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Mobility in Tourism

A comparative analysis of energy use for mobility in tourism from an economic, environmental and energetic point of view

DIPLOMA THESIS

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Christian Hrabal, BSc

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Wien, 25. Mai 2022

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Sincerely, *Chris*

Kurzfassung

Seit Anbeginn der Menschheit gab es den internen Drang, die Welt zu erkunden und Neues zu entdecken. Dieser hat sich über Jahrtausende in die Richtung entwickelt, für einen gewissen Zeitraum seine Gewohnheiten abzulegen und aus dem Alltag auszubrechen. In den vergangenen Jahren ist das Verlangen, die Welt zu sehen und den eigenen Horizont zu erweitern, unaufhörlich gestiegen. Ob Orte in der Umgebung, ferne Länder oder abgelegene Ziele, die Beliebtheit von Reisen steht außer Frage. Verlockend sind besonders Flüge und Kreuzfahrten, welche zum Teil große Distanzen überbrücken und die entlegendsten Destinationen erreichen. Jedoch werden dadurch reichlich Treibhausgase freigesetzt, welche die Menschheit seit der der jüngsten Vergangenheit zu den größten Herrausforderungen zählen kann. Obwohl die Schifffahrt zu den effizientesten und umweltfreundlichsten Varianten des Transportwesens gehört, werden doch 3,3% der globalen Emissionen durch diese freigesetzt. Als Reaktion auf diese Entwicklung wurden 2015 im Pariser-Klimagipfel Maßnahmen beschlossen, um die Erhöhung der globalen Temperatur auf unter 2°C zu halten. Dieses Maßnahmenpaket wurden von 195 Ländern der Welt unterzeichnet.
In dieser Arbeit werden die Transportvarianten, welche in touristischem Zusammenhang verwendet werden, ihren Eckdaten entsprechend in umwelt-, energetisch- und wirtschaftlichem Aspekt analysiert. Die Werkzeuge, um dies zu bewerten, sind die Lebenszyklusanalyse (LCA), Energieketten & Umwandlung und Lebenszykluskosten (LCC). In diesem Kontext werden mögliche Alternativen kurz angeschnitten und vorrangig für den privaten Sektor präsentiert.
Durch die Lebenszyklusanalyse, um genauer zu sein *Well-To-Wheel*-Emissionen, werden die Treibhausgase der verschiedenen Transportmittel erfasst und miteinander verglichen. Den Erwartungen entsprechend, sind elektrisch versorgte Fahrzeuge deutlich CO_2 ärmer und effizienter als ihre, mit fossiler Energie betriebenen Konterparts, insbesondere wenn erneuerbare Energien im Spiel sind. So stoßen Elektroautos, versorgt von regenerativer Energie, bis zu 75% weniger CO_2 aus als benzinbetriebene Fahrzeuge.
Die Energiekette und deren dazugehörigen Umwandlungen, von der einen in die andere Energieform, werden verwendet, um die Effizienz einzelner Transportvarianten zu bestimmen und zu bewerten. Beispielsweise sind Kreuzfahrtschiffe, die zu den mit Verbrennungsmotor betriebenen Fahrzeugen zählen, etwa um 20% effektiver als dieselbetriebene. Jene sind aber wiederum um ungefähr 50% weniger effektiv als Züge, sofern diese durch erneuerbare Energie versorgt sind.
Lebenszykluskosten, aufgeteilt in Anschaffungskosten und jährliche Ausgaben, werden herangezogen, um eine wirtschaftliche Auswertung zu erfassen. Relativ gesehen fallen bei Flugzeugen deutlich höhere Wartungskosten an als bei Bussen, hervorgerufen durch die häufigeren Serviceintervalle. Busse haben im Gegensatz dazu recht hoche Betriebskosten.
Weiters werden drei Fallstudien herangezogen um die Unterschiede der Transportmittel zu verdeutlichen. Eine Route verläuft von Wien nach Berlin, welche mit Auto, Bus, Zug und Flugzeug bewältigt wird. Wenig überraschend ist dabei, dass eine Reise per Flugzeug die meisten klimagefährlichen Gase ausstößt, was auch mit der Flughöhe, auf der dies geschieht, zusammenhängt, jedoch wird das Ziel in vergleichsweise kürzerer Zeit erreicht. Aus energetischer Sicht sind, ab-

