coal market in times of geopolitical tensions and climate policy

Since coal combustion is the largest contributor to anthropogenic global warming, it has great potential for climate protection, which is why reductions in coal combustion are a major component of climate policy efforts. While almost 32 million terajoules of the nearly 40 million terajoules of energy generated globally from coal in 2020 will be consumed by the industrial sector, the direct consumption of coal energy for the transport sector is around 34,000 terajoules (IEA, 2022). Thus, the transport sector directly consumes only 0.1 percent of the global energy generated from coal. It should be noted that a large proportion of the world's transport services are provided using other fossil fuels, mainly oil products, and that electrification of the transport sector is a goal of global climate protection efforts (UNFCC, 2021). Although almost one third of global operating coal capacity has a phase out date and a large proportion of the remaining capacity is under the purview of carbon neutrality targets, the current pace of global coal phase out is not sufficient to be compatible with the goals of the *Paris agreement* (Global Energy Monitor, 2023, p. 3).

The International Energy Agency's *Net Zero Emissions by 2050* Scenario nevertheless assumes the possibility of achieving these goals with a reduction of industrial and energy-related CO_2 emissions of 40 percent by 2030 and to net zero in 2050 (IEA, 2021, p. 47). Such a scenario would require comprehensive efforts and favorable global political conditions and can only be classified as realistic to a limited extent. A phase-out of coal as an energy source would be necessary in OECD countries by 2030 and globally by 2040 (Global Energy Monitor, 2023, p. 17). Despite the shortages and large price increases for energy in 2022 and the associated increase in demand for coal, there can be no talk of a comeback for this energy source (Global Energy Monitor, 2023, p. 4). The temporary U-turn of the European Union towards coal was based on the, compared to other fuels, relatively favorable conditions after Russia's attack on Ukraine and was accelerated by lower outputs from hydropower and nuclear plants due to weather events and technical problems (IEA, 2022, p. 7). The global trend assumes an all-time high for coal in 2022 and a plateauing in the following years, whereby the development depends very strongly on China, which is responsible for 50 percent of global coal consumption (IEA, 2022, pp. 8-12). The number of new coal plants under construction or pre-construction has significantly decreased globally since 2015 although China is currently forcing the construction of new facilities (Global Energy Monitor, 2023, p. 9).

For Europe, the climate policy-induced decline in coal consumption, which fell by a quarter between 2018 and 2021 (Eurostat, 2022), as well as the strong dislocations in the energy sector, mean major changes in the coal market. Europe's own production of 57 megatons in 2021, which took place almost exclusively in Poland, contrasts with imports of over 160 megatons (Eurostat, 2022). In April 2022, the European Union decided to impose an import ban on coal from Russia (Council of the European Union, 2023), which till this decision had accounted for the largest share of coal imports into the European Union (Eurostat, 2022). The lack of supplies from Russia is compensated by South Africa, Colombia, or other smaller supplier countries such as Tanzania, Botswana, or Indonesia (IEA, 2022, p. 8). This significantly increased transport costs, as Russian coal could easily be exported to Europe via a short shipping route or rail connection (IEA, 2022, p. 8). Other potential suppliers include the USA, Australia, and Kazakhstan, but many of the alternative suppliers include logistical, meteorological, social, environmental, and political issues (Stala-Szlugay & Grudziński, 2022, p. 42), which include potentially destabilizing effects on supply chains.

Geopolitical tensions and changes in supply chains, especially in the European market, have led to significant price dynamics on the coal market. In August 2021, coal of the API 2 reference at the Rotterdam marketplace crossed the $100 per ton threshold, fluctuated between $100 and $179 per ton in the following months, and reached a record level of $438 per ton on 7 March, from which the market price recovered only slowly, settling again about a year later at a level similar to that just before the Russian war of aggression (Intercontinental Exchange, 2023). Within this market, individual types of coal are also exposed to other dynamics and are associated with increased transport costs. An analysis by the British Heritage Railway Association from May 2022 describes the availability of coal as subject to massive uncertainties in supply as well as in price and reports shortages of Colombian, Kazakh and Polish coal as well as efforts to import coal from Southeast Asia (Heritage Railway Association, 2022, p. 2).

A new focus since this phase was particularly on so-called artificial coal (Heritage Railway Association, 2022, p. 3), that means coal products that ideally have similar combustion properties to classic steam coal. Feedback from heritage railways documenting their experiences with such products concluded that there was a useful performance, but that intensive residues and deposits in the firebox, the pipes and the smoke chamber caused problems and questions (Heritage Railway Association, 2022). Furthermore, many of these fuels have a significantly higher chlorine content compared to conventional steam coal, which poses problems for the fireboxes (Heritage Railway Association, 2022, p. 5) and also produces more environmentally harmful emissions. Fuel suppliers announce an investigation of the residues to draw conclusions about the product and try to replace the molasses binder, which is responsible for the chlorine emissions, with a resin binder with a lower chlorine content (Heritage Railway Association, 2022, p. 12).

Basically, it can be observed that the general global trend in coal consumption is declining, apart from China, and that the mining of coal will also decrease accordingly. On the one hand, this can limit the variety of different types of coal and, on the other hand, increase prices. For heritage and touristic railways, this means that the decline of global coal production will pose major problems, as high-grade coal, which will still be necessary for the purpose of steel production in the future, does not have the grain size needed for steam locomotives, which is more difficult to produce (Serchinger, 2017). A prominent example during the writing of this thesis is the political debate on the closure of the open cast Ffos-y-Fran mine at Merthyr Tydfil in South Wales, on which around 150 heritage railways in Great Britain claim to depend on (Longhorn, 2023). While a recent decision by Merthyr Tydfil's regional government is against extending the mining permit, a final policy decision at a higher level has yet to be made (Lewis, 2023). In a study written in 2017, coal from the Ffos-y-Fran mine, along with coal from the Upper Silesian coalfield in Poland, is classified as the only coal from European extraction that meets environmentally friendly pollutant specifications (Serchinger, 2017).

In summary, both the decline in coal production in Europe and global developments may lead to procurement problems and price increases. Geopolitical conflicts and tensions have a great potential to change commodity chains and prices, as the Russian war of aggression in Ukraine clearly shows. The high requirements of coal for steam locomotives in its chemical composition as well as in its physical properties impose major constraints on the procurement of the fuel. Long transport distances further increase the carbon footprint of coal and frequently varying coal qualities also offer the potential of increased pollutant emissions due to disadvantageous chemical compositions and a lack of experience of locomotive personnel in the burning behavior and use of the fuel. Efforts to replace traditional bituminous coal with alternative fuels are discussed in the following *Chapter 2.5*.

2.5 Oil and Biocoal as alternative fuels for steam locomotives

As already mentioned in the previous chapters, coal is the dominant form of fuel for steam locomotives. In addition to the technical development, the development of the infrastructure on steam-powered lines was also oriented towards coal as a fuel. Bituminous coal has the positive characteristics of a high energy density of around 20-30 MJ/kg (Stockholm Convention on persistent organic pollutants, 2013, pp. 261-263) and easy mechanical handling due to the characteristics of a solid fuel. The hydrophobic properties (Fengler, et al., 2017, p. 8) of coal also enable easy transport and uncomplicated open storage. Due to fluctuating availability and prices, alternative firing systems using other coal products like wood and oil have developed in addition to the classic firing with bituminous coal. The emissions from steam locomotives mentioned in *Chapter 2.3* and the global move away from coal for environmental reasons described in *Chapter 2.4*, as well as the supply difficulties caused by political and economic upheavals following the war in Ukraine, have led to a search for alternative fuels to ensure that steam locomotives can continue to be operated in the future. The approaches from the literature differ mainly between a switch to oil firing, which does not mean a move away from fossil fuels given the current supply of fuels, and a switch to biomass-based firing processes, which would be carbon neutral.

The principle of oil firing is not a late development in the history of steam locomotive design. The first oil-fired steam locomotive boilers were already in use in the USA and England in the 1870s and 1880s (Giesl-Gieslingen, 1986, p. 128). Due to the increase in oil firing in Galicia, it was also possible from 1894 onwards in the Austro-Hungarian

Monarchy to carry out trials with oil firing in order to reduce the smoke plague in the *Arlberg* tunnel (Giesl-Gieslingen, 1986, p. 129). A distinction must be made here between supplementary oil firing, especially in the initial stage to increase output peaks, whereby the basic load was still provided by a coal fire, and oil main firing, which required constructive changes in the firebox (Giesl-Gieslingen, 1986, pp. 129-130). Further conversion phases from coal to oil firing, partly as supplementary firing, partly as main firing, took place in occupied Austria from 1945 onwards, but were abandoned again in the mid-1950s and the steam locomotives were converted back to coal for cost reasons (Giesl-Gieslingen, 1986, p. 131). Internationally, oil-fired locomotives were never widespread, with a peak of around 6 percent around 1950 (Giesl-Gieslingen, 1986, p. 134). There were phases of dominant oil-firing in the south-west of the USA and also in Europe especially after the Second World War namely in Romania, Spain, France, Bulgaria and to some extent in the Federal Republic of Germany (Giesl-Gieslingen, 1986, pp. 131-132). One reason for this was that the American imported coal frequently used at the time caused problems with too intensive smoke development due to its high proportion of volatile components (Giesl-Gieslingen, 1986, p. 132). The largest railway company with a purely oil-fueled steam locomotive fleet was the *East African Railways*, a merger of the railways of Kenya, Uganda, and Tanganyika (Giesl-Gieslingen, 1986, p. 134). Analogous to the issue of different coal qualities, there are also different qualities of oil fuel with different combustion properties and pollutant emissions. Since the initial phase of oil firing, distillation residues, called *Mazut*, or heavy fuel oils, called *Bunker C* with a sulfur content of over 1 percent (Serchinger, 1998, p. 2) have been used as fuel (Giesl-Gieslingen, 1986, p. 129). The use of oils of this quality is associated with high pollutant emissions (Lawn, et al., 1987, pp. 175-179) and is nowadays just as criticized as coal. Individual examples of oil-fired steam locomotives can be seen in heritage use outside Austria.

In the 1990s, the construction and delivery of a series of eight new rack-and-pinion steam locomotives for the *Brienz Rothorn Bahn* in the Bernese Oberland region of Switzerland and the *Schafbergbahn* in the Salzkammergut region of Austria caused a sensation. The *Modern Steam* concept on which the design of these steam locomotives is based was developed by Roger Waller of the Swiss Locomotive and Machine Factory *SLM* and is characterized by light weight, high thermal efficiency, environmental friendliness, easy maintenance, and simple one-man operation (Serchinger, 1998, p. 1). These steam locomotives are fired with extra-light fuel oil, which is used for domestic central heating, and efficiency is increased by a newly developed burner system, well insulation of the boiler and cylinders, an electronic preheater and mechanical optimization of the power transition (Serchinger, 1998, pp. 2-3). Compared to the previous generation of steam locomotives on the *Brienz Rothorn Bahn* from the 1930s, the weight has been reduced by 25 percent and fuel consumption per train trip by 41 percent, while the power has increased by 36 percent and speed by 56 percent (Serchinger, 1998, p. 2). Another meaningful comparison with diesel locomotives on the *Brienz Rothorn Bahn* shows that the carbon dioxide emissions of the new steam locomotives are about twice as high due to the still lower thermal efficiency (Serchinger, 2018, p. 3). There was also slightly higher sulfur dioxide values due to the sulfur content of fuel oil, but carbon monoxide was only a fifth and nitrogen oxides only a ninth of the emissions of the diesel locomotive (Serchinger, 1998, p. 8). The extent to which these modern steam locomotives can be seen as part of the cultural heritage at the present time requires individual assessment. Although these steam locomotives are still steam constructions based on Stephenson's concept, the technical and design changes are extremely intensive compared to classic steam locomotives to be able to reach the increased efficiency. The acquisition of these locomotives on the *Schafbergbahn* and the *Brienz Rothorn Railway* was done for commercial reasons but is a unique late development and probably a basis for steam operation in the decades to come. In the course of the *Modern Steam* concept, a former East German class 52 standard-gauge steam locomotive was also reconstructed and optimized at many points (Dampflokomotiv- und Maschinenfabrik DLM AG, 2020, p. 12), but without taking into account the preservation of the historical substance, which is why this example will not be discussed in more detail.

In the context of preserving cultural heritage, the conversion of historic steam locomotives to light oil firing is much more relevant than the construction of new locomotives. The first project in Austria was the conversion of a locomotive of the *Zillertalbahn* from coal to light oil or diesel firing. The conversion of locomotive No. 5 from 1930, which started in 2008, included a new blast pipe and a new superheater in addition to the conversion of the firing system and resulted in a double thermodynamic efficiency, which, thanks to an Austrian tax exemption on diesel, led to unchanged fuel costs compared to coal and saved personnel hours (Serchinger, 2018, p. 5). Due to the cancelling of the tax exemption on diesel, experiments were carried out with preheated crude ester, a vegetable fat-based residue from the production of biodiesel, which led to lower performance due to the lower calorific value compared to diesel (Serchinger, 2018, p. 6), but proved that a theoretically carbon neutral oil firing is feasible. The steam locomotive No 5 of the Zillertal Railway has meanwhile been converted back to coal firing (Zillertalbahn, n.d.).

Figure 8 Modern oil firing is possible on historically authentic vehicles such as the steam locomotive "Heidi" on the Rhaetian Railway (Own work, 2016)

An extremely prominent example is the restoration and recommissioning of steam locomotive No. 11 *Heidi* on the *Rhaetian Railway RhB* with light oil firing to avoid line fires (Dampflokomotiv- und Maschinenfabrik DLM AG, 2015). The Swiss company *DLM*, which developed the *Modern Steam* concept, carried out the holistic reconstruction and adaptation for the firing of extra-light fuel oil in cooperation with the owners' association and the *Rhaetian Railway* assembling a new boiler, a light oil firing system, an electric preheater, a new blowpipe system and new components for the mechanical mechanism (Dampflokomotiv- und Maschinenfabrik DLM AG, 2020, p. 2020). After the first commissioning in 2014 (Historic RhB, 2014, pp. 42-43) and various test runs as well as technical adjustments, the locomotive went into operation on the *RhB* network in 2016 (Dampflokomotiv- und Maschinenfabrik DLM AG, 2020, p. 22) and is currently in service several times a year. The external appearance of the locomotive is the same as in the time of its delivery in 1902, because the technical innovations are hidden inside (Dampflokomotiv- und Maschinenfabrik DLM AG, 2015). The technical, financial, and labor costs for this successful project show the dimension of such an adaptation, taking into account the preservation of the original substance. The material costs alone for the restoration and conversion of the machine amounted to around 1.3 million Swiss francs (Club 1889, 203). Comparable projects by the *DLM* company are the conversions of a steam locomotive for the Australian *Puffing Billy Railway*, a steam locomotive for the railway on the German island of Borkum and a steam-powered cogwheel locomotive for the *Matterhorn-Gotthard Bahn* in Switzerland (Dampflokomotiv- und Maschinenfabrik DLM AG, n.d.) The latter is now at the *Dampfbahn Furka Bergstrecke*, where it is parked due to its weaker performance with the new boiler and consideration to rebuild the old coal boiler are existing (Dampfbahn Furka Bergstrecke, 2023). A current project of DLM is the conversion of a narrow-gauge locomotive to light oil firing for the *Sächsisch Oberlausitzer Eisenbahn Gesellschaft* in the State of Saxony with funds from a political coal restructuring fund, from which a saving of 40 percent in CO_2 emissions and minimized smoke emissions is to be achieved (Zittauer Schmalspurbahn, 2021). This pilot project is of great importance for the region because in eastern Germany historic steam railways are in several regions integrated into the public transport system and accordingly many steam locomotives are in daily use. As the locomotive from Saxony is a standard locomotive that is used on several narrow-gauge railways in Germany, this prototype has the potential to provide information on a possible adaptation of an entire series.

It should be noted that apart from the restoration of a single standard-gauge steam locomotive according to the *Modern Steam* concept, which involved rough and externally visible changes, all other conversions were carried out on narrow-gauge locomotives (Dampflokomotiv- und Maschinenfabrik DLM AG, 2020), which are considerably smaller in size than most standard-gauge locomotives. The high financial outlay associated with an adaptation of the firing system is combined with a reduction in emissions but does not change the principle of burning fossil fuels.

Biocoal fuels are made of biomass and have similar combustion properties like conventional coal. In principle, it is possible to fire steam locomotive boilers with wood, but due to the significantly lower energy density (Stockholm Convention on persistent organic pollutants, 2013, pp. 261-263) it is not possible to generate the same amount of steam as with coal firing. Furthermore, with a halved calorific value, the fuel stocks that a steam locomotive carries itself are also halved. A prominent example of large-scale combustion of wood are the Romanian forestry railways, which used large quantities of waste wood from timber production as fuel (Muica & Turnock, 2003, p. 16). For less energy-intensive performance of steam locomotives, such as on lowland lines with low trailer loads and moderate speeds, wood can certainly be a serious alternative. Fuel products made from wood, which have a higher energy density, have greater potential.

Table 2: Biocoal Compared to solid Biofuels (derived from: Fengler, et al., 2017)

Characteristic	**Wood**	**Wood Pellets**	**Biocoal**	**Charcoal**	**Coal**
Moisture Content in weight %	30–45	7–10	1–5	1–5	10–15
Calorific Value in MJ/kg	9–12	15–16	36–46	33.5–40	36–56.5
Volatiles in %	70–75	70–75	55–65	10–12	15–30
Hydroscopic Properties	hydrophilic	hydrophilic	hydrophobic	hydrophobic	hydrophobic

A research project of the *Coalition for Sustainable Rail* and the Natural Resources Research Institute at the University of Minnesota looked experimentally at torrefied biomass as a substitute for coal in steam locomotives (Fengler, et al., 2017). In a process known as partial pyrolysis, raw biomass gets heated to between 250 and 300 degrees Celsius in a sealed and oxygen less environment and causes a decomposition of the material and a breakdown of the sappy lignin (Fengler, et al., 2017, p. 6). The process leads to a significantly higher energy density as well as to hydrophobic properties of the material. has a thermal efficiency of up to 90 percent due to the recirculation of the dissolved gases into the reaction system and is thus more efficient than the drying of biomass in woodchip production (Fengler, et al., 2017, pp. 6-7). In the comparison to other fuels presented in *Table 2*, the significantly higher average values for the calorific value compared to *Table 1* are striking, but a relationship to other fuels can still be derived. Furthermore, torrefied biomass does not contain coal-typical emissions, such as heavy metals, sulfur, Phosphorus, or net carbon emissions, but retains the simple transport properties of coal depending on the grain size (Fengler, et al., 2017, p. 7). Challenges in the development of torrefying biomass lie in the search for the ideal compaction method, whereby dry solid loss, and the question of the use of binders are particularly important (Fengler, et al., 2017, p. 8). In addition to testing the fuel, the current research of the two institutions is also concerned with the development of an integrated torrefaction reactor and small-scale power plants for the use of the fuel outside of steam locomotives (Fengler, et al., 2017, p. 10). To investigate the combustion of biocoal in steam locomotives, which differs significantly from combustion in the laboratory and in power plants, the coal was burned in locomotives of an American park railway (Fengler, et al., 2017, p. 11).