gesehen vom Flugzeug, alle Transportmittel in ähnlichen Größenbereichen in Bezug auf die Besetzungsrate. Selbstverständlich darf der finanzielle Aspekt nicht vernachlässigt werden, bei welchem das Flugzeug für die Konsumierenden im Vergleich sehr gut abschneidet, Zugticketpreise hingegen sind relativ teuer.

Die nächste Route führt von Wien nach Tokio, hierfür wurden zwei verschiedene Flugrouten ausgewählt und in weiterer Folge verglichen. Diese Routen stoßen relativ zur längeren Strecke auch mehr Emissionen aus. Weiters ist es kaum überraschend, dass für die größere Distanz auch mehr Energie benötigt wird und die dadurch höher anfallenden Kosten für die Airlines zu höheren Ticketpreisen führen.

Abschließend wird eine Kreuzfahrt im Mittelmeer untersucht, wobei bezüglich des Verbrauches und Ausstoßes zwischen der Fahrt von Hafen zu Hafen und dem Betrieb im Hafen selbst unterschieden wird.

Abstract

Since the dawn of humanity, the internal drive to explore the world has been present. Over centuries this transformed to a form of breaking habits and escaping everyday life for a period of time. In recent years, the urge to see the world and to broaden one's horizons has risen. Whether places in close distance, faraway countries or remote locations, the popularity of voyages is without question. Hence, air travel and cruises are quite tempting to cover long-distances and get to remote places, although plenty of greenhouse gases (*GHGs*) are released into the air, which counts to the one of largest challenges humanity has to face, in the most recent past. Even though transportation by ship is the most efficient and environmentally reasonable mode, about 3.3% of global emissions are exhausted by them. As countermeasure, the Paris Agreement set actions to keep the rise of the global temperature under 2°C. 195 nations of the world signed this agreement. In this thesis, different transport modes, used in a context of tourism, are analysed with regards to their environmental, energetic and economic aspects. The tools used to asses these factors will be the Life-Cycle-Assessment (*LCA*), Energy-Chains & Conversion and Life-Cycle Costs (*LCC*), respectively. Using this context, potential alternatives will be broached and presented mainly for the private sector.

Within the Life-Cycle Analysis, to be more precise *Well-To-Wheel-Emissions*, the released *GHGs* are recorded and compared with each other. As one might expect, electricity driven vehicles (*EVs*) have presently been recorded to have a lesser extend considering the released CO_2 emissions and are more efficient than their fossil fuel driven counterparts, especially if the former are powered by renewable energies. Thus EVs, moved by regenerative energy, exhaust up to 75% less gasses than conventional gasoline powered cars.

Energy chains and their associated conversions, from one form of energy to another, are utilized to evaluate the efficiency of different transport modes. Considering vehicles with combustion engines, cruise vessels are 20% more efficient than diesel-engined cars, but are approximately 50% less efficient than electric trains, provided they are powered by renewable energies.

Life-Cycle Costs, mainly split into acquisition costs and annual expenditures, are used to assess the economic perspective. Relatively speaking, planes have significantly higher maintenance costs compared to buses, caused by the more frequent service intervals. Buses on the other hand have quite high operational costs.

Three different case studies are examined to further demonstrate the differences between the modes of transportation. The first route leads from Vienna to Berlin, covered by car, bus, train and plane. As expected, travel through the air has the highest amount of *GHGs* released, which is connected to the altitude the gasses are expelled at, however the needed time to travel is by far the least. With exception of the plane, from an energetic point of view, every vehicle is in the same range related to their rate of occupation. Nevertheless, the economic aspect is of considerable importance as well, where planes perform very well in comparison with other transportation, trains on the other hand are comparatively expensive.

The second case examines two different routes leading from Vienna to Tokyo, both taken by

plane. In this case more gasses are released, relative to the longer distance. Furthermore it is obvious that the longer route requires more energy and leads to higher costs for the airlines as well, leading to more expensive fare tickets.
The concluding cases will be the cruise in the Mediterranean Sea, while separating the needed energy and the released gasses between the expenses for the voyages at sea and in the port.

Contents

CHAPTER 1

Introduction

1.1 Motivation

Nowadays people strive for a good work-life balance and in order to achieve this, vacations are more important than ever (another major factor in this time especially are the continuous restrictions caused by the ongoing pandemic, as of March 2022). Consequently, tourism is a considerable contributor to the increasing energy consumption in the transport sector. The determining factors for planning a holiday are:

- destination,
- method of transport and
- receiving a good value for the money you are investing.

However, only small percentage of people are concerned about the environmental or energetic point of view of their endeavour.

1.2 Background

In general, reasons for travelling can be divided into these following major categories:

- Getting to the desired destination:
  If it is in a relative close vicinity, the usage of your own car will be favoured, maybe public transportation such as buses or trains. The further the destination is located, overnight trains, buses and planes become more attractive. Even these, very distinct transport vehicles, have some points in common, for example bus and car efficiency revolving around the traffic they are in, because the exhausted gas will be significantly higher when they are stuck in traffic. Travelling by train depends heavily on the country one is in, since energy prices and their CO_2-*amount per* kWh [1] differ vigorously. Having tailwind while travelling by plane will reduce kerosene usage.

[1] According to the Federal Environment Agency, Austria releases in average about 130 g/kWh, Germany 480 g/kWh CO_2 (only concerning the inland-production)

- The journey is the reward:
  In this case, one might go on a round-trip by car, but most likely people will choose a cruise trip. Since it is very attractive to have a comfortable everyday life and seeing a new exciting city (often world heritage sites) along the way. Ignoring all the negative effects it has on the environment, because long-distance travelling ships (no matter if container vessel or ship used for tourism) burn heavy fuel oil, containing a high sulphur content, due to it being the most cost efficient fuel than any other on the market.

In the work of Dawson et al. (2014) the consumption of the cruise vessel Artania, with a travelling route from Bremerhaven, around Iceland and along the Norwegian-Coast back to Bremerhaven (duration of 17 days, with a consumption of 578.8 tons heavy fuel oil and 472 tons marine diesel) matches the yearly consumption of 1600 gasoline driven cars (Nerem (2018)), which is presented in Figure 1.1[2]. These properties are to be expected for other transport modes as well, especially aeroplanes.

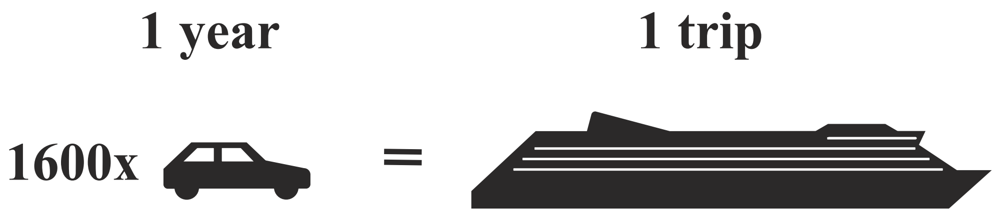

Figure 1.1: *Annual consumption of gasoline cars vs. 1 cruise trip (17 days) (Dawson et al. (2014), Nerem (2018))*

1.3 Objective and Scope

No matter the holiday one undertakes, three factors are of major importance. These being the expenditures, the needed energy (efficiency of the conversion from one energy form to another) and the released emissions along the way (including the emissions during the production of the vehicle) and analysing these marks the core objective of this thesis. This especially affects the following transportations, that are used in this thesis as examination objects:

- Private vehicles
- Public (long distance) buses
- Electricity driven trains
- Aeroplanes
- Cruise vessels

Another objective of this thesis is to conduct various case studies and analysing the economic, energetic and environmental aspects respectively, while finding the best possible transport mode. The various transport modes used for tourism will be evaluated by the following standards:

[2]Due to the higher emissions of HFO, the released CO_2 of this cruise ship would be higher than the emissions of 1600 gasoline driven cars

- **Environmental Aspect**
  Here the objective is to compare the emissions released during a vehicles lifetime, using a method called *Well-To-Wheel-Emission*, a trimmed version of the *Life-Cycle-Assessment (LCA)*.
- **Energetic Aspect**
  Here, the objective is to compare the used energy needed to move vehicles over a set energy input. Since many steps are needed to get from the original source of energy to the one utilized to move vehicles, *Energy-Chains* will be used.
- **Economic Aspect**
  And here, the objective is to compare the costs emerging during the lifetime of a vehicle, which is called *Life-Cycle-Cost (LCC)*.

1.4 Method of Approach

Firstly, literature of the present means of transportation will be collected using scientific papers, books, credible internet sources and official published reports from the Federal Environment Agency of Austria and analysed according to their environmental, energetic and economic aspects. For the environmental part, the emissions according to Emi (2021), which contain the directly released emissions (TtW) and the emissions during production (WtT). Cruise vessels are not contained in this publication, so the papers by Gilbert et al. (2017) and Chatzinikolaou and Ventikos (2014) will be used to gain information on the consumption and emissions, which will be compared with the other vehicles. The report by Edwards et al. (2014) marks the base for the energetic part, since it contains conversion from primary to secondary energy (WtT). The TtW efficiency (engine) is collected via various other sources to gain the complete conversion chain (WtW). The economic part will be done according to Farr and Faber (2019) and Galar et al. (2017), which use LCC to determine the costs over the vehicles lifetime. Furthermore, a comparison for all means of transportation will be conducted (including cruise vessels), according to the aforementioned aspects.
Additionally, different case studies will be conducted, according to the established tools, to give further insight in this topic, with a focus on energetic and environmental performances, as well as undertaking a Life-Cycle-Analysis to gain testimonial evidence on the economic effectiveness.

1.5 Structure

The structure of this thesis will be as follows:

Chapter 1-Introduction gives a general overview over this work and a rough method of approach.

Chapter 2-Literature Review introduces relevant publications and reports regarding this topic, as well as statistics from Austrian (and European) tourism.

Chapter 3-Methodology presents relevant information and the methods used to obtain results. The introduced tools are Well-To-Wheel-Emissions, Energy-Chains & Conversion and Life-Cycle Costs.

Chapter 4-Transport Modes in Tourism describes the modes of transportation frequently used in tourism.

Chapter 5-Comparison and Alternatives assembles the transport modes from Chapter 4 and puts them into perspective. Furthermore, alternatives to the conventional transportation are listed.

Chapter 6-Case Studies - Introduction introduces the routes and the vehicles which use them. These routes are *Vienna - Berlin*, *Vienna - Tokyo* and a cruise trip in the Mediterranean Sea.

Chapter 7-Case Studies - Results presents the environmental, energetic and economic results elicited from the routes *Vienna - Berlin*, *Vienna - Tokyo* and a cruise trip in the Mediterranean Sea.

Chapter 8-Discussion provides a discussion of the general results and the various case studies presented in this thesis.

Chapter 9-Conclusion introduces concluding remarks.

CHAPTER 2

Literature Review

This chapter presents existing literature regarding the environmental, energetic and economic aspects of transportation. The collected information is taken from reliable sources, such as official Federal Governmental Establishments or scientific databases that contain journals, books and conference proceedings.