The first tests resulted in useful results during start-up and caused clearly cleaner combustion, but the physical properties meant that consumption was very high, and many particles were carried away by the air flow and left the chimney as embers. A second test cycle with larger pellets gave similarly good combustion results, high steam potential and similar temperatures to coal, but the problem of spark emission persisted due to inhomogeneous densification of the material (Fengler, et al., 2017, p. 14). After the first two rounds of testing, it was concluded that although the torrefied biomass burned at a similar average temperature, the lower bulk density and higher porosity resulted in a larger surface area that burned faster and, combined with the lack of ideal densification binder, led to disintegration and the emission of fuel particles in the exhaust stream (Fengler, et al., 2017, p. 18). Further trials with another pelletizing machine and an industrial standard biomass binder at 1 percent mass gave promising results and are part of the research to optimize the densification of the material (Fengler, et al., 2017, pp. 20-21). Observations in further experiments on the behavior on a full scale steam locomotive showed on the one hand that sufficient heat could be generated with torrefied biomass to cover the steam demand, even if the hard working exhaust under test condition led to ember emissions and on the other hand that a pre-blended mixture of 50 percent each torrefied biomass and pulverized coal led to a desirably slower burning of the fuel but required more frequent shoveling (Coalition for Sustainable Rail, n.d.).

In addition to experimental trials, larger-scale deployments of a mixture of pulverized coal and biocoal have also taken place in the UK. The product *Ecoal 50* from the British fuel supplier *CPL* consists of 25-25 percent anthracite coal, 20-25 percent biomass from olive stone, 15-35 percent petroleum coke, 0-10 percent bituminous coal and 15-20 percent molasses (CPL Industries, 2017) and has already been used several times. A qualitative assessment of the fuel performance of various coal products from the year 2022 (Advanvced Steam Traction Group, 2022) with 9 different feedback data gives a good picture of the combustion behavior during operation. On a scale of zero to five, the *CPL Ecoal 50* achieved average results in the categories steam performance, quantity of fuel used, quantity of ash in the ashpan and clinker formation, and good results in the categories ignition time, intensity of fuel loss, spark throwing, smoke color, quantity of char in the smokebox and smoke odor (Advanvced Steam Traction Group, 2022). A determining factor for the Ecoal product is probably the high price, which makes it harder to afford for standard-gauge railways compared to narrow-gauge railways. In the context of Austrian heritage and touristic railways, the experiences of the *Welshpool & Llanfair Light railway* are of particular importance, as they used a former *Zillertalbahn* class U locomotive, a standard steam locomotive type still widely used on Austrian narrow-gauge railways, for 60 days in 2022 and undertook trials with biofuels (Welshpool & Llanfair Light Railway, 2023, pp. 10-12). An email contact made during the writing phase of this thesis was unable to provide accurate empirical data by the time the paper was completed. The *Harzer Schmalspurbahnen*, which operate an extensive narrow-gauge railway network in the German states of Saxony-Anhalt and Thuringia, have decided to focus on the future use of biomass-based coal products after a negative feasibility study on the conversion of their steam locomotives to hydrogen (Harzer Schmalspurbahnen, 2022).

However, the research and reports from the USA and Great Britain do provide empirical values that show the potential of biocoal in principle but also include side effects that can only be handled through further investigation and optimization of these fuels and their production for large-scale substitution of fossil coal. The experience gathered by the *Heritage Railway Association* shows a general tendency towards problematic side effects of processed coal products, regardless of their biomass content (Heritage Railway Association, 2022). Even the supplier CPL, which continues to research on the development of a 100 percent biomass fuel, is critical and does not expect such a fuel to be available in the near future (Heritage Railway Association, 2022, p. 12).

3. Methodology

This thesis focuses on a survey of the carbon dioxide emissions of Austrian heritage railways and on the problems identified in the literature in the field of fuel management as well as on experience and viewpoints on fuel adaptations. Due to the extremely diverse types of organizations in the field of Austrian heritage and touristic railways, which range from informally organized associations of older railway enthusiasts to hierarchically structured modern mobility companies, a hybrid method was chosen in which the survey could be conducted either by telephone interview, personal exchange or by form. The results were inserted into a standardized survey sheet. In some cases, additional information relevant to this thesis emerged from the responses and was noted on the survey sheet. The hybrid form proved to be extremely beneficial for the data range of the survey, as some institutions, especially volunteer ones, did not record the data asked for. In these cases, contact with directly in steam service involved people proved to be helpful. In some cases, data on the number and length of trips and days of operation were generated from timetable books and kilometer data was taken from the Austrian Railway Atlas (ÖBB Infrastruktur, 2010). In some cases, the data was generated in a joint exchange between staff and the author of this thesis over several days. It was sometimes very difficult to make official contact with the institutions, so that informal direct contact with employees was alternatively looked for. Here, the personal network of the author of this thesis proved to be particularly valuable. In total, complete data could be collected from 21 of 25 institutions. Four institutions did not respond to the inquiry during the survey period. Of these institutions, two, namely the Zillertalbahn and the Achenseebahn, were of particular importance due to their uniquely high frequency of trips, while two other institutions only play a subordinate role in the overall picture of emissions. It was possible to compensate the data of the *Zillertalbahn* and the *Achensee*bahn with other sources such as reports, timetables media releases and an extrapolation was possible., The also missing data of the *Lokteam Trumau* and the *Schafbergbahn* were also extrapolated, so that the results of this work can provide a representative picture. The specific procedure for these railways is described in detail in the individual results in *chapter 4.2*. Of 21 datasets, eleven were collected in a written form, eight were collected verbally or by electronic messengers, and two were collected in a hybrid form.

The survey sheet was divided into a section with five key figures on operation and fuel consumption and a section with ten qualitative questions on fuel management as well as on experience and standpoint in fuel adaptations. The first indicator of the survey, coal consumption, is the most important parameter for measuring carbon dioxide emissions since the emissions result from the carbon burned in bituminous coal. A calculation with average emission values generated from the literature would have implicated a danger of great inaccuracies, since the field of investigation turned out to be extremely heterogeneous. In the technical field, steam locomotives differ not only in their track gauge but also in their basic dimensions, the original purpose of use and the state of the art at the time they were put into service. Furthermore, the railway lines show great differences in their elevation profiles. These can be roughly divided into flatland or valley lines, mountain lines and rack railways. Basically, the line profile always depends on the topography of the surrounding landscape and the degree of effort that was expended during line construction to prevent extensive uphill sections. An individual survey of all heritage and touristic railways in steam operation proved to be necessary to generate a comprehensive perspective on the subject. In addition to the data from the year 2022, average values from previous years were collected from railway companies that usually run steam operations but were unable to do so in 2022 for various reasons, so that they could be included in an extrapolation. This extrapolation was used for a detailed analysis of the data, showing emissions per kilometer, emissions per passenger and emissions per passenger kilometer.

The calculation of carbon dioxide emissions in this thesis assumes that the carbon is completely burnt. According to the combustion formula $C + O_2 = CO_2$, which requires two molecular oxygen atoms with an atomic mass of 16 for one molecular carbon atom with a mass of 12, this results in a factor of 2.67 for O_2 compared to C. Including the mass of the carbon atom, this results in a total factor of 3.67. When calculating carbon dioxide emissions from steam locomotives, the use of different types of bituminous coal results in different carbon contents of the fuel. This figure, expressed as a percentage, can vary even within coal mines, as coal is a natural raw material. A preliminary enquiry with some railways in Austria prior to writing this paper revealed a wide variety of coal origins, purchased from a wide variety of traders, some of which are difficult to trace back to a specific coal mine. As explained in *chapter 2.4*, the year 2022 has seen major upheavals on the coal market, so it can be assumed that new coal types arose on the market. Since coal types are partly mixed not only during storage but also during operation (ÖGEG, 2023, personal communication, 6 May), a differentiation between individual coal types would have been hardly feasible. In this respect, the use of an average value for the carbon content makes sense, but there are different numbers, which are generally between 60 percent for lignite and more than 80 percent for anthracite (Hong & Slatick, 1994). The most meaningful reference appears to be the range of 75 to 85 percent taken from a German-language standard work for steam locomotives (Schwarze, et al., 1964, p. 885). The lower value of 75 percent carbon content taken from this corresponds to the highest qualities of Polish coal (Schwarze, et al., 1964, pp. 884-885), which is still frequently used in Austria for steam locomotives. This value of 75 percent was applied in the individual analysis of the data in the following chapter. This led to a rounded factor of 2.75 when multiplied by the coefficient from coal combustion. However, to calculate the total Austrian emissions, calculations were also made assuming a carbon content of 70 and 80 percent, to offer a deviation of plus and minus 5 percent. This results in a range from 2.57 to 2.94 kilogram CO_2 per kilogram of coal depending on the quality from poor to excellent. Different water contents between 0 and 6 percent (Schwarze, et al., 1964, pp. 884-885) are not taken into account.

In order to provide analysis of emissions in relation to mileage and passengers, these data were also collected. The question about the number of operational steam locomotives as well as the days of operation was asked to achieve a picture of the extent of steam operation in the individual institutions. The total number of operational steam locomotives in Austria also included the additional possibility of recording the extent of rolling stock of technical monuments in operation. The first four qualitative questions of the survey sheet investigated potential problems in the procurement and storage of coal in the last two years and the 20 years before that. During the course of the survey, the author became concerned that the wording of the questions about procurement and stocks over the past 20 years was misleading, since the same question about a 2-year period would actually be included in the 20-year period. This concern turned out to be unfounded when analyzing the results, probably due to the chronological order of the questions. In the case of verbal surveys, it was possible to point out the intention of the question anyway. Individual personal queries about the clarity of these questions resulted in positive feedback. The fifth qualitative question, which asked about problems with the quality of coal in the last two years, was added later due to the current relevance of this topic, which emerged from the literature section of this work, after initial results had already been received. The missing data were collected by briefly asking the institutions concerned. The question about limited service and the reasons for it was asked in order to show whether problems with the fuel could be the cause and also helped to clarify the scope of operations. The last four questions asked about experience with alternative fuels, potential plans for bituminous coal substitution, attitude toward technical adaptation of the furnace, and the possibility of retrofitting without additional funding.

The limitations of this thesis lie in the collection of quantitative key figures in the absence of verification of the data. An assessment of the data quality is not feasible due to the technical, operational, and topographical conditions described above in combination with the variance caused by the human factor. In addition, in the area of combustion, the emission calculation did not take into account any unburned coal components, which would tend to lower the carbon dioxide emissions in a small dimension. In the area of extrapolation, average values from past years include the risk that future values will differ from those of the past. Another area of limitations arises from the lack of numbers of indirect emissions such as emissions from mining and transport of coal or emissions from production and maintenance of equipment and facilities of railway companies. In the extrapolation of carbon dioxide emissions per passenger kilometer, a large deviation is realistic, since a complete return trip of passengers is assumed due to the lack of passenger kilometers collected. In the context of the collection of qualitative data on procurement, stocks, quality of coal and fuel alternatives, it should be noted that this survey, which is based on a supplementary research question, only covers parts of the problem area, and therefore only provides a general overview. In principle, the tight time frame for this Master's thesis can also be seen as a limitation for the quality of the survey, the evaluation as well as for description and discussion. The entire period for writing this thesis was limited to two months as provided for in the programme plan.

4. Research Chapter

4.1 Field of Research

The following list collects the key figures on vehicles, operation, fuel consumption and fuel procurement for all operational routes and locations of steam locomotives in Austria. These are based on their scope of operation divided into the categories touristic or heritage railway, regular railway with touristic or heritage service, network steam locomotive operators and network steam locomotive operators with heritage railway.

Figure 9: Overview of steam locomotive service in Austria including heritage and touristic railways [green], regular railways with touristic or heritage service [blue], network operators [red] and Network steam operators with heritage railway [yellow] (Own work)

Touristic and heritage railways offer a service aimed at tourists and railway enthusiasts and do not have an official public transport mandate. They either serve as destinations themselves or are connected to other destinations. The operation is primarily for this purpose, which means that there are no conflicts with scheduled traffic and the timetable and vehicles are adapted to the tourist or historical requirements, while complying with safety regulations. Regular railways with touristic or heritage service are railways that primarily have a public transport mission and are used as a regular means of transport. In addition to this service, there are additional services adapted for tourist purposes on this route, often operated with historic rolling stock, including steam locomotives. The timetable as well as the historic vehicles used must meet all requirements in order to ensure a high level of punctuality, safety and immunity to disruption in modern operations. Network steam locomotive operators are connected to the public networked standard gauge network in Austria and Europe and operate their vehicles on it. The high technical and operational demands, which are explained in more detail in *Chapter 2.1*, often have a conflict potential with the substance and equipment of historic vehicles, especially steam locomotives. Network steam operators with heritage railways are connected to the public networked standard gauge network of Austria and Europe, but also operate a museum railway connected to it.

In addition to the comments made in this chapter, it should be noted that the expenses of heating in steam locomotive operation apart from the actual transport performance in operation are associated with great expense. Here the Bregenzerwald-Museumsbahn serves as an example (Annex A4-A7), which has supplemented the survey sheet of this research with detailed background information. The fire needed to operate the steam locomotive must be lit as early as 4 o'clock in the morning and must be maintained as a stand-by fire throughout the day in all phases without any movement of the engine for being available for shunting and other activities. The following railways are sorted by province from west to east. All route and kilometer data given were taken from the Railway Atlas of Austria (ÖBB Infrastruktur, 2010). All data on coal operation and fuel in this chapter are taken from the survey sheets or attachments to it (Annex A1) of this research, unless otherwise stated.

4.2 Individual Results

Rheinbähnle – Rhine Regulation Railway (Annex A2)

The narrow-gauge heritage railway *Rheinbähnle* is operated by the *Rheinschauen* Association and runs on the network of the former service railway of the *International Rhine Regulation* between the mouth of the Alpine Rhine into Lake Constance and a quarry in the Vorarlberg municipality of Koblach, crossing the national border between Austria and Switzerland. In addition to diesel-electric locomotives, two wood pellet fired steam locomotives are available for operation. In 2022, around 20 tonnes of wood pellets were burnt on 53 operating days with a total of 795 steam locomotive kilometers travelled and 4235 passengers transported.

Bregenzerwald-Museumsbahn – Bregenzerwald-Heritage Railway (Annex A3-A7)

The *Bregenzerwald-Museumsbahn* operates on the last remaining 5-kilometer-long section of the Bregenzerwald Railway, which originally connected the capital of Vorarlberg, Bregenz on Lake Constance, with the rear part of the Bregenzerwald region. Most of the operation, which is strongly interwoven with the region's tourism, is handled by two steam locomotives, one of which was operational in 2022. With around forty-two thousand passengers in the 2022 season on 43 operating days, the Bregenzerwald-Museumsbahn has the most passengers in steam operation on Austrian heritage and touristic railways. Around 23 tonnes of coal, which equates to around 63 tonnes of carbon dioxide, were consumed on around 1370 kilometers, whereby large deviations from the average coal consumption could be observed with different locomotive crews (Annex A4-A7). Stockpiling and procuring the fuel proved to be very difficult in the last two years, as the very low-smoke Siberian coal previously used was no longer available due to the trade embargo against Russia. The organization must face the fact, that the ecologically sensitive region reacts very critically to strong smoke development (Annex A4-A7). The Bregenzerwald-Museumsbahn is willing to use alternative fuels in the future, not only because of quality problems with bituminous coal, but also with the aim of ecologisation. It has already achieved initial positive results with binders in a preliminary study at the ETH Zurich on the question of whether fossil coal can be substituted by synthetic coal in historical steam operation, which must, however, be brought to application maturity in further large studies that are difficult to finance (Annnex A3-A5).

Zillertalbahn – Zillertal Railway

The Zillertal Railway is a narrow-gauge branch line in the district of Schwaz in Tyrol. Starting in Mayrhofen, it connects the touristically heavily frequented communities of the Ziller valley to the railway junction in Jenbach and thus to the international railway network. In addition to a half-hourly passenger service during the day, the Zillertal Railway also operates freight and a nostalgic steam train services. The steam train runs on the Zillertal Railway at weekends in May, five times a week from the beginning of June to the end of August and six times a week in September (Zillertaler Verkehrsbetriebe AG, 2021). As the author of this thesis did not receive any data from the Zillertal Railway despite several requests, available published data is used for the calculation. Since no data is available for the 2022 season and the data from 2021 and 2020 is not meaningful due to the pandemic-related disruptions in the tourism industry, the data from 2019 is used. The annual report 2019 shows that the Zillertal Railway operated 215 steam trains with a total of 38,961 passengers and covered 6824 kilometers (Zillertaler Verkehrsbetriebe AG, 2020), furthermore another source shows a coal consumption of 1.6 tons per round trip (Serchinger, 2018, p. 5) on the 31.7 kilometer route, which results in a coal consumption of 0.0252 tons per kilometer. Multiplied by the kilometer performance of the steam trains in 2022, this results in a coal consumption of 172 tons, corresponding to CO2 emissions of 473 tons. The Zillertal Railway's own workshop in Jenbach is considered a specialist facility for steam locomotives and frequently accepts lucrative external orders (Zillertaler Verkehrsbetriebe AG, 2020). In 2008, a steam locomotive was converted to a modern oil firing system (Serchinger, 2018, p. 5), which was even operated with vegetable fuel for experimental purposes (Serchinger, 2018, p. 6). However, this locomotive has been converted back to coal firing in the meanwhile (Zillertalbahn, n.d.). Currently, the Zillertal Railway is receiving special attention due to its plans to change the traction of its regular operation from diesel to hydrogen (Schreiner & Fleischhacker, 2018), although this concept is politically highly controversial (ORF Tirol, 2023). To what extent a traction conversion of scheduled services to hydrogen will affect the use of steam locomotives is unclear yet.

Figure 10 Locomotive No. 5 of the Zillertal Railway in the phase with oil firing while refueling at the diesel filling station (Own work , 2013)

Achenseebahn – Achensee Railway

Closely interwoven with the Zillertal Railway is the Achensee Railway, which also starts at Jenbach station and runs for a total of 6.7 kilometers, first with the help of a rack to the Eben line peak at an altitude of 440 meters and then in adhesion mode to the *Achensee* boat station. The cultural value of this railway line is extremely high, as it has been operated continuously by steam since its opening in 1889. The four locomotives and carriages correspond to those of the original equipment. In 2020, the historic components of the Achensee Railway were listed as historical monuments (Bundesdenkmalamt, n.d.). The Achensee Railway is now 60 percent owned by the Province of Tyrol, while the neighboring communities and the Zillertal Railway, which provides the two managing directors, each hold 20 percent. As in the case of the Zillertal Railway, no statement was made, the data is based on published information. According to a press release on a frequency increase in 2023, the Achensee Railway carried around 70,000 passengers on 1046 single-trips with three locomotives in 2022 (Lok Report, 2023). A report by the Ministry of Transport from the same year states the consumption of the identical steam locomotives of the Achensee Railway at around 350 kg of coal per trip (Bundesanstalt für Verkehr, 2011, p. 43). In 2023, there will be 1448 trips, whereby 172 trips of newly introduced holiday service will only take place on the 3.3 kilometers long flat adhesion section between the ship station and Eben (Achensee Schifffahrt, 2023), and a significantly lower coal consumption for this service can be assumed. As an estimate, a total coal consumption of around 25% of the average consumption is assumed for half the route without a large difference in altitude. For the calculation, 1276 trips with full consumption added with 172 trips with a factor of 0.25 are put in relation to the estimated total coal demand for the year of 350 tons (Lok Report, 2023), which means an average consumption of around 396 kilos in full line service of coal per trip. Multiplying these 396 kilos by the 7008 kilometers of the previous season results in a consumption of around 277 tons of coal in 2022. The CO2 emissions are therefore 762 tons. The medium-term goal is one hundred thousand annual visitors (Tirol Werbung, n.d.).

Pinzgauer Lokalbahn – Pinzgau Local Railway (Annex A8)

The *Pinzgauer Lokalbahn* is a 52.7-kilometer-long narrow-gauge railway in the region of Oberpinzgau in Salzburg, which in scheduled operation is the main transport axis of the touristically strong national pakr region *Hohe Tauern*. In addition to the extensive scheduled traffic operated by the transport division of the energy and service provider Salzburg AG, there are also historic trains, most of which are operated by one of two operational steam locomotives. Due to severe damage to big parts of the line after a flood, only 15.3 kilometers of it could be used in 2022 and the steam train service was also severely limited accordingly. In a regular season, 50 days of steam operation cover 5300 kilometers and carry about 13,000 passengers, whereas in 2022 the limited operation covered 1080 kilometers with about 8000 passengers. The coal consumption of 15 tonnes in 2022 led to carbon dioxide emissions of 41.25 tonnes, whereas in a normal year 40 tonnes of coal are burned and thus 110 tonnes of carbon dioxide are released. *The Pinzgauer Lokalbahn* stated that it has had no problems with procurement, stocks, and quality of coal and teseted of different types of coal to reduce smoke emissions. In 2023, the *Pinzgauer Lokalbahn* will also put its second steam locomotive back into service after several years of repairing in its own workshop. A technical conversion of its steam locomotives is viewed critically.

Figure 11 The pinzgau local railway offers steam locomotive rides in summer as well as in winter (Own work, 2015)

Schafbergbahn – Schafberg Mountain Railway

The *Schafbergbahn* in the Salzkammergut region is a meter-gauge rack railway that runs from the valley town of *Sankt Wolfgang am Wolfgangsee* to the final station of *Schafbergspitze* at 1732 meters above sea level. The view from this mountain of the alpine and lake landscape of the Salzkammergut was the reason for building the line, which went into operation in 1893. Together with the *Wolfgangsee* shipping line and the *Salzkammergut Lokalbahn*, which connected the region with the imperial summer residence in *Bad Ischl* and with the city of Salzburg, the *Schafbergbahn* was woven into a well-thought-out networked tourism concept. The cogwheel railway's length of 5.9 kilometers and the difference in altitude of 1190 meters result in an average gradient of 20.5 percent. The service of the railway, which is operated by the energy and service provider *Salzburg AG*, is carried out with diesel vehicles and modern Swiss steam locomotives with oil firing described in more detail in *Chapter 2.5*. Rarely, one of two operational coal-fired steam locomotives with a pushed wagon from the time of the opening is also used. Since the author of this thesis was not given any information by the *Schafbergbahn* management, the survey was carried out using available data as an extrapolation. According to the timetable for the year 2022 there were 4 services with historic coal fired steam traction (Salzburg AG Tourismus, 2022). 500 kg of bituminous coal are required for one round trip with ascent and descent (Mackinger, et al., 2014, p. 92), resulting in a coal consumption of around 2 tons for 2022. The passenger figures can be derived from an average occupancy rate of 75% assumed by the former director of the operating company (Mackinger, 2023, personal communication, 22 May) as well as from the capacity of one wagon (Salzburg AG, 2017), of 60 persons. The assumed 180 annual passengers and the coal consumption illustrate the subordinate role of coal-fired steam operation on the Schafbergbahn. The carbon dioxide emissions of the coal-fired steam locomotives thus amounted to 5.5 tons in 2022. The much larger dimensions of the scheduled operation are difficult to extrapolate due to the mixed operation with steam and diesel traction combined with the use of a de facto same fuel combined with different consumptions (Serchinger, 1998, pp. 2-7) and go beyond the scope of this paper.

Taurachbahn – Taurach Railway (Annex A9)

The 11-kilometer-long narrow-gauge *Taurachbahn* in the *Lungau* region in the province of Salzburg is the former westernmost section of the *Murtalbahn* and is operated as a heritage railway in the summer months. It is closely interwoven with the region as a tourist attraction. The umbrella organisation of the railway line, the *Club 760* association owns one of the largest collections of Austrian and European narrow-gauge vehicles, some of which are in service on *Taurachbahn*. In 2022, the total of five operational steam locomotives covered 1320 kilometers on 38 operating days, carrying around 27,000 passengers (Thomaser, 2022, pp. 51-52). Coal consumption was around 12 tonnes, which corresponds to carbon dioxide emissions of 33 tonnes. Scarce supplies and problems in procuring coal were experienced in the last two years. There is a negative attitude towards the technical conversion of steam locomotives.

Nostalgiebahnen in Kärnten – Nostalgic Railways in Carinthia / *Ferlacher Bahn* – Ferlach Railway (Annex A10)

The association of *Nostalgiebahnen in Kärnten* operates its main workshop in *St. Veit an der Glan*, which is connected to the ÖBB network, as well as the *Historama* technology museum in *Ferlach* and a heritage railway between Ferlach and Weizelsdorf. Furthermore, the upper *Rosentalbahn* line between Weizelsdorf and Rosenbach, which is owned by the province of Carinthia, is managed by the association. In addition to trips on the *Rosentalbahn* and its own heritage railway, trips are also made several times on the ÖBB network, where a class 93 steam locomotive is used in addition to electric vehicles. On the *Ferlacher Bahn* in 2022, due to maintenance work of a smaller locomotive, the class 93 was also used this year. In the process, 26 tonnes of bituminous coal, with carbon dioxide emissions of 71 tonnes, were burned in coal-fired steam operation on a total of 28 operating days with around 11,890 passengers over a total of 970 kilometers. Coal was difficult for the NBiK to procure in the last two years. Additional to the coal consuming class 93, the second machine, a steam tram locomotive was fired exclusively with wood on 6 out of 9 trips. With regard to alternatives to firing, the use of pellets is planned for the future, while a technical conversion of steam locomotives is viewed critically.

Gurkthalbahn – Gurkthal Railway (Annex A11)

The Gurkthalbahn museum railway is the 3.3-kilometer-long remnant of a former 28.9-kilometer-long narrow-gauge railway in the district of St. Veit an der Glan in Carinthia. It has been operated with steam locomotives since 1974, and in 2022 covered around 180 kilometers with 1600 passengers on 10 operating days. The steam locomotives are fired exclusively with firewood, with around one cubic meter being burnt per operating day, which corresponds with a conversion factor of 0.621 (Austrian Energy Agency, 2009, p. 10) to around 6.2 tonnes. Currently, two steam locomotives are in operation on the *Gurkthalbahn*.

Figure 12 The Austrian Society for Railway History also conducts trips on lines of the Austrian Federal Railways, such as the Ennstal line (Own work, 2014)

ÖGEG Lokpark – ÖGEG locomotive park / *Ampflwanger Bahn* – Ampflwang Railway (Annex A12)

The Ampflwang locomotive park in Upper Austria and the *Ampflwangerbahn* heritage railway is the largest section of the Austrian Society for Railway History *ÖGEG*. Here, in addition to the 10.4-kilometer-long former coal railway, the area of the sorting and loading plant as well as the workshop of the *Wolfsegg-Trauntal* coal mining company is operated under the name *Lokpark Ampflwang* The area was equipped with a large turntable and a locomotive roundhouse for the 2006 provincial exhibition. In addition to several operational locomotives of all traction types, there are many locomotives on the site that have been saved from scrapping without direct use. In addition to trips on the heritage railway, ÖGEG also offers trips on the ÖBB network. The 3 steam locomotives in operation in 2022 covered 1797 kilometers and carried 4220 passengers on 18 operating days. The annual coal consumption is around 75 tonnes and corresponds to a carbon dioxide emission of 206 tonnes. Problems in procuring coal have been comparatively minor over the past two years, but the quality has not been as good as usual. By blending higher quality coal from stockpiles, such problems can be mitigated.

Apart from private experiments with wood briquettes by ÖGEG volunteers, no use of alternative fuels has been considered; in any case, a technical retrofit is viewed critically because the financial means for it could not be acquired. In addition to the heritage railway and the locomotive park, ÖGEG also operates the Danube steamship *Schönbrunn* and the narrow-gauge heritage railway in the Steyr Valley.

ÖGEG Steyrtalbahn – ÖGEG Steyrtal Railway (Annex A13)

Between Grünburg and the district capital of Steyr in south-eastern Upper Austria, a heritage railway operates on the 16.5-kilometer-long northern section of the former narrow-gauge *Steyrtalbahn*, which was closed in 1982. In its biggest extension, the railway had a network of 55 kilometers. It is operated by the Austrian Society for Railway History and plays an important role in the tourism of the region. In 2022, three operational steam locomotives covered 3046 kilometers on 59 days and transported 19,207 passengers. Due to scarce coal supplies and high coal prices in 2022, the operation was limited by one out of three roundtrips for 2023. Coal consumption with the accessible not high-quality coal was around 70 tonnes in 2022, corresponding to around 192 tonnes of carbon dioxide. Experience with alternative fuels was gained in the form of firewood with a former Romanian forestry locomotive designed for this purpose, but it has in the since been sold. There is a negative attitude towards a technical conversion of the firing system.

Murtalbahn – Murtal Railway (Annex A14)

The *Murtalbahn*, operated by the provincial railways of Steiermark *Steiermarkbahn*, is a narrow-gauge railway line that opens up the upper Mur valley in the provinces of Styria and Salzburg and connects the two district capitals of Tamsweg and Murau with the Unzmarkt connection to the standard gauge network of the ÖBB. The *Murtalbahn* runs several times a day in public passenger traffic and irregularly in freight traffic, but also offers nostalgic trips with steam locomotives, using different sections of the 65-kilometer-long line. The original extension of the line to Mauterndorf is now operated under the name *Taurachbahn* in heritage traffic. There are two operational steam locomotives on *Murtalbahn*, which covered 1728 kilometers on 33 operating days in

2022, carrying 8899 passengers. The consumption of coal, which was also associated with procurement problems for *Murtalbahn* in the last two years, was 22 tonnes, which corresponds to carbon dioxide emissions of around 60 tonnes. A technical conversion of the steam locomotives is viewed critically.

Stainzerbahn – Stainz Railway (Annex A15)

The *Stainzerbahn* is a narrow-gauge railway line connecting the town of Stainz with the standard-gauge network of the Graz-Köflach railway. The tourist service, which is operated by the community of Stainz under the name *Stainzer Flascherlzug*, is mostly steam operated, but had to be run by a diesel locomotive in 2022, as no steam locomotive was available due to repair work. For the year 2023, however, 82 steam service days with a total of 2215 kilometers are planned again and, as in the years before the pandemic, twenty thousand passengers are expected to use the steam service. In addition to about 60 tonnes of bituminous coal, which provides 175 tonnes of carbon dioxide, a further 196 solid cubic meters of firewood, which according to a conversion factor of 0.73 (Austrian Energy Agency, 2009, p. 10) is equivalent to about 143 tonnes, cover the energy requirements of the 11.3-kilometer-long line. The firewood is used to reduce smoke emissions in flat sections of the line in residential areas but is not sufficient to generate steam in steeper sections. The two locomotives used on the Stainz Railway belong to a standard type of Romanian forest railway locomotives and are designed for firing with wood. The *Stainzerbahn* is basically positive about a technical adaptation of its locomotives for other firing methods, also because there have been problems with the procurement, supplies, and quality of coal in the last two years.

Museumstramway Mariazell – Heritage Tram Mariazell (Annex A16)

The *Museumstramway Mariazell* line is one of the most unusual routes in Austria to be operated with steam locomotives. The standard-gauge tramway line, now about 3 kilometers long, was built as a tour route for a large private tramway collection and connects the town of Mariazell with the outlying station of the narrow-gauge *Mariazell Railway* and Lake Erlaufsee. In 2022, the Heritage Tram Mariazell carried 26,800 passengers on 36 days of steam operation and covered 2700 kilometers with its two steam locomotives. The procurement of low-smoke coal posed problems for the Museumstramway Mariazell even before the energy crisis of 2021. Siberian bituminous coal could still be procured through a Dutch trader, but at greatly increased prices. Coal consumption in 2022 was 26 tonnes, which corresponds to carbon dioxide emissions of around 71 tonnes. In the medium term, the electrification of the entire line and a substitution of the steam locomotives by historical trams is planned.

Figure 13 The Heritage Tram Mariazell offers services with historic vehicles such as the former Salzburg steam tramway "Hellbrunn" on a newly built route (Own work, 2019)

Steirische Eisenbahnfreunde – Styrian Railway Friends (Annex A17)

The Association of *Steirische Eisenbahnfreunde*, based in Lieboch southwest of Graz, looks after locomotive No. 671 of the *Graz-Köflacher Bahn*, which was built in 1860 and, as a former locomotive of the *Südbahngesellschaft*, is considered to be the world's oldest steam locomotive in continuous operation. In 2022, No. 671 was used for several trips on one day and covered approximately 40 kilometers with a total of 1000 passengers. Due to the high cost of coal, it is becoming increasingly difficult for the locomotive operators to offer steam journeys. Coal consumption in 2022 was 6 tonnes, which corresponds to carbon dioxide emissions of around 16 tonnes. A technical retrofitting of the engine's firing system would be open in principle, but there are no financial means for this in sight. The extent to which the locomotive's status under monument protection stands in the way of conversions is questionable.

Feistritztalbahn – Feistritztal Railway (Annex A18)

The *Feistritztalbahn* line is a 23.9-kilometer-long narrow-gauge railway in eastern Styria and provides access to the *Feistritz* valley from the district capital of Weiz. While regular passenger services were discontinued several years ago, remaining freight services, which served a talcum mine, were discontinued in 2015. In recent years, the *Feistritztalbahn* line has run into difficulties because a complex network of different infrastructure operators, operating companies and an insolvent investor could no longer guarantee operation on the entire line. The railway facilities at the starting point of the line were dismantled for a reconstruction of the standard gauge station, which means that there is no longer a direct connection or a turning facility. In 2022, however, dedicated railway enthusiasts succeeded in setting up a provisional shuttle service with a steam locomotive on the 4.7-kilometer-long section from Birkfeld to Koglhof, which was able to transport 3,600 passengers on 21 days on a total of 630 kilometers. The coal consumption of 20 tonnes in 2022 corresponds to carbon dioxide emissions of 55 tonnes. An in the meanwhile fixed fault with the blast pipe of the class U steam locomotive could reduce coal consumption by around a third on the first trips in 2023. There were no problems with coal procurement, and a donation of bituminous coal no longer needed for a domestic heating , is even ensuring particularly good performance at the moment. While there is a generally positive attitude towards a technical adaptation, all efforts are currently being made to push ahead with the renovation of the line and to ensure the preservation of the *Feistritztalbahn* as a cultural monument.

Ybbsthalbahn Bergstrecke – Ybbstal Railway Mountain line (Annex A19)

Located in the *Mostviertel* region of Lower Austria, the *Ybbsthalbahn Bergstrecke* line between Kienberg-Gaming and Lunz am See connects the Erlauf valley with the Ybbstal valley via the Pfaffensattel Pass and, along with the short trunk of the *Citybahn Waidhofen*, is the remainder of a former 76.6-kilometer narrow-gauge network, which was discontinued in 2009 and dismantled in the early 2010s. The scenic and topographically demanding 17.3-kilometer-long *Ybbsthalbahn Bergstrecke* is an established excursion destination in the region, but the extensive maintenance of this mountain line is a constant challenge for the operating association *Österreichische Gesellschaft für Lokalbahnen* ÖGLB. In recent years, there have always been problems with the quality of the coal, as extremely efficient steam generation is necessary to haul full load on the steep mountain route. Alternative fuels would have to have correspondingly high calorific values. There are no plans to use such fuels, but there would be a positive attitude towards converting to oil firing. However, the necessary funds are not in sight. The steam operation planned for 2022 did not materialize due to a technical defect of the steam locomotive and was carried out with diesel locomotives. Therefore, no coal-based emissions from the *Ybbsthalbahn Bergstrecke* are included in the overall calculation of this paper. According to a joint projection by the author of this thesis and a representative of *ÖGLB*, around 22 tonnes of coal and thus around 60 tonnes of carbon dioxide are emitted in a normal season on 18 steam driving days with two return trips each, covering 1246 kilometers.