2.1 Environmental Focus

According to David et al. (2021), using a *Life-Cycle Analysis* is the most efficient way conclude how environmentally friendly a transport mode is, since it contains direct emissions (released after burning a fuel) and indirect emissions (expelled during the production). In this report, commissioned by the *Federal Environment Agency of Austria*, a wide variety of different cars were taken into account and grouped by their technology to get in motion (conventional combustion, electric, fuel cell, etc.) and their size (class). For the direct emissions, the fuel consumption per kilometre ($[kWh/km]$) is applied, which depends on the weight of the vehicle and the released emissions to produce (extract, refine and transport) the corresponding fuel (gas, diesel, 'electricity' or hydrogen). Furthermore an *Emission-Factor*, regarding the chassis (including the engine for conventional cars), electrical engine, powertrain, battery, fuel cell and hydrogen tank is calculated according to the used energy source (the resulting unit is either $[kgCO_{2e}/kg]$ or $[kgCO_{2e}/kWh]$) and the amount of recycled materials used, to determine the indirect emission. The results are presented in various ways, like an accumulated amount of released CO_{2e} during the vehicles median lifetime, or normalized by their average occupation and yearly covered distance ($[CO_{2e}/pkm]$).

In similar fashion, the *Federal Environment Agency of Germany* conducted a similar report. Although this review by Schelewsky et al. (2020) solely takes the emissions caused by the combustion into account, the data is broken down into individual routes. Moreover, it's not focused solely on cars, but includes other transport modes, like buses, trains and national planes.

A study that exclusively focuses on buses in Beijing, performed by Wang et al. (2011), analyses the fuel consumption and the exhausted gases according to different exhaust emission standards[1]

[1] EURO III - $2300 mgCO/km$, $150 mgNO_x/km$, introduced January 1^{st} 2000; EURO IV - $1000 mgCO/km$, $80 mgNO_x/km$, introduced January 1^{st} 2005

and driving profiles (idle, acceleration, deceleration and cruise speed). Overall, this study provides similar results as the report from Schelewsky et al. (2020).

As for trains, in comparison to the aforementioned transport modes, the direct emissions drop out, since no fuel is combusted to move them. Contrary to that, indirect emissions are indeed present and, accounting to an article published by de Bortoli et al. (2020), a complex mixture of various factors. This is ascribed to the facts, that roads are easier built than new tracks for rail traffic, the environmental impact from laying the roadbed and rails, the usage of heavy building machines and the load (passengers/freight) of direct transport weight heavier. However, this could be narrowed down by large fractions of recycling at the end of the trains lifetime.

The publication by Lo et al. (2020) describes skyways to different destinations in Italy undertaken by various airlines, while taking into account every part of the flight process. On the contrary, Kumaş et al. (2019) only considers the take-off and landing at a Turkish airport, done by various planes. Both focus on the directly expelled fumes.

Unfortunately it is rare to find suitable sources regarding cruise vessels in this regard. However to presume them being similar to ferries or other marine transportation is reasonable, hence the reports published by Cucinotta et al. (2021) and Chatzinikolaou and Ventikos (2014), describing the *Life-Cycle Assessment* of two sister ferries with Heavy-Fuel Oil and Liquid-Natural-Gasses as fuel (with HFO having a greater environmental impact than LNG) and shipping in general. Contrary to Cucinotta et al. (2021), which added all emissions together, the study by Chatzinikolaou and Ventikos (2014) separated them into operation, building, maintenance and dismantling (for further recycling).

A summary of various transport modes in to one comprehensive and comparable matter was conducted in the report Emi (2021) by FEA-Austria, which contains data from 2019 to 2021 and was evaluated in July 2021.

2.2 Energetic Focus

In the report by David et al. (2021), not only the carbon footprint was analysed, but the specific energy consumption as well, delivering results for cars powered by different energy sources and different sizes (classes). The discovery is a relation between the higher consumption and the dependency on overall dimensions and weight.

Furthermore it is of interest to know the primary energy origin and the pathways taken to obtain the desired energy form. These compositions of conversions, done by the *Joint Research Centre (JRC)* of the European Commission, are condensed in the report by Edwards et al. (2014). It is the revised edition of the 4th version, containing the production (e.g. extracting oil or capturing gasses), transport, manufacturing and the distribution, while laying the main focus on the energy (and GHG) balance. Moreover the *Well-To-Tank (WtT)* pathway left the energy or GHG emissions associated with construction and/or dismantling out (including them, would make it a LCA). The efficiencies for the engines themselves (*Tank-To-Wheel (TtW)*) were unregarded.

Similar to Edwards et al. (2014), the report by Brinkman et al. (2005) involves WtT as well as TtW combining them into *Well-To-Wheel*. In this study, various pathways starting at different primary energy sources are simulated and examined. Additionally the emissions for the paths are evaluated.

In the paper Rokicki et al. (2021) published, all transportation of the European Union is summarised into one overall consumption, but separated by countries. These account for about

30% of the accumulated energy consumption in the EU. As one might expect, the total energy used for transportation was higher in the states with dense traffic systems.

In a more specific article, Chiara et al. (2017) compares energy consumption of high-speed trains (HST) and air-travel for passenger transport. In the case of trains, the most prominent HSTs, such as the French TGV, the German ICE or the Japanese Shinkansen were compared with each other and additionally with a variety of plane types (distinguished by their occupation). Further the various planes were compared on the same route using the specific energy consumption per kilometre and passenger or seat ($[kWh/pkm]$ or $[kWh/stkm]$) during different phases of the flight.

The paper by Simonsen et al. (2018) examines a remodelled cruise ship, finding the energy consumption and the correlating specific fuel consumption, while being at sea and in port (hotelling functions). If the ship has a longer stay at port the energy consumption per hour is lower, since the energy used for manoeuvring in port weights less, than a shorter time spent in port.

2.3 Economic Focus

Unfortunately transport modes in the private sector are rare to find. However, generalised literature can be found such as the books from Farr and Faber (2019) and Galar et al. (2017), which give a good universal overview to sell the idea behind the *Life-Cycle Cost (LCC)*.

The study conducted by Banar and Özdemir (2015) compares the costs of regional as well as high-speed trains over their respective lifespan of 40 years. Additionally to the expected data such as material, transportation and energy costs (for the train itself and the railway infrastructure), external costs (expenses for released emissions) were heeded, which demonstrated that the expenses for the high-speed version was slightly higher than its counterpart ($[€/pkm]$).

Scheiner (2018) analyses potential criteria on the choice of the taken transport mode, but generalises the topic without presenting concrete numbers.

2.4 Touristical Focus

This chapter provides a general overview of the touristic behaviour of Austrians and further, a few extensions to Europe as a whole. Since CoViD-19 still has a massive impact on tourism, a comparison of chosen years prior and after the pandemic in the case of Austria is exemplified (years 2019 and 2020, to show the development caused by the pandemic).

2.4.1 Tourism in Austria

As for Austria, the years 2019 and 2020 will be examined (as of February 2022, no data regarding 2021 has been officially published).

According to Wurian (2021), 60.3% of the Austrian population (over 15 years of age) travelled in 2020; 12.65 million voyages overall, which is a deficit of around 40.3% (21.2 million) to the previous year, as depicted in Figure 2.1 (Table E.1, with detailed values, can be found in Appendix E).