Museums-Lokalbahnverein Zwettl – Heritage Local Railway Association Zwettl (Annex A20)

With an ÖBB class 92 steam locomotive, the Heritage Local Railway Association Zwettl *MLV* mainly operates on the nearby ÖBB lines Schwarzenau-Waldausen and Schwarzenau-Waidhofen an der Thaya, both of which are located in the Waldviertel region of Lower Austria. In 2022, the small-structured association carried out eight days of service with a total of 2210 passengers and covered 785 kilometers. Coal consumption amounted to 13 tonnes, which corresponds to carbon dioxide emissions of around 36 tonnes. So far, there have never been problems with the procurement of coal, but with the quality of the fuel. Due to the topography in the region, which requires full power from the steam locomotive on the steep sections, no fuels with lower performance could be used. A technical conversion of the steam locomotive is therefore viewed critically.

Niederösterreich Bahnen – Lower Austria Railways (Annex A21-A22)

Niederösterreich Bahnen NÖB is a St. Pölten based railway company owned by the province of Lower Austria, which operates the *Mariazellerbahn* and the *Citybahn Waidhofen* lines in scheduled traffic as well as the *Wachaubahn*, the railway line Retz-Drosendorf, the *Waldviertelbahn* and the *Schneebergbahn* in tourist traffic. In the last two years, steam operation on the lines described in detail below suffered from scarce coal reserves and difficult procurement, but the quality met the requirements. There are no plans to use alternative fuels in their steam locomotive fleet, and the company is critical of any technical retrofitting of the firing system.

Waldviertelbahn – Waldviertel Railway (Annex A21-A22)

The Waldviertelbahn is a narrow-gauge railway operated by *Niederösterreich Bahnen* in the north of Lower Austria, which connects the district capital Gmünd with Litschau in the north and Groß Gerungs in the south. Trains run daily on the 68.4-kilometer-long network during the summer season, some of which are operated by steam at weekends. The two class *Mh* locomotives were originally built for the *Mariazellerbahn* line but were used most of the time on the Waldviertelbahn. The transition from scheduled operation to nostalgic operation was smooth on the Waldviertelbahn in the 1980s. Today, on 31 operating days in 2022, the two operational steam locomotives carried 7577 passengers on a total of 2785 kilometers. Coal consumption was 30 tonnes, resulting in carbon dioxide emissions of 82 tonnes.

Mariazellerbahn – Mariazell Railway (Annex A21-A22)

The *Mariazellerbahn* line, which connects the capital of Lower Austria, Sankt Pölten, with the pilgrimage site of Mariazell in Styria, was electrified with alternating current only five years after the opening of continuous operation in 1906 due to the early popularity of the railway. The 84-kilometer-long line is operated by *Niederösterreich Bahnen* in modern regular service over the whole year, but at weekends it is used by electric or steam-powered historic trains. A steam locomotive of the *Mh* series, specially built for the demanding mountain route of the *Mariazellerbahn*, is maintained for this purpose by the *Club Mh.6*, which also operates the 4.8-kilometer-long connecting line on the remaining section of the former *Krumpe* line. On 14 days of steam operation, a total of 2224 kilometers were covered, and 2506 passengers were transported. Coal consumption was 32 tonnes, which corresponds to carbon dioxide emissions of 88 tonnes.

Schneebergbahn – Schneeberg Mountain Railway (Annex A21-A22)

The *Schneebergbahn* line is a meter-gauge rack railway operated by *Niederösterreich Bahnen* that runs 9.8 kilometers from the village of Puchberg am Schneeberg at 577 meters above sea level, to the *Hochschneeberg* mountain station, which lies at 1796 meters above sea level on the plateau of the highest mountain of Lower Austria, The Schneeberg Mountain Railway is operated with modern diesel vehicles, joined on selected days by steam locomotives. In 2022, one steam locomotive in operation covered a distance of 20 kilometers on 10 days, carrying around 1000 passengers. The coal consumption of 12 tonnes corresponds to carbon dioxide emissions of around 33 tonnes.

Waldviertler Eisenbahnmuseum – Waldviertel Railway Museum (Annex A23)

The *Waldviertler Eisenbahnmuseum* is located in the former ÖBB locomotive roundhouse at Sigmundsherberg station, which is an important railway junction in the Waldviertel region of Lower Austria. Among the many exhibits is a class 93 steam locomotive, which is very typical for the region. In 2022, this locomotive was not in service on the ÖBB network but was used for demonstration purposes in the area of the depot and consumed around 5 tonnes of coal, which resulted in carbon dioxide emissions of almost 14 tonnes. On steam days, the museum attracted in total 600 visitors. Scarce reserves, difficult procurement and poor quality also caused problems for the Waldviertel Railway Museum in the last two years. In 2023, the steam locomotive will not be in service due to repair work.

Lokteam Trumau – Locomotive Team Trumau

The *Lokteam* association looks after a class 52 locomotive, which was taken over from the former ÖBB Erlebnisbahn, and operates trips on the ÖBB network with it. The only trip in 2022 was from its depot in Trumau in the Baden district of Lower Austria to Ernstbrunn in the Weinviertel region and back, covering a distance of 174 kilometers. No data was communicated by the locomotive team, but a passenger number of 250 passengers was obtained from the organizer of the trip (Regiobahn, 2023, personal communication, 23 May). To calculate the coal consumption, the 41.7 kilogram per kilometer average consumption of ÖGEG is used, as their steam locomotives are of a similar size and are also used on the ÖBB route network. According to this extrapolation, the locomotive team has a coal consumption of around 7 tonnes, which means carbon dioxide emissions of around 19 tonnes. The risk of a deviation in the context of the overall statistics is low due to the overall small amount of coal.

Eisenbahnmuseum Das Heizhaus Strasshof – Railway Museum Strasshof (Annex A24)

The railway museum *Das Heizhaus* in Strasshof contains the largest collection of Austrian steam locomotives, most of which come from the collections of the Republic of Austria described in more detail in *Chapter 2.1*. Some of these locomotives are operational and were regularly used in the past for special trips on the ÖBB network; these trips now only take place very rarely. At the moment, the problem of a lack of exceptions for the *Entities in Charge of Maintenance* certificates for museum vehicles, which are obligatory in the EU, is being dealt with. Furthermore, there have been problems with the availability, procurement, and quality of coal in the last two years. The technical adaptation of steam locomotives for alternative fuels is viewed negatively, whereby it should be noted that in addition to extremely high costs, the monument protection of most locomotives would represent a further difficulty. Most of the public traffic during steam days takes place on the extensive grounds of the former locomotive depot. In 2022, three operational steam locomotives carried 6123 passengers on 23 days, covering 1455 kilometers. The coal consumption was 30 tonnes and thus corresponds to 82.5 tonnes of carbon dioxide.

Liliputbahn – Prater Liliput Railway (Annex A25)

The *Liliputbahn* is a light railway with a track gauge of 381 millimeters which runs from the *Wurstelprater* amusement park on a 3.9-kilometer circuit through the extensive green spaces of the *Prater* park and, in addition to diesel locomotives for daily operation, also uses two steam locomotives on certain days. In 2022, one steam locomotive was operational, covering a total of 1587 kilometers on 42 operating days. No data is available on the exact number of passengers in steam operation, as the Liliputbahn does not conduct a different passenger survey between the individual types of traction for organizational reasons. However, an extrapolation can still show the order of magnitude of the passenger numbers. According to the new operations manager, the utilization rate for steam operation is 100 percent in most cases (Liliput Railway, 2023, personal communication, 24 May). With 400 steam trips in 2022 with a classic carriage unit with 48 seats, this results in a total of 19,200 passengers. This estimation does not include passenger changes and phases with lower utilization, but on some steam days additional capacity is created with supplementary wagons. The Liliputbahn has been suffering from the upheavals in the coal market for the past two years, as the low-smoke Welsh bituminous coal with the right grain size for the small fireboxes is no longer available and stocks have been depleted. The Polish bituminous coal used as a substitute corresponds to that of other heritage and tourism railways in Austria but has a grain size that is too large for the purposes of the Liliputbahn and produces too much smoke. Trials with a product made from processed pulverized bituminous coal with a biomass component from olive pits were unable to produce sufficient flames in the firebox to achieve the necessary boiler output. Stocks of the product, which was found to be unsuitable for the use of the railway, are mixed with the Polish bituminous coal in small quantities at the plant. The consumption of two tonnes of bituminous coal in 2022 led to 5.5 tonnes of carbon dioxide.


Figure 14 Polish coal mixed with a proportion of biocoal on the Prater Liliput Railway (Own work, 2023)

4.3 Emission Results

Table 3: CO_2 emissions* and operation data of Austrian coal fired railways for the year 2022

Institution	CO_2 from coal in t	Coal in t	Locomo tives	Service days	Service km	Passen gers	Remarks
Rheinbähnle	0.0	0	2	53	795	4235	wood fuel
Bregenzerwald-Museumsbahn	63.3	23	1	43	1370	42000	
Zillertalbahn	473.0	172	3	215	6.824	38961	
Achenseebahn	761.8	277	3	165	7008	70000	
Pinzgauer Lokalbahn	41.3	15	1	18	1080	8000	limited service
Schafbergbahn	4.8	2	1	4	48	240	
Taurachbahn	33.0	12	5	38	1320	27000	
Nostalgiebahnen in Kärnten	71.5	26	2	28	970	11890	
Gurkthalbahn	0	0	2	10	180	1600	wood fuel
ÖGEG Lokpark / Ampflwanger Bahn	206.3	75	3	18	1797	4220	
ÖGEG Steyrtalbahn	192.5	70	3	59	3046	19207	
Murtalbahn	60.5	22	2	33	1728	8899	
Stainzerbahn	0.0	0	0	0	0	0	locomotive reparation
Museumstramway Mariazell	71.5	26	2	36	2700	26800	
Steirische Eisenbahnfreunde	16.5	6	1	1	40	1000	
Feistritztalbahn	55.0	20	1	21	630	3600	limited service
Ybbsthalbahn Bergstrecke	0.0	0	0	0	0	0	locomotive reparation
MLV Zwettl	35.8	13	1	8	785	2210	
Waldviertelbahn	82.5	30	2	31	2785	7577	
Mariazellerbahn	88.0	32	1	14	2224	2506	
Schneebergbahn	33.0	12	1	10	200	1000	
Waldviertler Eisenbahnmuseum	13.8	5	1	3	4	600	
Lokteam Trumau	19.3	7	1	1	174	250	
Eisenbahnmuseum Strasshof	82.5	30	3	23	1455	6123	limited service
Liliputbahn	5.5	2	1	42	1587	19200	
Total	**2411.4**	**877**	**43**	**874**	**38750**	**307118**	

*) Based on an average conversion factor for coal to CO_2 of 2.75 (Chapter 3)

Table 3 shows the total overview of all quantitative data collected, which indicates a carbon dioxide emission of all coal-fired Austrian heritage and touristic railways of 2411 tonnes for the year 2022. This calculation is based on the calculation factor for bituminous coal to carbon dioxide of 2.75. If the total coal consumption is calculated on the assumption that poor quality bituminous coal was burnt throughout, the calculation with a factor of 2.57 results in a carbon dioxide emission of 2254 tonnes. Assuming that bituminous coal of consistently high quality was fired, a factor of 2.94 results in carbon dioxide emissions of 2575 gigatons. This numbers can be seen in *Table 4*. The derivation of the factors is described in more detail in *Chapter 3* of this thesis. The deviation of the emissions with the factor 2.75 by one ton compared to the table is due to rounded values in the main overview. Caution: It must not be concluded from this list that poorer coal quality leads to lower carbon dioxide emissions. In reality, the opposite is the case, as energy is lost when heating non-combustible components such as water.

Table 4: Total Results for the year 2022 (Table 3) with different conversion factors from carbon to carbon dioxide

Coal quality	**poor**	**medium**	**high**
Factor	2.57	2.75	2.94
CO_2 Emissions	2254 t	2412 t	2579 t

Some heritage and touristic railways in Austria had a limited steam operation in 2022, which can be expected to increase again. The following extrapolation made for this reason is largely based on the data from 2022, but supplements these with other existing values for railways that did not operate steam services in 2022, or only to a limited extent. For the Achenseebahn, which is extremely important in the statistics due to the large number of trips, the expected key figures for 2023 are inserted. For the flood damaged Pinzgauer Lokalbahn, the average data for operation on the entire line are used.

Table 5: Extrapolation of total CO_2 emissions (Table 6) with different conversion factors from carbon to carbon dioxide

Coal quality	**poor**	**medium**	**high**
Factor	2.57	2.75	2.94
CO_2 Emissions	2755 t	2948 t	3152 t

Table 6: Extrapolation for annual CO_2 emissions* and operation data of coal fired railways of Austria

Institution	CO_2 from coal in t	Coal in t	Locomo tives	Service days	Service km	Passen gers	Remarks
Bregenzerwald-Museumsbahn	63.3	23	1	43	1370	42000	
Zillertalbahn	473	172	3	215	6.824	38961	
Achenseebahn	962.5	350	4	144	9117	100000	plans for 2023
Pinzgauer Lokalbahn	110	40	2	50	5300	13000	average numbers
Schafbergbahn	4.8	2	1	4	48	240	
Taurachbahn	33	12	5	38	1320	27000	
Nostalgiebahnen in Kärnten	71.5	26	2	28	970	11890	
ÖGEG Lokpark / Ampflwanger Bahn	206.3	75	3	18	1797	4220	
ÖGEG Steyrtalbahn	192.5	70	3	59	3046	19207	
Murtalbahn	60.5	22	2	33	1728	8899	
Stainzerbahn	165	60	1	82	2215	20000	average numbers
Museumstramway Mariazell	71.5	26	2	36	2700	26800	
Steirische Eisenbahnfreunde	16.5	6	1	1	40	1000	
Feistritztalbahn	55	20	1	21	630	3600	limited service
Ybbsthalbahn Bergstrecke	101.8	37	1	18	1246	6000	average estimation
MLV Zwettl	35.8	13	1	8	785	2210	
Waldviertelbahn	82.5	30	2	31	2785	7577	
Mariazellerbahn	88	32	1	14	2224	2506	
Schneebergbahn	33	12	1	10	200	1000	
Waldviertler Eisenbahnmuseum	13.8	5	1	3	4	600	
Lokteam Trumau	19.8	7	1	1	174	250	
Eisenbahnmuseum Strasshof	82.5	30	3	23	1455	6123	limited service
Liliputbahn	5.5	2	1	42	1587	19200	
Total	**2948.1**	**1072**	**43**	**922**	**47565**	**362283**	

*) Based on an average conversion factor for coal to CO_2 of 2.75 (Chapter 3)

Since on the *Stainzerbahn* no steam locomotive was in operation in 2022 due to repairs, but one is already in operation again in 2023, an average value from the years is also used for this line. The same applies to the Ybbsthalbahn Bergstrecke on which steam operation plays a major role in regular years. The *Rheinbähnle* line and the *Gurkthalbahn* are no longer taken into account due to the lack of coal as fuel. This extrapolation results in carbon dioxide emissions of around 2947 tonnes per year.

Table 7: Annual Carbon dioxide emissions (Table 6) per passenger in kg

Institution	CO_2 per passenger (kg)
Lokteam Trumau	77.00
ÖGEG Lokpark / Ampflwanger Bahn	48.87
Mariazellerbahn	35.12
Schneebergbahn	33.00
Schafbergbahn	22.92
Waldviertler Eisenbahnmuseum*	22.92
Ybbsthalbahn Bergstrecke	16.96
Steirische Eisenbahnfreunde	16.50
Museums Lokalbahnverein Zwettl	16.18
Feistritztalbahn	15.28
Eisenbahnmuseum Strasshof*	13.47
Zillertalbahn	12.14
Waldviertelbahn	10.89
ÖGEG Steyrtalbahn	10.02
Achenseebahn	9.63
Pinzgauer Lokalbahn	8.46
Stainzerbahn	8.25
Murtalbahn	6.80
Nostalgiebahnen in Kärnten	6.01
Museumstramway Mariazell	2.67
Bregenzerwald-Museumsbahn	1.51
Taurachbahn	1.22
Liliputbahn	0.29
Average	**16.3**

*) Visitors of the museum on steam service days

Applying the factors for different coal qualities results in a range of 2755 to 3152 tonnes of carbon dioxide emissions. For better comparability, further derivations are made from the survey with the data of the extrapolation with the conversion factor 2.75. In the context of heritage and touristic Railways, the emission quantities per kilometer or per person should always be considered under the aspect that behind the decision to travel with a steam locomotive is most of the time no need for mobility from one place to another, but rather the focus is on experiencing historical technology. Nevertheless, in the course of this survey it also makes sense to put the emission data in relation to the number of journeys and passengers. It is important to note, however, that track gauge, topography, speed, and the technology of the steam locomotive are strongly determining factors. Another important role is played by the additional operating hours of a steam locomotive, like test rides, the preparation, shunting and post-processing of trips, as well as maintaining operational readiness, are included in the fuel numbers in addition to mileage. The additional relevance of the human factor and its competences in heating the steam locomotive have already been reported on several times in this thesis. The average CO_2 emission over all Austria is 16.3 kg per passenger of steam service on heritage and touristic railways.

If it is assumed that the experience of a steam locomotive is in the dominant motivation for passengers and the distance travelled is not a relevant criterion, the key figure carbon dioxide per person is appropriate. *Table 7* shows that the area of higher emissions includes standard-gauge institutions, long lines, and railway lines with a large difference in altitude. The lower range is dominated by narrow-gauge railways. As far as the two highest values are concerned, it should be noted that the *Lokteam Trumau* only made one trip over a longer distance and that *ÖGEG* keeps several steam locomotives in operation on several days in its locomotive park in Ampflwang. The *Liliputbahn* at the lower end has by far the lowest value due to its small construction, low speed, and short distance.

The carbon dioxide emissions per kilometer in Table 8 clearly show a tendency towards higher consumption on standard-gauge and rack railways, which is evident from the seven institutions ranked first. The *Waldviertler Eisenbahnmuseum* as the first-ranked institution has the circumstance that the locomotive can only move under steam on a few meters of track in the museum area and stands most of the time. The only steam journey of *Steirische Eisenbahnfreunde* in 2022 took place as a shuttle service on a short section of track. It is noticeable that 16 institutions are as well as the average of 60 kilogram below 100 kilogram of carbon dioxide per kilometer. However, this graph is not meaningful with regard to the number of passengers carried, which also partly results in the wagon load.

Table 8: Annual Carbon dioxide emissions (Table 6) per km in t

Institution	**CO_2 per km (t)**
Waldviertler Eisenbahnmuseum	3.438
Steirische Eisenbahnfreunde	0.413
Schneebergbahn	0.165
ÖGEG Lokpark / Ampflwanger Bahn	0.115
Schafbergbahn	0.115
Lokteam Trumau	0.111
Achenseebahn	0.106
Feistritztalbahn	0.087
Ybbsthalbahn Bergstrecke	0.082
Stainzerbahn	0.074
Nostalgiebahnen in Kärnten	0.074
Zillertalbahn	0.069
ÖGEG Steyrtalbahn	0.063
Eisenbahnmuseum Strasshof	0.057
Bregenzerwald-Museumsbahn	0.046
Museums Lokalbahnverein Zwettl	0.046
Mariazellerbahn	0.040
Murtalbahn	0.035
Waldviertelbahn	0.030
Museumstramway Mariazell	0.026
Taurachbahn	0.025
Pinzgauer Lokalbahn	0.021
Liliputbahn	0.003
Average	**0.062**

A suitable indicator for comparison purposes is carbon dioxide emissions per passenger kilometer. This figure is calculated by dividing the emissions per person by the route length assuming a roundtrip per person and for railways with different route lengths, by the average route length. In this extrapolation, the transport performance and the number of kilometers have the effect of improving the distribution of the standard-gauge railways. Railways with high passenger numbers are relatively favored here. The significantly higher output of rack railways, which results from the energy required to overcome the meters in height, is clearly visible here. Fourteen out of nineteen Railways have carbon dioxide emissions of less than 0.5 kg per kilometer. The arithmetic average of all Austrian heritage railways is also around 0.5 kg per kilometer. *Steirische Eisenbahnfreunde* and *Lokteam* offered this year only one trip and *Eisenbahnmuseum Strasshof* as well as *Waldviertler Eisenbahnmuseum* offered mainly services on their museum area, so that no meaningful data can be generated in these cases and for this are excluded from the calculation.

Table 9: Carbon dioxide emissions (Table 6) per passenger kilometer in kilogram

Institution	**CO_2 per passenger kilometer (kg)**
Schafbergbahn	1.98
Schneebergbahn	1.68
Feistritztalbahn	1.59
Achenseebahn	0.76
ÖGEG Lokpark / Ampflwanger Bahn	0.62
Ybbsthalbahn Bergstrecke	0.49
Museums Lokalbahnverein Zwettl	0.47
Museumstramway Mariazell	0.44
Stainzerbahn	0.37
ÖGEG Steyrtalbahn	0.30
Mariazellerbahn	0.21
Zillertalbahn	0.19
Nostalgiebahnen in Kärnten	0.18
Waldviertelbahn	0.17
Bregenzerwald-Museumsbahn	0.15
Murtalbahn	0.12
Pinzgauer Lokalbahn	0.08
Liliputbahn	0.07
Taurachbahn	0.06
Average	**0.52**

4.4 Fuel management results

In the context of coal consumption, ten questions were asked about qualitative assessments. The first two questions on procurement showed a very clear picture. Out of 19 institutions, 14 stated that they had experienced issues in the procurement of coal in the last two years, but only two institutions had experienced procurement problems in the previous 20 years. A similar picture emerged for the questions targeting scarce coal supplies in the same periods. In the last two years, 11 out of 19 institutions had short coal supplies, while only one institution had this problem the 20 years before. Poor coal quality has been a problem for 9 institutions in the last two years.

Likewise, 9 out of 19 institutions stated that they currently offer limited train services. The reasons for this are the high costs of coal at three institutions, at another two no steam locomotives are currently available due to repair work, one was able to resume steam operation this year after a failure of the steam locomotive last year. On two Railways the line is currently interrupted, and one institution is affected by certification problems for the ÖBB network.

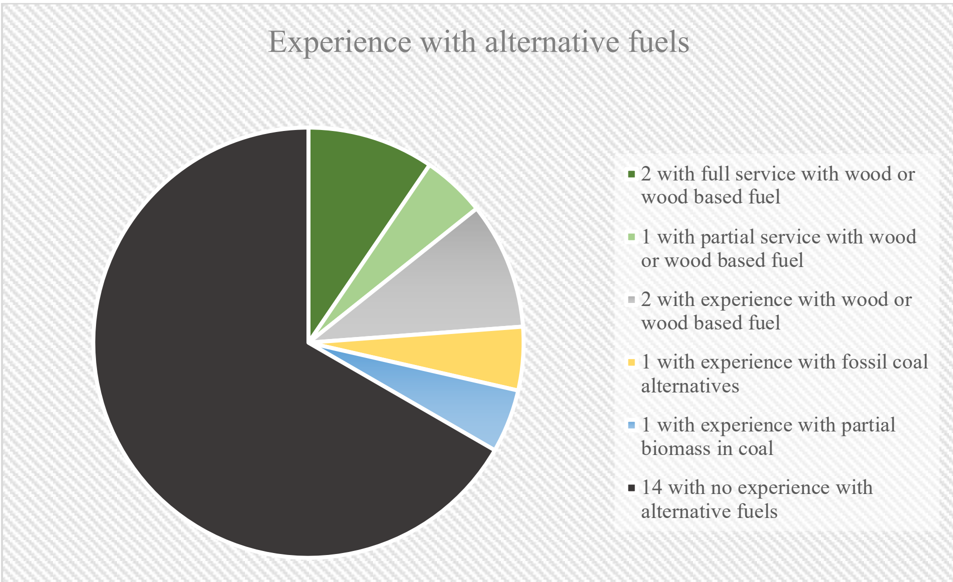


Figure 15 Experience with alternative fuels of steam driven Austrian heritage and touristic railways

Out of 19 institutions, two railway lines run completely on wood, one railway line runs partly on wood, and another two railway lines have experience with wood or wood-based fuels. One heritage railway has experience with coke and lignite briquettes, and one light railway further has recent experience with a fuel consisting of pulverized coal and biomass material, but this has been unsuccessful for the small sized steam locomotive, where it was tested. The number of institutions without experience with alternative fuels to bituminous coal is 14. It should be noted that one company that did not participate in the survey converted a locomotive to oil firing, which has since been dismantled. Of the total of 19 institutions, only two are currently planning to use alternative fuels in the future, with one institution planning to use wood pellets and another intensively searching for a suitable fuel. Four institutions are positive about a technical retrofit, nine are critical and six are negative. Due to the high costs, however, all institutions state that such a retrofit would not be possible without external financial support.

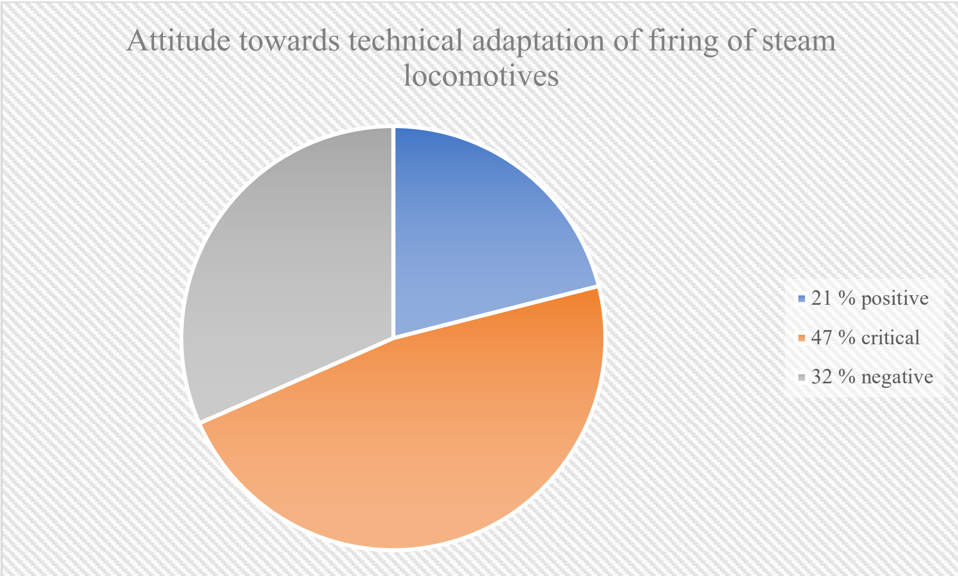


Figure 16 Attitude towards technical adaptation of firing of Austrian heritage and touristic railways.

5. Summary and Conclusion

The carbon dioxide emissions of steam-operated Austrian heritage and touristic railways in 2022 amounted to approximately 2412 tons, although values between 2254 and 2279 tons would be possible assuming different coal qualities. An extrapolation has been made due to the fact that some institutions were not be able to operate steam in 2022 due to repairs or restrictions. Based on an estimated range between 2755 and 3152 tons, this results in an average value of 2948 tons of carbon dioxide. This means that annual carbon dioxide emissions from steam-powered heritage and touristic railways in Austria can be assumed to be around 3 kilotons. The given numbers are only direct emissions, as there are no data for indirect emissions for historic rail vehicles that have far exceeded their planned useful life.

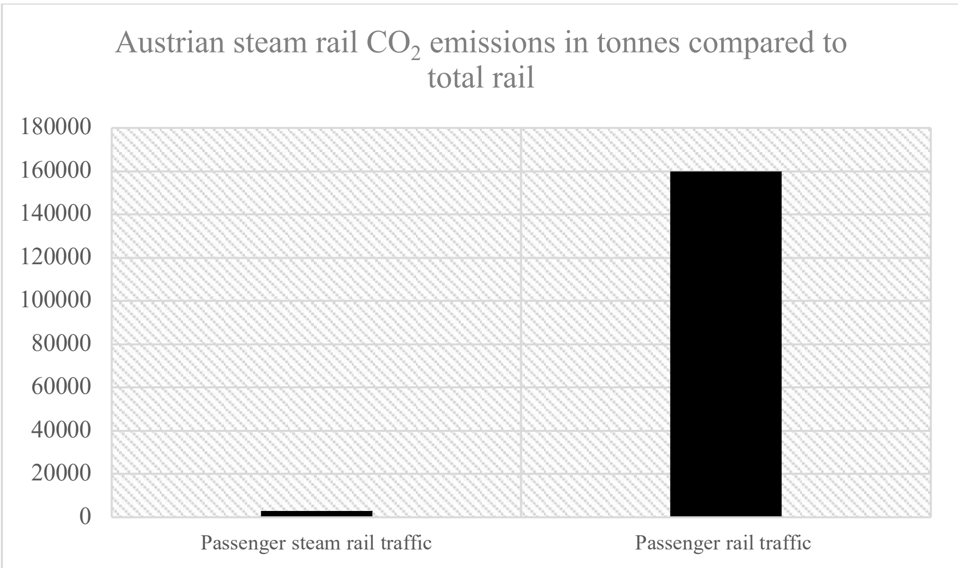


Figure 17: Austrian steam rail CO_2 emissions compared to total rail

Steam locomotives account for around 0.004 percent of Austria's total greenhouse emissions of 77.5 million tons of CO_2 equivalents (Umweltbundesamt, n.d.). Compared to the entire Austrian transport sector, which emitted 21.6 million tons of carbon dioxide in 2021 and accounts for 27.8 percent of total emissions (Umweltbundesamt, n.d.), the emissions of all Austrian steam locomotives are in the order of one ten-thousandth. Steam locomotives, insofar as they are included in these statistics, account for about 1.8 percent of the 160 thousand tons emitted in Austrian passenger rail transport, which is calculated from 8433 billion passenger kilometers by rail (Statistik Austria, 2021) with 0.019 kilogram of carbon dioxide directly emitted per passenger kilometer (Umweltbundesamt, 2022). Compared to other forms of traction in rail transport, the steam locomotive is clearly more inefficient due to its poor efficiency, which makes the reason for its replacement in the past seem very logical.

Figure 18: CO_2 emissions of Austrian coal fired steam railway fleet compared to old-timer car fleet

Although the average carbon dioxide emission on Austrian steam railways per passenger kilometer of 520 grams is about twice as high as the average value of 270 grams of the Austrian passenger car fleet (Umweltbundesamt, 2022), nine out of nineteen heritage and touristic railways, including most of the narrow-gauge railways, have lower emissions. The calculation of annual emissions of the entire Austrian old-timer road fleet of about 258 thousand vehicles riding on average 700 kilometers per year (Schamburek & Sobotka, n.d.) and consuming on average assumed 0.2 liters per kilometer (EIA, 2012, p. 59) with a gasoline to carbon dioxide factor of 2.31 (University of Exeter, n.d.), comes to 83 thousand tons of carbon dioxide per year. Compared to this, the fleet of steam locomotives perform significantly better. A full comparison would include historic diesel vehicles as well, but there is little reliable data, and it would be difficult to differentiate between historic and non-historic vehicles.

Even if the carbon dioxide emissions per passenger kilometer are in the range of modern cars, a reduction of emissions is generally desirable. The difficult availability of usable steam locomotive coal on the market at the moment indicates no long-term perspective for the fuel as the decarbonization of European and international economies continues. This makes the search for alternatives seem very relevant. Although only two out of nineteen operators of coal-fired steam railways plan to use a different fuel in the future, the majority of institutions had problems with coal. A potential relaxation of the market may ease the situation, but there will be an increasing reliance on exports, which will mostly worsen the indirect carbon footprint of the fuel. However, a long-term solution could only be achieved by adapting the fuel. The possible options are the operation with oil, subsequently with climate-friendly oil products, or the use of biomass-based coal substitutes, often called biocoal. The conversion of steam locomotives to oil firing requires a major technical and financial effort that cannot be undertaken without additional financial contributions. The fuels suitable for this purpose are currently fossil or contain only small quantities of vegetable components. Conversion to oil firing involves the risk of technological path dependency but would solve fuel procurement and quality problems in the coming years and would additionally eliminate the issue of flying sparks in times of increasingly long periods without precipitation.

While fossil oil has technical benefits during operation and is easily available on the market, there is a lack of affordable products in the field of biocoal that was able to demonstrate the necessary combustion properties in large scale use. Further research on biocoal is urgently needed and requires adequate funding. Although the use of biocoal is basically intended to preserve the historical condition of steam locomotives, minor adaptations, and adjustments to certain components, such as the blowpipe system, the firebox or the ash pan, could contribute to a success, but further research is also needed in this constructive context.

The question of whether oil or biocoal is the better alternative to bituminous coal also requires a discussion of the different applications. For Railways whose steam locomotives have a large number of operating days and a high mileage per year, oil may be a suitable alternative, while for steam locomotives with a low frequency of trips and the goal of preserving historical technology, biocoal may be a viable alternative.

Since neither large-scale oil conversions nor a widely applicable biocoal fuel are realistically possible in Austria at the present time, it is necessary to ensure the supply of high-quality coal to Austrian heritage and touristic railways. For this purpose, joint procurement of the fuel would ideally be considered in coordination with neighboring European countries, since bundled procurement in large quantities has the potential for greater choice on the market, and pollutants could be better monitored. A large-scale procurement of coal could ensure the security of supply of a suitable fuel in the future, but also carries the risk of dependencies. However, the isolated role of heritage and touristic railways must also be taken into account in future legislation to enable exemptions in the event of potential coal bans. Of the national net sink emissions in Land Use, Land-Use Change and Forestry LULUCF of approximately 3 megatons reported in the Austrian greenhouse gas Projections for the years 2030 to 2040 (Umweltbundesamt, 2021, pp. 76-77), current emissions from coal-fired steam locomotives would account for about 0.1 percent and for this be covered in a carbon neutral future.

A key factor in preventing carbon dioxide emissions from steam locomotives is personel. The potential for saving expensive fuel and avoiding unnecessary emissions can be achieved by a high level of efficient firing and driving competence among locomotive crews. The significant differences in the coal consumption of different locomotive crews observed on the *Bregenzerwald-Museumsbahn* show the great potential that training and further education of locomotive crews has. Additional training and education measures mean an additional investment of time for the steam locomotive personnel, who work voluntarily for the majority of the institutions. Such efforts must be made attractive and efficient in order to have the desired effect.

To conclude, the carbon dioxide emissions of steam-powered heritage and touristic railways play a negligible role in relation to total greenhouse gas emissions. Per passenger kilometer, it is in a similar range with modern fossil fuel-based passenger cars. In the short term, the absence of financial means to convert to other combustion methods and the lack of large-scale availability of viable alternative fuels with coal properties, it is necessary to secure the supply of high-quality bituminous coal. Additionally, increased efforts in the development of biocoal products are highly recommended. In the long term, a phase-out of bituminous coal should be targeted and decisions on the future fuel should be made in individual analysis. To reach this objective, large-scale facilities for a cost effective production of suitable products are needed in the biocoal sector. In the area of oil firing, it must be ensured that firing with non-fossil fuels is economically feasible. The changed political and economic framework conditions in the context of the use and availability of fossil fuels pose major challenges for the operating organizations in order to maintain the scope of operation of the rolling cultural heritage of steam locomotives.

Figure 19: Mixed passenger and freight train on the Taurach railway with vehicles of the extensive collection of the Club 760 association (Own work, 2018)

References

Achensee Schifffahrt, 2023. *Fahrplan 2023.* [Online]
Available at:
https://www.achenseeschifffahrt.at/uploads/tx_bh/fp_hs_23_.pdf?mod=1680245009
[Accessed 24 May 2023].

Advanvced Steam Traction Group, 2022. *Qualitative Assessment of Fuel Performance.* [Online]
Available at: https://www.bglr.org/wp-content/uploads/2022/05/ASTT.QualitativeAssessmentOfFuelPerformance.15_5_22.pdf
[Accessed 23 May 2023].

Anon., 2015. Das Ende der ÖBB-Erlebnisbahn. *Eisenbahn Österreich*, March, Issue 3, p. 149.

Austrian Energy Agency, 2009. *Empfohlene Umrechnungsfaktoren für Energieholzsortimente bei Holz- bzw. Energiebilanzberechnungen.* [Online]
Available at: https://www.klimaaktiv.at/dam/jcr:dfa2dd20-3e64-4b4e-aea4-cf1c9d3179ad/Umrechnungsfaktoren%20für%20Energieholzsortimente%20bei%20Bilanzberechnungen.pdf
[Accessed 26 May 2023].

Bond, T., Bhardwaj, E., Dong, R., Jogani, R., Jung, S., Roden, C., Streets, D., Chaopricha, N., 2007. Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850–2000. *Global Biogeochemical Cycles*, 21(2). DOI: 10.1029/2006GB002840

BP, 2021. *Statistical Review of World Energy.* [Online]
Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf
[Accessed 12 May 2023].

Breeze, P., 2015. *Coal-Fired Generation.* Cambridge, Massachusetts: Academic Press. https://doi.org/10.1016/B978-0-12-804006-5.00012-5.

British Transport Comission, 1957. *Handbook for Railway Steam Locomotive Enginemen.* London: British Transport Comission.

Bundesanstalt für Verkehr, 2011. *Bremanstand der Fahrt 13.* [Online]
Available at: https://www.bmk.gv.at/dam/jcr:f13c8358-9961-4ddc-bf37-76411244613a/
[Accessed 24 May 2023].

Bundesdenkmalamt, n.d. *Achenseebahn in Jenbach unter Denkmalschutz.* [Online]
Available at: https://www.bda.gv.at/service/aktuelles/achenseebahn-in-jenbach-unter-denkmalschutz.html
[Accessed 24 May 2023].

Club 1889, 203. *G 3/4 11 «Heidi» (1902).* [Online]
Available at: https://club1889.ch/lok_g_3_4_11
[Accessed 22 May 2023].

Coalition for Sustainable Rail, n.d. *EVERETT RAILROAD TESTING.* [Online]
Available at: https://csrail.org/everett
[Accessed 23 May 2023].

Council of the European Union, 2023. *EU restrictive measures against Russia over Ukraine (since 2014).* [Online]
Available at: https://www.consilium.europa.eu/en/policies/sanctions/restrictive-measures-against-russia-over-ukraine/
[Accessed 15 May 2023].

CPL Industries, 2017. *Product Safety Data Sheet Ecoal.* [Online]
Available at: https://s7g10.scene7.com/is/content/wickes/Coal-Firewood-Logs-Homefire-Ecoal-50-Smokeless-Coal-10-Kg-Bag~C1856_151160_COSHH_0
[Accessed 23 May 2023].
Dampfbahn Furka Bergstrecke, 2023. *HG 2/3 Nr. 7.* [Online]
Available at: https://www.dfb.ch/de/stories/hg-2-3-nr-7
[Accessed 22 May 2023].

Dampflokomotiv- und Maschinenfabrik DLM AG, 2015. *SUCCESSFUL LOAD TESTS WITH MODERNIZED STEAM LOCOMOTIVE "HEIDI".* [Online]
Available at: https://dlm-ag.ch/en/successful-load-tests-with-modernized-steam-locomotive-heidi/
[Accessed 22 May 2023].

Dampflokomotiv- und Maschinenfabrik DLM AG, 2020. *MODERNE DAMPFTRAKTION.* [Online]
Available at: https://dlm-ag.ch/wp-content/uploads/2020/06/2020-06-15_Moderne-Dampftraktion_Homepage.pdf
[Accessed 22 May 2023].

Dampflokomotiv- und Maschinenfabrik DLM AG, n.d. *Modernised steam locomotives.* [Online]
Available at: https://dlm-ag.ch/en/modernised-steam-locomotives/
[Accessed 23 May 2023].

Doleschal, E., Gerl, H., Petrovitsch, H. & Saliger, W., 1999. *Triebfahrzeuge Österreichischer Eisenbahnen. Diesel-Lokomotiven und Diesel-Triebwagen.* Düsseldorf: Alba. ISBN: 3870941758.

EIA, 2012. *Annual Energy Review 2011.* [Online]
Available at: https://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf
[Accessed 30 May 2023].

Eisenbahntechnische Rundschau, 2019. *ECM-Zertifizierung – spätestens im Juni 2022 für alle Fahrzeuge!.* [Online]
Available at: https://eurailpress-archiv.de/SingleView.aspx?show=1237769
[Accessed 21 May 2023].

Eurostat, 2022. *Coal production and consumption statistics.* [Online]
Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Coal_production_and_consumption_statistics#Consumption_and_production_of_hard_coal
[Accessed May 2023 2023].

Fengler, W. A., MSME & Ward, D. A., 2017. *Preserving Solid Fuel Firing in a Post-Coal World.* [Online]
Available at:
https://static1.squarespace.com/static/55e5ef3fe4b0d3b9ddaa5954/t/59fc6104e31d19b703b95a15/1509712137097/CSR_Torrefied_Biomass_Paper.pdf
[Accessed 22 May 2023].

Giesl-Gieslingen, A., 1981. *Die Ära nach Gölsdorf.* Wien: Verlag Josef Otto Slezak.

Giesl-Gieslingen, A., 1986. *Anatomie der Dampflokomotive International.* Wien: Verlag Josef Otto Slezak.

Global Energy Monitor, 2023. *Boom and Bust Coal 2023: Tracking the Global Coal Plant Pipeline.* [Online]
Available at: https://globalenergymonitor.org/report/boom-and-bust-coal-2023/
[Accessed 15 May 2023].

Graf, B., 2022. *Bewegliche Denkmale in Österreich/Liste von Schienenfahrzeugen.* [Online]
Available at:
https://de.wikipedia.org/wiki/Bewegliche_Denkmale_in_Österreich/Liste_von_Schienenfahrzeugen
[Accessed 21 May 2023].

Harzer Schmalspurbahnen, 2022. *Wasserstoff als Alternative zur Steinkohle für Dampfloks der HSB?.* [Online]
Available at: https://www.hsb-wr.de/Aktuelles/News/
[Accessed 24 May 2023].

Heritage Railway Association, 2022. *Coal Supplies – Update for HRA Members.* [Online]
Available at: https://www.bglr.org/wp-content/uploads/2022/05/Coal-Update.pdf
[Accessed 23 May 2023].

Historic RhB, 2014. *Die Bündner Kulturbahn.* [Online]
Available at: https://issuu.com/historic-rhb/docs/rhb_kulturbahn_2015_low
[Accessed 22 May 2023].

Hong, B. D. & Slatick, E. R., 1994. *Carbon Dioxide Emission Factors for Coal.* [Online]
Available at: https://www.eia.gov/coal/production/quarterly/co2_article/co2.html
[Accessed 23 May 2023].

IEA, 2021. *Net Zero by 2050.* [Online]
Available at: https://www.iea.org/reports/net-zero-by-2050
[Accessed 15 May 2023].

IEA, 2022. *Coal 2022.* [Online]
Available at: https://www.iea.org/reports/coal-2022
[Accessed 15 May 2023].
IEA, 2022. *World Energy Balances 2022 Coal.* [Online]
Available at: https://www.iea.org/fuels-and-technologies/coal
[Accessed 15 May 2023].

Igel, M., 1990. *Handbuch des Lokomotivbaues.* facsimile of the 1923 edition ed. Solingen: Steiger.

Intercontinental Exchange, 2023. *API2 Rotterdam coal futures at the beginning of each week from January 4, 2021 to April 10, 2023 (in U.S. dollars per 1,000 metric tons).* [Online]
Available at: https://www.statista.com/statistics/1308104/weekly-api2-rotterdam-coal-futures/
[Accessed 15 May 2023].

Joos, F., 2006. *Technische Verbrennung.* Berlin, Heidelberg: Springer. https://doi.org/10.1007/3-540-34334-2.

Kraus, H. G., 1992. *Weiße Kohle für Österreichs Bahnen.* Wien: Verlag Pospischil.

Lawn, C., Cunningham, A.T.S., Street, P.J., Matthews, K.J., Sarjeant, M., Godridge, A.M., 1987. *The combustion of heavy fuel-oil. Principles of Combustion Engineering for Boilers.* [Online]
Available at:
https://www.researchgate.net/publication/312922739_The_combustion_of_heavy_fuel-oil
[Accessed 22 May 2023].

Lewis, A., 2023. *Councillors have decided to refuse plans for Ffos y Fran opencast mine in Merthyr Tydfil.* [Online]
Available at: https://www.herald.wales/south-wales/councillors-have-decided-to-refuse-plans-for-ffos-y-fran-opencast-mine-in-merthyr-tydfil/
[Accessed 15 May 2023].

Lok Report, 2023. *Österreich: Achenseebahn erhöht 2023 Frequenz.* [Online]
Available at: https://www.lok-report.de/news/europa/item/38466-oesterreich-achenseebahn-erhoeht-2023-frequenz.html
[Accessed 24 May 2023].

Longhorn, D., 2023. *Mine decision 'short-sighted' says heritage rail group.* [Online]
Available at: https://news.railbusinessdaily.com/mine-decision-short-sighted-says-heritage-rail-group/?fbclid=IwAR2J_PYu9A3IvTRAdMLqGVh_x_x0wQe6dJ9sqiTYvLnaOTSI_4JPulL1ltQ
[Accessed 15 May 2023].

Mackinger, G., Ortner, M. & Prokop, W., 2014. *50 Jahre Reihe 5099.* Wien: Railway Media Group. ISBN: 978-3-902894-18-2.

Maedel, K.-E., 1965. *Die deutschen Dampflokomotiven gestern und heute.* Berlin: VEB Verlag Technik.

Mangia, C., Cervino, M. & Gianicolo, E. A., 2015. Secondary Particulate Matter Originating from an Industrial Source and Its Impact on Population Health. *Int J Environ Res Public Health,* 12(7), p. 7667–7681. DOI: 10.3390/ijerph120707667.

Meineke, F. & Röhrs, F., 1949. *Die Dampflokomotive.* Berlin: Springer-Verlag.
Muica, N. & Turnock, D., 2003. *The railway age in the Carpathian forests: A study of Romania.* [Online]
Available at: https://scindeks-clanci.ceon.rs/data/pdf/0354-8724/2003/0354-87240307009M.pdf
[Accessed 23 May 2023].

ÖBB Infrastruktur, 2010. *Eisenbahnatlas Österreich.* Köln: Schweers + Wall. ISBN: 978-3-89494-138-3

ÖBB, 2021. *Regelwerk 50 01.01. Technischer Netzzugang.* [Online]
Available at:
https://infrastruktur.oebb.at/de/geschaeftspartner/schienennetz/technischer-zugang/probefahrten/dokument?datei=50-01-01_TNZ.pdf
[Accessed 21 May 2023].

ORF Tirol, 2023. *Aufregung um die Zukunft der Zillertalbahn.* [Online]
Available at: https://tirol.orf.at/stories/3206815/
[Accessed 24 May 2023].

Österreichische Gesellschaft für Eisenbahngeschichte, 1997. *Sonderfahrten der ÖGEG 1998.* [Online]
Available at: https://www.eisenbahn.gerhard-obermayr.com/nostalgiebetrieb/oegeg/sonderfahrten/1998/
[Accessed 21 May 2023].

Österreichische Raumkonferenz, 1980. *Die Nebenbahnen Österreichs – ihre verkehrs- und Raumwirtschaftliche Bedeutung.* Wien: ÖROK.
Abbasi, S., Jansson, A., Sellgren, U. & Olofsson, U., 2013. Particle Emissions From Rail Traffic: A Literature Review. *Critical Reviews in Environmental Science and Technology,* 23(13), pp. 2511-2544. DOI: 10.1080/10643389.2012.685348.

Ritchie, H., Roser, M. & Rosado, P., 2020. *CO_2 and Greenhouse Gas Emissions.* [Online]
Available at: https://ourworldindata.org/co2-and-greenhouse-gas-emissions
[Accessed 12 Mai 2023].

Sachslehner, J., 2014. *Auf Schienen durch das alte Österreich.* Wien, Graz, Linz: Pichler Verlag Styria. ISBN: 9783222134814

Salzburg AG Tourismus, 2022. *Schafbergbahn Preise.* [Online]
Available at:
https://www.5schaetze.at/content/dam/tourism/downloads/preislisten/de/2022_Preisliste_SchafbergBahn.pdf
[Accessed 23 May 2023].

Salzburg AG, 2017. *BZ 102-103 Vorstellwagen.* [Online]
Available at: https://www.5schaetze.at/content/dam/tourism/downloads/typenblätter-/sbb/Typenblatt%20BZ%20102-103.pdf
[Accessed 25 May 2023].

Schamburek, C. & Sobotka, R., n.d. *Oldtimer in Österreich.* [Online]
Available at: https://oldtimerfakten.at/storage/downloads/1/document.pdf
[Accessed 30 May 2023].

Schiendl, W., 2015. *Die Eisenbahnen in Bosnien und der Herzegowina 1867–1918.* Wien: Bahn im Film. ISBN: 9783950309652

Schröpfer, H., 2002. *Triebfahrzeuge österreichischer Eisenbahnen. Dampflokomotiven BBÖ und ÖBB.* Düsseldorf: Alba. ISBN: 3870941855

Schreiner, H. & Fleischhacker, N., 2018. *Zillertalbahn 2020+ Energieautonom mit Wasserstoff.* [Online]
Available at: https://www.zillertalbahn.at/data.cfm?vpath=ma-wartbare-inhalte/ma-downloadfiles/quelle-etr-juni-2018-nr-6-wwweureilpressde-etr
[Accessed 24 May 2023].

Schwarze, J. et al., 1964. *Die Dampflokomotive.* Berlin: Transpress VEB Verlag für Verkehrswesen.

Schweinfurth, S. P., 2009. *An Introduction to Coal Quality.* [Online]
Available at: https://pubs.usgs.gov/pp/1625f/downloads/ChapterC.pdf
[Accessed 12 May 2023].

Serchinger, R. W., 1998. *Modern Steam Traction and the Protection of the Environment.* [Online]
Available at: http://advanced-steam.org/wp-content/uploads/2017/07/Barcelona-1998-Modern-Steam-Traction-and-the-Protection-of-the-Environment-R.W.-Serchinger.pdf
[Accessed May 2023].

Serchinger, R. W., 2017. *Kohlequalität und Dampflokemissionen.* [Online]
Available at: https://www.vdmt.de/164-2016/875-kohlequalitaet-und-dampflokemissionen
[Accessed 13 May 2023].

Serchinger, R. W., 2018. *Commercial sustainability via environmental improvements - Technical and Training Challanges.* [Online]
Available at:
http://www.sephys.ch/Reinhard%20Serchinger%27s%20Wattrain%20Paper%20January%2027-2013%20version_2018.pdf
[Accessed 11 May 2023].

Slezak, J. O., 1967. *Der Giesl-Ejektor.* Wien: Verlag Josef Otto Slezak.

Stala-Szlugay & Grudziński, Z., 2022. Alternative directions of coal supply to Poland as a result of the Russian-Ukrainian war. *gospodarka surowcami mineralnymi – mineral resources management*, 38(3), pp. 31-47.
Statistik Austria, 2021. *Verkehrsstatistik 2021.* [Online]
Available at: https://www.statistik.at/fileadmin/publications/Verkehrsstatistik-2021.pdf
[Accessed 30 May 2023].

Stockholm Convention on persistent organic pollutants, 2013. *Toolkit for Identification and Quantification of Releases of Dioxins, Furans and Other Unintentional POPs.* [Online]
Available at: https://toolkit.pops.int/Publish/Downloads/UNEP-POPS-TOOLKIT-2012-En.pdf
[Accessed 12 May 2023].

Straka, F., Pavel, G. & Martin, O., 2012. *Der Nordast der Waldviertler Schmalspurbahnen.* Wien: Railway Media Group. ISBN: 9783950305784

Thomaser, M., 2022. *Evalueriung Taurachbahn,* Mauterndorf: s.n.

Tirol Werbung, n.d. *Sie fährt wieder: Neustart für die Achenseebahn.* [Online]
Available at: https://www.b2b.tirol/news/neustart-fuer-die-achenseebahn
[Accessed 28 May 2023].

Umweltbundesamt, 2021. *GHG Projections and Assessment of Policies and Measures in Austria.* [Online]
Available at:
https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0766.pdf
[Accessed 31 May 2023].

Umweltbundesamt, 2022. *Emissionsfaktoren bezogen auf Personen-/Tonnenkilometer.* [Online]
Available at:
https://www.umweltbundesamt.at/fileadmin/site/themen/mobilitaet/daten/ekz_pkm_tkm_verkehrsmittel.pdf
[Accessed 30 May 2023].

Umweltbundesamt, n.d. *Treibhausgase.* [Online]
Available at:
https://www.umweltbundesamt.at/klima/treibhausgase#:~:text=Die%20größten%20Verursacher%20der%20THG,Tonnen%20CO2%2DÄquivalent.
[Accessed 30 May 2023].

UNFCC, 2021. *Climate Action Pathway Transport.* [Online]
Available at:
https://unfccc.int/sites/default/files/resource/Transport_Vision%26Summary_2.1.pdf
[Accessed 15 May 2023].

University of Exeter, n.d. *Calculation of CO2 emissions.* [Online]
Available at:
https://people.exeter.ac.uk/TWDavies/energy_conversion/Calculation%20of%20CO2%20emissions%20from%20fuels.htm
[Accessed 30 May 2023].

Welshpool & Llanfair Light Railway, 2023. *Annual Report and Accounts 2022.* [Online]
Available at:
https://drive.google.com/file/d/1iYGvJmIPFnI5zupyBiGSlxRvUDB2FR45/view
[Accessed 23 May 2023].

World Health Organization Regional Office for Europe, 2013. *Health effects of particulate matter: policy implications for countries in eastern Europe, Caucasus and central Asia.* [Online]
Available at: https://apps.who.int/iris/handle/10665/344854
[Accessed 13 May 2023].

Ziegler, M., 2018. *Wenig Auslauf für die Dampfloks.* [Online]
Available at: https://www.wienerzeitung.at/nachrichten/chronik/wien-chronik/961084-Wenig-Auslauf-fuer-die-Dampfloks.html
[Accessed 21 May 2023].

Zillertalbahn, n.d. *Dampflokomotive Nr. 5 "Gerlos".* [Online]
Available at: https://www.zillertalbahn.at/data.cfm?vpath=technische-details-excel/lok-5
[Accessed 22 May 2023].

Zillertaler Verkehrsbetriebe AG, 2020. *Geschäftsbericht 2019.* [Online]
Available at: https://www.zillertalbahn.at/data.cfm?vpath=ma-wartbare-inhalte/ma-downloadfiles/zvb-geschber-18-8_2019-web_version-final-zur-verwendung
[Accessed 23 May 2023].

Zillertaler Verkehrsbetriebe AG, 2021. *Fahrplan 2022.* [Online]
Available at: https://www.zillertalbahn.at/data.cfm?vpath=ma-wartbare-inhalte/ma-downloadfiles/fahrplan-2022_a3-stand-22112021
[Accessed 24 May 2023].

Zittauer Schmalspurbahn, 2021. *Minus 40% CO2 – geht das?*. [Online] Available at: https://www.zittauer-schmalspurbahn.de/minus-40-co2-geht-das/ [Accessed 22 May 2023].

Zoubek, D., 2004. *Erhaltene Dampflokomotiven in und aus Österreich 2004 = Preserved Austrian steam locos 2004.* Guntramsdorf: Eigenverlag D. Zoubek. ISBN: 3200001747

List of tables

Table 1 Variance of heating values of different solid fuels (derived from: Stockholm Convention on persistent organic pollutants, 2013) 15

Table 2: Biocoal Compared to solid Biofuels (derived from: Fengler, et al., 2017) 28

Table 3: CO_2 emissions* and operation data of Austrian coal fired railways for the year 2022 55

Table 4: Total Results for the year 2022 (Table 3) with different conversion factors from carbon to carbon dioxide 56

Table 5: Extrapolation of total CO_2 emissions (Table 6) with different conversion factors from carbon to carbon dioxide 56

Table 6: Extrapolation for annual CO_2 emissions* and operation data of coal fired railways of Austria 57

Table 7: Annual Carbon dioxide emissions (Table 6) per passenger in kg 58

Table 8: Annual Carbon dioxide emissions (Table 6) per km in t 60

Table 9: Carbon dioxide emissions (Table 6) per passenger kilometer in kilogram 61

List of figures

Figure 1 Two historic monuments: Trestle bridge from 1889 and steam locomotive class Uv from 1902 on the Ybbstal Railway Mountain line (Own work, 2015) 2

Figure 2 Gölsdorf's construction later ÖBB class 92 operated by the Heritage Local Railway Association Zwettl at a guest excursion on the Ampflwang Railway (Own work, 2023) 5

Figure 3 Class 93 steam locomotive on the Zayatal railway: These locomotives ran until the end of the steam era at Austrian Federal Railways (Own work, 2014) 8

Figure 4 Czechoslovakian construction class 556: 1950s design with stoker firing at a guest operation in Austria (Own work, 2014) 11

Figure 5 Coal, as here on the Steyrtal Heritage Railway, is with a few exceptions the most common fuel type for steam locomotives in Austria (Own work, 2022) 12

Figure 6 Polish bituminous coal for firing on steam locomotives (Own work, 2023) ... 16

Figure 7 Typical smoke plume with high soot content in special operational situations of steam locomotives (Own work, 2015)... 18

Figure 8 Modern oil firing is possible on historically authentic vehicles such as the steam locomotive "Heidi" on the Rhaetian Railway (Own work, 2016)........................ 26

Figure 9: Overview of steam locomotive service in Austria including heritage and touristic railways [green], regular railways with touristic or heritage service [blue], network operators [red] and Network steam operators with heritage railway [yellow] (Own work).. 35

Figure 10 Locomotive No. 5 of the Zillertal Railway in the phase with oil firing while refueling at the diesel filling station (Own work , 2013).. 39

Figure 11 The pinzgau local railway offers steam locomotive rides in summer as well as in winter (Own work, 2015) 41

Figure 12 The Austrian Society for Railway History also conducts trips on lines of the Austrian Federal Railways, such as the Ennstal line (Own work, 2014)........................ 44

Figure 13 The Heritage Tram Mariazell offers services with historic vehicles such as the former Salzburg steam tramway "Hellbrunn" on a newly built route (Own work, 2019) 47

Figure 14 Polish coal mixed with a proportion of biocoal on the Prater Liliput Railway (Own work, 2023)... 54

Figure 15 Experience with alternative fuels of steam driven Austrian heritage and touristic railways... 62

Figure 16 Attitude towards technical adaptation of firing of Austrian heritage and touristic railways. 63

Figure 17: Austrian steam rail CO_2 emissions compared to total rail 64

Figure 18: CO_2 emissions of Austrian coal fired steam railway fleet compared to old-timer car fleet 65

Figure 19: Mixed passenger and freight train on the Taurach railway with vehicles of the extensive collection of the Club 760 association (Own work, 2018) 68

Annex

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

↳ Betrieb mit Holzpellets.

Unternehmen / Verein: Rhein-Schauen Lustenau Datum 17.05.23

Kohlenverbrauch gesamt 2022 zirka 20 Tonnen

Betriebsfähige Dampflokomotiven 2022 2, 1 in Betrieb, 1 nicht verwendet

Dampfbetriebstage 2022: 53

Gefahrene Kilometer 2022 Dampf: 795

Fahrgäste Dampf: 4235

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja Nein X

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

Ja Nein X

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja Nein X

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja Nein X

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja Nein X

Ist das aktuelle Zugangebot eingeschränkt?

Ja Nein X Wenn ja, warum: ______________

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja Nein X Wenn ja, welche: ______________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja Nein X Wenn ja, welche: ______________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv kritisch negativ X

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja Nein X

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Bregenzerwaldbahn-Museumsbahn Datum 21. Mai 2023

Kohlenverbrauch gesamt 2022 22,7 t

Betriebsfähige Dampflokomotiven 2022 1

Dampfbetriebstage 2022: 43

Gefahrene Kilometer 2022 Dampf: 1.370

Fahrgäste Dampf: ca. 42.000

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

☒ Ja ☐ Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

☒ Ja ☐ Nein

Ist das aktuelle Zugangebot eingeschränkt?

☐ Ja ☒ Nein Wenn ja, warum: ____________

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

☐ Ja ☒ Nein Wenn ja, welche: ____________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

☒ Ja ☐ Nein Wenn ja, welche: noch auf der Suche

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

☐ positiv ☒ kritisch ☐ negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

☐ Ja ☒ Nein

AW: Datenerhebung Dampftraktion

MÜLLER Oskar <oskar.mueller@fhv.at>
So, 21.05.2023 22:55
An: HARTINGER Leonhard Pius Albert <leonhard.hartinger@da-vienna.at>

3 Anlagen (3 MB)

Erhebungsformular zum Kohleverbrauch Österreichischer Museums.pdf; Kohleverbrauch_BWB.jpg; coal_1.jpg;

Sehr geehrter Herr Hartinger,

ich habe dieses Wochenende die Daten zur Kohle bekommen und gebe sie Ihnen mit diesem Mail gerne gleich weiter.

Zum Kohleverbrauch noch eine Vorbemerkung zu den Zahlen und zur Methode: Wie schon besprochen, gibt es zwischen den verschiedenen Lokbesatzungen merkliche Unterschiede im Kohleverbrauch. Das hängt vor allem davon ab, mit welchem Geschick der jeweilige Heizer die Feuerbüchse beschickt, ab auch davon, wie der jeweilige Lokführer den Regler und die Steuerung bedient. Es ist ja schon vom Automobil bekannt, dass der persönliche Fahrstil den Kraftstoffverbrauch verändert. Bei Dampfloks ist dieser Faktor noch viel stärker ausgeprägt. Das liegt u.a. auch daran, dass es auf diesen historischen Maschinen keine Elektronik gibt, welche die steuerungsrelevanten Parameter genau misst und auf einem Display anzeigt. So muss die Lokmannschaft zu technisch/chemischem Grundverständnis und zur Streckenkenntnis auch noch ein gutes Gespür/Gefühl für die augenblickliche Situation aufbringen und verschiedene Phänomene (optische und akkustische Beobachtungen) richtig verarbeiten und interpretieren.

Wir haben zu der im Betrieb beobachteten nicht gerade geringen Streuung im Kohleverbrauch leider keine Messwerte, da die Lokmannschaften die Kohle beim morgendlichen Befüllen des Tenders auf ein Förderband schaufeln und so nicht wiegen können. Die Arbeit, einzelne Kübel zu befüllen und mit einer Waage zu wiegen, haben wir unseren - freiwillig tätigen - Mannschaften nicht zugemutet. (Das wäre betriebsgefährdend ;o) Dennoch sind die Differenzen am Abend merklich. Selbst wenn eine Mannschaft in diesem Fall ihre Kohle wiegen würde, wäre es nicht seriös, diesen Wert als repräsentativ zu nehmen und zu verallgemeinern.

Mir war es daher wichtig, Ihnen als repräsentativen Wert zumindest einen zeitlichen Mittelwert über alle Lokmannschaften und über mehrere Jahre zu berechnen. Dazu hat mir unser Geschäftsführer das Datum und die Liefermenge für die seit 2015 bestellten Kohlelieferungen aus den Bestellungen herausgesucht. In der kumulierten Darstellung ergibt sich daraus immerhin ein brauchbares Bild -> Sie finden das Diagramm im Dateianhang.

Die Abszisse dieses Diagramms stellt die Zeitachse dar, welche die Tage ab der ersten Kohlelieferung zählt. Der Nullpunkt liegt beim 15. Mai 2015. Die letzte verzeichnete Lieferung liegt 2607 Tage später am 8. Juli 2022. Die Punkte im Diagramm stehen am jeweiligen Lieferdatum mit der entsprechenden kumulierten Liefermenge. In dieser kumulierten Darstellung entspricht die Steigung zwischen zwei Lieferungen dem durchschnittlichen Kohleverbrauch pro Tag in diesem Intervall. Danach kann man die Werte zurückrechnen.

Man erkennt gut, dass der Durchschnitt über die verschiedenen Mannschaften zeitlich ziemlich gleichmäßig verläuft, sodass sich ein guter Fit durch eine Regressionsgerade ergibt (Formel ist in der Abbildung angegeben). Der mittlere Tagesverbrauch liegt somit über die letzten 7 Jahre bei 0,0714 to/Tag. Man sieht am Verlauf auch schön den Einbruch des Verbrauchs während des Corona-Lockdowns und die darauffolgende Wiederaufnahme des Betriebs mit dem „üblichen" Verbrauch.

Aus dem (über das Kalenderjahr geglätteten) mittleren Tagesverbrauch von 71,4 kg/Tag ergibt sich so ein mittlerer Jahresverbrauch von 22,7 to, der auch gut mit unserem letztjährigen Verbrauch übereinstimmt. Und da wir nicht das ganze Jahr Betrieb haben, entsprechen diese knapp 23 to zugleich auch dem durchschnittlichen Saisonverbrauch (von Mitte Mai bis Ende September). Da wir pro Saison im Fahrplanbetrieb im Mittel 137 Dampffahrten durchführen (plus rund 6 Sonderfahrten/Saison), ergibt sich ein mittlerer Verbrauch pro Fahrt von 158,75 kg Steinkohle. Da sich weiters eine Fahrt über eine Streckenlänge von 10 km erstreckt, liegt der mittlere Kilometerverbrauch bei rund 15,9 kg Kohle pro km. (Wie gesagt: die individuellen Werte schwanken pro Lokmannschaft dann doch merklich um diesen Mittelwert.)

Der mittlere Kohleverbrauch streut im Österreichvergleich sicher auch von Standort zu Standort mit den unterschiedlichen Streckenprofilen: Der Energieverbrauch ist auf Bergstrecken größer als in der Ebene. Dasselbe gilt für Schmalspurstrecken mit engen Kurvenradien im Gegensatz zu großen Kurvenradien. Unsere Strecke folgt z.B. einem U-Profil. In jeder Richtung geht es bei der Ausfahrt aus dem Bahnhof zunächst einmal bergab, dann folgt die Strecke am Talgrund dem Flussbett der Bregenzerache entlang, um danach auf einem Anstieg von rd. 16 Promille wieder dem Zielbahnhof zuzustreben. Zusätzlich weisen einzelne Kurven beim „Wälderbähnle" enge Rekordwerte von nur 80 m Kurvenradius auf. (Auf unserem heutigen Streckenabschnitt wurde auch zu ÖBB-Zeiten kaum schneller als mit 40 km/h gefahren.)

Aber das ist nun zumindest einmal ein repräsentativer Wert für unser Streckenprofil und das „Gemisch" unserer Lokmannschaften. Aber hier noch eine Anmerkung: Die verfeuerte Kohle dient nicht allein dem Antrieb während der Fahrt, sondern auch der Erzeugung des Dampfdrucks beim Anheizen und während der Ruhephasen. Hier ist auch der Verbrauch für das Anheizen und für das über den Betriebstag gehaltene Bereitschaftsfeuer enthalten. (Vom Anheizen kurz nach 4 Uhr morgens bis zum Löschen des Feuers um 18 Uhr vergehen immerhin etwas über 13 Stunden, in denen das Feuer gehalten wird - mit einigen Rangiermanövern zwischendurch, die immerhin zu den „Bewegungen während des Betriebs" gezählt werden können. So kommen wir ungefähr auf ein Verhältnis von 4 Stunden Fahrzeit in 12 Stunden Betriebszeit. Und bei der Dampflok kann im Unterschied zum Dieselbetrieb der Motor in den Ruhezeiten eben nicht einfach abgestellt werden. Das relativiert natürlich ebenfalls die oben gegebene Kennzahl „Verbrauch pro Kilometer", die als Mittelwert immer vor dem Kontext des Standortes und des Betriebsmodus' interpretiert werden muss.)

Nun zur Alternativkohle: Die „Bregenzerwaldbahn" befährt als Museumsbahn einen Naturraum, in dem viel Wert auf Umweltschutz gelegt wird. Historische Technik, die im Betrieb erlebt werden kann, verbunden mit kulturellen Initiativen und dem Naturraum, ergänzen sich gut und sind eine wertvolle Kombination. Damit die über 100 Jahre alten historischen Dampfmaschinen in diesem Kontext nicht durch Starkqualm dieses System gefährden, verfeuern wir schon seit beinahe zehn Jahren raucharme und teure Steinkohle aus Sibirien. Eine zufriedenstellende Lösung war das für uns allerdings auch damals schon nicht: Erstens tritt die verwendete Kohle einen weiten Transportweg bis zu uns an (was ja auch nicht gerade erstrebenswert ist) und - zweitens - ändert natürlich abgebaute Kohle ständig ihre Eigenschaft: War sie noch bis gestern eine vielgelobte rauch- und schwefelarme Kohle, so ist ihre Konsistenz 200 m weiter im Flötz (bei einer Lieferung im Folgejahr) plötzlich so, dass sie unerwartet viel Rauch entwickelt (auch wenn sie aus demselben Bergbau stammt). Wir machen uns daher schon einige Zeit Gedanken darüber, wie dieses oben beschriebene Zusammenspiel von Kultur, historischer Technik und Freizeitraum auch auf anderer Basis zukunftstauglich funktionieren kann.

Somit ergab sich die Frage, ob Lokomotivkohle auch aus umweltfreundlich gewonnener synthetischer Kohle aus Holzvergasung gewonnen werden kann. Der Heizwert der Kohle sollte dafür ausreichend sein.

Nun erzeugt in Dornbirn (also in unmittelbarer Nachbarschaft) die Familie Ilg seit 2015 mit einem Holz-Gas-Kraftwerk Strom und Wärme aus unbehandelter Biomasse (unter dem Namen „Biomassehof Ilg“). Dabei wird in zwei "Syncraft"-Anlagen als Nebenprodukt hochwertige Biokohle produziert, die als pulverförmiger Staub ausgeschleust und mit Wasser befeuchtet wird (siehe http://biomassehofat.srv272.adino.at/biowaerme/pflanzenkohle/). Die dort erzeugte Pflanzenkohle wird z.B. bereits heute als Grillkohle verkauft. Aus Sicht des Umweltschutzes wäre die Verwendung einer solchen Kohle ein ganz entscheidender Verbesserungsschritt (noch dazu mit in der Produktion geregelter gleichbleibender Qualität).

Ich habe über eine Empfehlung aus meinem Kollegenkreis mit Prof. Ingo Burgert vom Institut für (Holz)Baustoffe (IfB) an der ETH in Zürich Kontakt aufgenommen, der sich bereit erklärt hat, die Frage anhand einer Kohlenprobe einer Voruntersuchung bzgl. der Machbarkeit zu unterziehen. Im November 2021 wurden dazu von uns zwei Eimer pflanzlicher Kohleproben nach Zürich ins Labor geschickt.

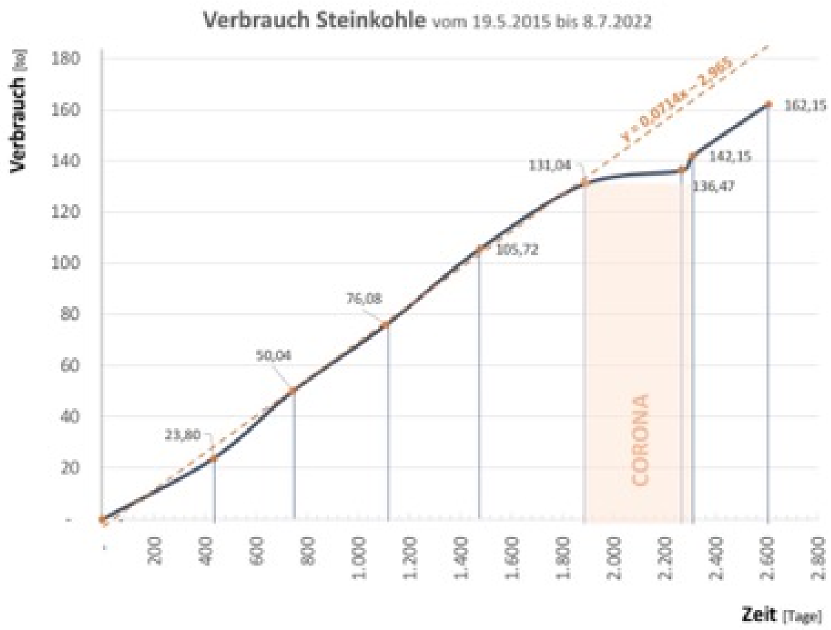
Die mit der Forschungsfrage „Kann fossile Kohle im historischen Dampfbetrieb durch synthetische Kohle aus Biomasse substituiert werden?“ einhergehende Herausforderung ist es, einen geeigneten „Klebstoff“ zu finden, mit dem der Kohlesand zu Lokomotiv-brauchbarer Körnung derart fest verbunden wird, dass die Kohlestücke auf dem Feuerbett bei 1500 °C nicht auseinandergerissen und als Funkenregen durch den Schlot geblasen werden. Weiters sollte der „Klebstoff“ keine die Maschine und die Umwelt schädigenden (z.B. ätzenden) Stoffe ausscheiden. Neben diesen geforderten technischen Eigenschaften sollte dieser „Klebstoff“ selbst auch wieder in seiner Produktion Nachhaltigkeitskriterien genügen.

In dieser mittlerweile abgeschlossenen Voruntersuchung konnte das Institut einen erfolgversprechenden Ansatz für die grundsätzliche Machbarkeit dieser Substitution aufzeigen. Dabei liegt die Innovation sowohl in der Erfüllung der wichtigsten technischen und chemischen Kriterien, als auch in einem an sich nachhaltigen Bindestoff, der mit der Chemie der Biokohle funktional verträglich ist. Die grundsätzlich positive Beantwortung der Forschungsfrage nach der Voruntersuchung bedingt als nächsten Schritt die Anwendungsforschung, in welcher die Entwicklung zur Anwendungsreife gebracht werden muss. Es braucht da sicherlich noch viele Abklärungen. Vom Institut wird von einer Projektdauer von rund einem Jahr Entwicklungsarbeit ausgegangen, welche uns als Auftraggeber rund 100.000 € kosten würde. Daran scheitert es derzeit noch für uns, bzw. daran, dass wir noch keinen zahlungskräftigen und -willigen Projektpartner finden konnten.

Anbei sende ich Ihnen im Dateianhang auch ein Foto von einem „Brikett“, das in diesem Vorversuch aus der Probe der pflanzlichen Kohle hergestellt wurde.

Mit besten Grüßen,
Oskar Müller

P.S.: Unser Jahrbuch mit dem Rückblick auf das Betriebsjahr 2022 sende ich Ihnen noch diese Woche zu. Es enthält im ersten Teil (der erste Abschnitt mit den weißen Seiten) die wichtigsten Veranstaltungen bei der Museumsbahn und einen Blick auf das Betriebsergebnis und die Fahrgastzahlenentwicklung. Ebenso sind da auch Berichte unserer Partnerbahnen zu finden - darunter die Versuche der W&LLR in Wales mit Kohlealternativen. Der zweite Teil (der Abschnitt mit den grauen Seiten) zeigt die Vereinstätigkeiten hinter den Kulissen und die damit verbundenen Herausforderungen (Werkstatt, Strecke, etc.) und im dritten Teil (der letzte Abschnitt mit den weißen Seiten) macht als Grenzübertritt unter dem Motto „Über den Zaun" einen Blick in die Geschichte. Viel Spaß beim Schmökern.



Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Pinzgauer Lokalbahn Datum 09.05.2023

Kohlenverbrauch gesamt 2022	15t	40t
Betriebsfähige Dampflokomotiven 2022	1	2
Dampfbetriebstage 2022:	18	ca.50
Gefahrene Kilometer 2022 Dampf:	1.080 km	5.300 km
Fahrgäste Dampf:	ca. 8.000	ca. 13.000

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

☐ Ja ☒ Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

☐ Ja ☒ Nein

Ist das aktuelle Zugangebot eingeschränkt?

☒ Ja ☐ Nein Wenn ja, warum: Wg. Hochwasser ist die Strecke nur bis Niedernsill betriebsbereit

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

☒ Ja ☐ Nein Wenn ja, welche: Testung von unterschiedl. Kohlevarianten -> bessere Kohlequalität -> weniger Rauch

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

☐ Ja ☒ Nein Wenn ja, welche: ______________________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

☐ positiv ☒ kritisch ☐ negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

☐ Ja ☒ Nein

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Taurachbahn — Datum 23.5.22

Kohlenverbrauch gesamt 2022: 12

Betriebsfähige Dampflokomotiven 2022: 5

Dampfbetriebstage 2022: 38

Gefahrene Kilometer 2022 Dampf: 1320

Fahrgäste Dampf: 27000

Mensinger / Studie / Telefon

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

(Ja) Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

(Ja) Nein

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja (Nein)

Ist das aktuelle Zugangebot eingeschränkt?

Ja (Nein) Wenn ja, warum: ____________

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja (Nein) Wenn ja, welche: ____________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja (Nein) Wenn ja, welche: ____________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv kritisch (negativ)

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja (Nein)

Master's Thesis 15th ETIA 2023, Leonhard Hartinger MEd

May 2023

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: NBiK Datum 22.5.23

Kohlenverbrauch gesamt 2022: 26t. per Mengen/Fahrplananalyse

Betriebsfähige Dampflokomotiven 2022: 2

Dampfbetriebstage 2022: 28

Gefahrene Kilometer 2022 Dampf: 916

Fahrgäste Dampf: 11990

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

(Ja) Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja (Nein)

Ist das aktuelle Zugangebot eingeschränkt?

Ja (Nein) Wenn ja, warum: ______

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja (Nein) Wenn ja, welche: ______

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

(Ja) Nein Wenn ja, welche: Pellets

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv (kritisch) negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja (Nein)

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Gurkthalbahn Datum 20.5.23

Kohlenverbrauch gesamt 2022 – * e-Mail

Betriebsfähige Dampflokomotiven 2022 2

Dampfbetriebstage 2022: 10

Gefahrene Kilometer 2022 Dampf: 190

Fahrgäste Dampf: 1600

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja Nein

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

Ja Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja Nein

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja Nein

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja Nein

Ist das aktuelle Zugangebot eingeschränkt?

Ja Nein Wenn ja, warum: ____________

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja Nein Wenn ja, welche: ____________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja Nein Wenn ja, welche: ____________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv kritisch negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja Nein

* 10 RM Holz

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: ÖGEG Ampflwang   Datum 6.5.23 Telefon

Kohlenverbrauch gesamt 2022: 75

Betriebsfähige Dampflokomotiven 2022: 3

Dampfbetriebstage 2022: 19

Gefahrene Kilometer 2022 Dampf: 1797

Fahrgäste Dampf: 4220

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

Ja **Nein** *

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja Nein

Ist das aktuelle Zugangebot eingeschränkt?

Ja **Nein** Wenn ja, warum: ______________________

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja Nein Wenn ja, welche: experimentelle Holzbriketts

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja **Nein** Wenn ja, welche: ______________________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv **kritisch** negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja **Nein**

*) Über Händler hat es funktioniert
Mischen mit Altbeständen, welche Dampfloks im Betrieb

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: ÖGEG Steyrtal-Museumsbahn Datum 09.05.2023

Kohlenverbrauch gesamt 2022	ca. 70 t
Betriebsfähige Dampflokomotiven 2022	3
Dampfbetriebstage 2022:	59
Gefahrene Kilometer 2022 Dampf:	3046
Fahrgäste Dampf:	19207

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

☒ Ja ☐ Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

☒ Ja ☐ Nein

Ist das aktuelle Zugangebot eingeschränkt?

☒ Ja ☐ Nein Wenn ja, warum: Im Dezember 2022 (Festlegung Sommerfahrplan 2023) war noch unsicher, wo, in welcher Menge und zu welchem Preis Kohle bezogen werden kann.

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

☒ Ja ☐ Nein Wenn ja, welche: Holz, ist aber nur für entsprechend ausgerüstete Loks verwendbar. Solche haben wir aber nicht mehr.

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

☐ Ja ☒ Nein Wenn ja, welche: ______________________________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

☐ positiv ☐ kritisch ☒ negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

☐ Ja ☒ Nein

Master's Thesis 15th ETIA 2023, Leonhard Hartinger MEd

May 2023

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: StB Murtalbahn   Datum 23.5.23

Telefon

Kohlenverbrauch gesamt 2022: 22

Betriebsfähige Dampflokomotiven 2022: 2

Dampfbetriebstage 2022: 33

Gefahrene Kilometer 2022 Dampf: 1728

Fahrgäste Dampf: 8899

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

Ja Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja **Nein**

Ist das aktuelle Zugangebot eingeschränkt?

Ja **Nein** Wenn ja, warum: ______

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja **Nein** Wenn ja, welche: ______

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja **Nein** Wenn ja, welche: ______

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv **kritisch** negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja **Nein**

Master's Thesis 15th ETIA 2023, Leonhard Hartinger MEd
May 2023

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Steinzeugbahn — Datum: 11.5.

Kohlenverbrauch gesamt 2022: 0 / 60

Betriebsfähige Dampflokomotiven 2022: 0 / 1

Dampfbetriebstage 2022: 82

Gefahrene Kilometer 2022 Dampf: 2215

Fahrgäste Dampf: 20.000

Telefon / Fahrplananalyse

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

(Ja) Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

(Ja) Nein

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

(Ja) Nein

Ist das aktuelle Zugangebot eingeschränkt?

(Ja) Nein Wenn ja, warum: Reparatur Damplok

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

(Ja) Nein Wenn ja, welche: Brennholz

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja (Nein) Wenn ja, welche: __________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

(positiv) kritisch negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja (Nein)

Master's Thesis 15th ETIA 2023, Leonhard Hartinger MEd

May 2023

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: MT Eisenbahnbedarf/Museumstramway Mariazell Datum 10.5.2023

Kohlenverbrauch gesamt 2022 26t

Betriebsfähige Dampflokomotiven 2022 2

Dampfbetriebstage 2022: 36 Tage

Gefahrene Kilometer 2022 Dampf: 2700 km

Fahrgäste Dampf: ca. 26.800

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja (X) Nein

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

Ja (X) Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja Nein (X)

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja (X) Nein

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja Nein (X)

Ist das aktuelle Zugangebot eingeschränkt?

Ja Nein (X) Wenn ja, warum: ______________________

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja (X) Nein Wenn ja, welche: Braunkohle/Koks

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja Nein (X) Wenn ja, welche: ______________________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv kritisch negativ (X)

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja Nein (X)

Master's Thesis 15th ETIA 2023, Leonhard Hartinger MEd

May 2023

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: StEF Steirische Eisenbahnfreunde Datum 22.5.23

Kohlenverbrauch gesamt 2022 6 Telefonisch / Fahrplananalyse

Betriebsfähige Dampflokomotiven 2022 1

Dampfbetriebstage 2022: 1

Gefahrene Kilometer 2022 Dampf: 40 *

Fahrgäste Dampf: 1000

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

(Ja) Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja (Nein)

Ist das aktuelle Zugangebot eingeschränkt?

(Ja) Nein Wenn ja, warum: hohe Kosten

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja (Nein) Wenn ja, welche: ______

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja (Nein) Wenn ja, welche: ______

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

(positiv) kritisch negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja (Nein)

*) Fahrt Andritz-Schleppbahn Familienfest

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Feistritztalbahn Datum 10.5.22

Kohlenverbrauch gesamt 2022 20

Betriebsfähige Dampflokomotiven 2022 1

Dampfbetriebstage 2022: 21

Gefahrene Kilometer 2022 Dampf: 630

Fahrgäste Dampf: 3600

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

Ja **Nein**

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **Nein**

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

Ja **Nein**

Ist das aktuelle Zugangebot eingeschränkt?

Ja Nein Wenn ja, warum: Streckenunterbrechung

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja **Nein** Wenn ja, welche: ____________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja **Nein** Wenn ja, welche: ____________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv kritisch negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja **Nein**

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Ybbstalbahn ÖGLB Datum 22.5.22

Kohleverbrauch gesamt 2022: 0 / 37

Betriebsfähige Dampflokomotiven 2022: 0 / 1

Dampfbetriebstage 2022: 0 / 18

Gefahrene Kilometer 2022 Dampf: 0 / 1246

Fahrgäste Dampf: 0 / 6000

Mengen / Hochrechnung persönlich in Kompendium

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

(Ja) Nein

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

Ja (Nein)

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

(Ja) Nein

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja (Nein)

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

(Ja) Nein

Ist das aktuelle Zugangebot eingeschränkt?

(Ja) Nein Wenn ja, warum: Reparatur

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja (Nein) Wenn ja, welche: ______

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja (Nein) Wenn ja, welche: ______

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

(positiv) kritisch negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja (Nein)

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Museums-Lokalbahnverein Datum 9.5.23

Telefon

Kohlenverbrauch gesamt 2022: 13

Betriebsfähige Dampflokomotiven 2022: 1

Dampfbetriebstage 2022: 9

Gefahrene Kilometer 2022 Dampf: 785

Fahrgäste Dampf: 2210

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja **(Nein)**

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

Ja **(Nein)**

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **(Nein)**

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **(Nein)**

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

(Ja) Nein

Ist das aktuelle Zugangebot eingeschränkt?

Ja **(Nein)** Wenn ja, warum: ____________

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja **(Nein)** Wenn ja, welche: ____________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen? *)

Ja **(Nein)** Wenn ja, welche: ____________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv **(kritisch)** negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja **(Nein)**

*) Strecken um Zwettl zu steigungsreich für andere Brennstoffe

Von: [redacted]@niederoesterreichbahnen.at>
Gesendet: Dienstag, 9. Mai 2023 10:12
An: HARTINGER Leonhard Pius Albert [redacted]
Betreff: AW: Erhebung Dampfbetrieb

Hallo Leo,

mal folgende Infos:

	MZB	WVB	NÖSBB
Betriebstage	14	31	~10
Zugkm	2 224	2 785	~200
Fahrgäste	2 506	7 577	~1000

Auf der Krumpe gab es im letzten Jahr nur 2 Dampferfahrten mit der Mh.6 (eher vernachlässigbar).

Kohleverbrauch in Menge muss ich noch ausheben lassen.

lg

Mit freundlichen Grüßen

[redacted]

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Niederösterreichbahnen (NÖVOG) Datum 09.05.2023

Betriebsfähige Dampflokomotiven 2022 4 Stück

Dampfbetriebstage 2022: lt. Aufstellung Mail

Gefahrene Kilometer 2022 Dampf: lt. Aufstellung Mail

Fahrgäste Dampf: lt. Aufstellung Mail

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

☒ Ja ☐ Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

☒ Ja ☐ Nein

Ist das aktuelle Zugangebot eingeschränkt?

☐ Ja ☒ Nein Wenn ja, warum: ______________________

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

☐ Ja ☒ Nein Wenn ja, welche: ______________________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

☐ Ja ☒ Nein Wenn ja, welche: ______________________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

☐ positiv ☒ kritisch ☐ negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

☐ Ja ☒ Nein

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Eisenbahnmuseum Sigmundsherberg, Datum 13.05.2023

Kohlenverbrauch gesamt 2022 5,0 to

Betriebsfähige Dampflokomotiven 2022 1

Dampfbetriebstage 2022: 3

Gefahrene Kilometer 2022 Dampf: 4

Fahrgäste Dampf: / Besucherzahl an Dampftagen ~ 600

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

☒ Ja ☐ Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

☐ Ja ☒ Nein

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

☒ Ja ☐ Nein

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

☒ Ja ☐ Nein

Ist das aktuelle Zugangebot eingeschränkt?

☒ Ja ☐ Nein Wenn ja, warum: Lok 93.1421 in Reparatur

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

☐ Ja ☒ Nein Wenn ja, welche: ____________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

☐ Ja ☒ Nein Wenn ja, welche: ____________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

☐ positiv ☐ kritisch ☒ negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

☐ Ja ☒ Nein

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: 1. österreichischer Straßenbahn u. Eisenbahn Klub Eisenbahnmuseum Straßhof Datum 17. 5. 2023

Kohlenverbrauch gesamt 2022: 30 t

Betriebsfähige Dampflokomotiven 2022: 3

Dampfbetriebstage 2022: 23

Gefahrene Kilometer 2022 Dampf: 1455

Fahrgäste Dampf: 6123

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

☐ Ja ☒ Nein bis ca. 2020

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

☒ Ja ☐ Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

☐ Ja ☒ Nein bis ca. 2020

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

☒ Ja ☐ Nein

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

☒ Ja ☐ Nein bei einem Lieferanten

Ist das aktuelle Zugangebot eingeschränkt?

☒ Ja ☐ Nein Wenn ja, warum: Behördliche Schwierigkeiten bezüglich ECM-Instandhaltungsausnahmen bei historischen Fahrzeugen.

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

☐ Ja ☒ Nein Wenn ja, welche: __________

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

☐ Ja ☒ Nein Wenn ja, welche: __________

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

☐ positiv ☐ kritisch ☒ negativ

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

☐ Ja ☒ Nein

Erhebungsformular zum Kohleverbrauch Österreichischer Museums- und Tourismusbahnen

Unternehmen / Verein: Liliputbahn im Prater   Datum 23.5.23

Formular / persönlich

Kohlenverbrauch gesamt 2022: 2t

Betriebsfähige Dampflokomotiven 2022: 1

Dampfbetriebstage 2022: 42

Gefahrene Kilometer 2022 Dampf: 1587

Fahrgäste Dampf: ______

Hatten Sie in den letzten 20 Jahren Probleme bei der Beschaffung von Kohle?

Ja **(Nein)**

Hatten Sie in den letzten 2 Jahren Probleme bei der Beschaffung von Kohle?

(Ja) Nein

Hatten Sie in den letzten 20 Jahren mit knappen Kohlevorräten zu kämpfen?

Ja **(Nein)**

Hatten Sie in den letzten 2 Jahren mit knappen Kohlevorräten zu kämpfen?

(Ja) Nein

Hatten Sie in den letzten 2 Jahren Probleme mit der Kohlenqualität?

(Ja) Nein

Ist das aktuelle Zugangebot eingeschränkt?

(Ja) Nein   Wenn ja, warum: Kohleknappheit, Kohlepreis

Haben Sie Erfahrungen mit alternativen Brennstoffen für Dampfloks?

Ja Nein   Wenn ja, welche: Briketts mit Biomasseanteil (Olivenkerne) *

Planen Sie in Zukunft die Verwendung von alternativen Brennstoffen?

Ja **(Nein)**   Wenn ja, welche: ______

Wie stehen Sie technisch gesehen einer Umrüstung der Feuerung bei Ihren Dampflokomotiven gegenüber?

positiv   kritisch   **(negativ)**

Wäre die Umrüstung der Feuerung Ihrer Dampflokomotiven ohne zusätzliche finanzielle Unterstützung möglich?

Ja **(Nein)**

*) unbrauchbar wegen mangelnder Flammenerzeugung; wird Polnischer Kohle beigemischt.