The favourite transport mode of Austrians with regards to travelling is the *private vehicle*. It accounts for around 72% (2020) of voyages, followed by *planes*, *trains* and *buses*, with the favourite destinations being Germany closely followed by Italy. A cruise is, in comparison,

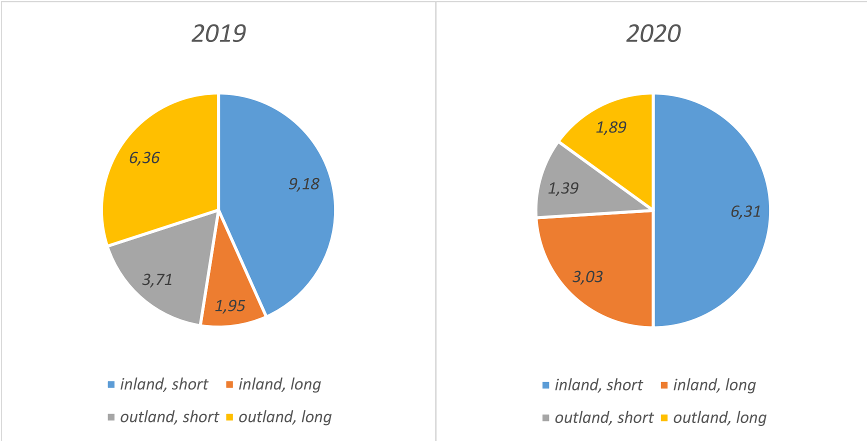

Figure 2.1: *Comparison of vacationers in 2019 and 2020 in million (Wurian (2021))*

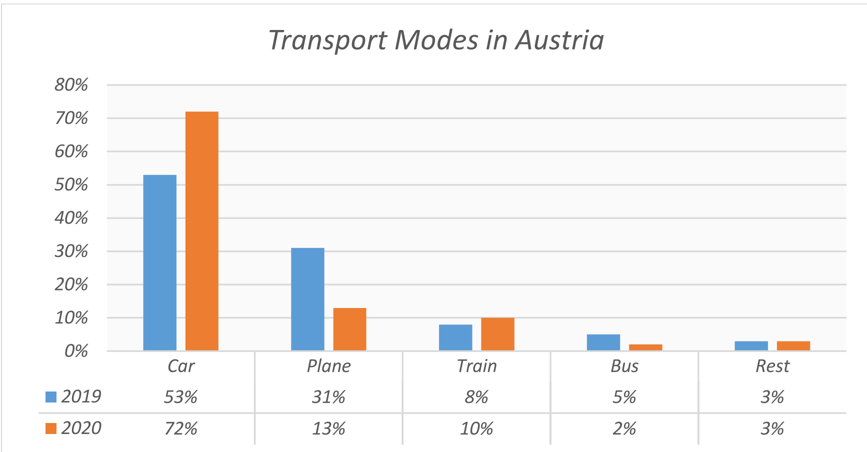

Figure 2.2: *Share of transport modes in 2019 and 2020 in Austria (Wurian (2021))*

relatively unpopular, with roughly 130 000 Austrians boarding a *cruise vessel*[1] with an average duration of 9 days (which is not considered in the statistics of Wurian (2021)).

The logical consequence of this forced decease and travel constraints (mainly for public transportation) is the relative increase of journeys with private vehicles as can be seen in Figure 2.2 (Wurian (2021)).

2.4.2 Tourism in Europe

For the entirety of the European Union (*EU-27* in addition *United Kingdom*) a total of 1255 million people travelled according to Palen and Dimitrakopoulou (2019), with an average of 73.3% travelling inside of Europe and the other 27.6% leaving for other countries. Just like Austrians, the average European preferably travels by car, around 64%, followed by planes, trains and buses. A detailed breakdown of the data for every member of the EU (plus the UK) can be found in

[1]according to https://de.statista.com/statistik/daten/studie/296402/umfrage/zahlen-zum-kreuzfahrtmarkt-in-oesterreich/ from 2018, February 2022

Appendix E.4. As no official data has been released for years since the start of the pandemic, a similar behaviour as in the Austrian case can be assumed. This indicates a further rise of trips by private vehicle and a decrease for other means of transportation (a major decrease in case of planes, due to heavy restrictions).

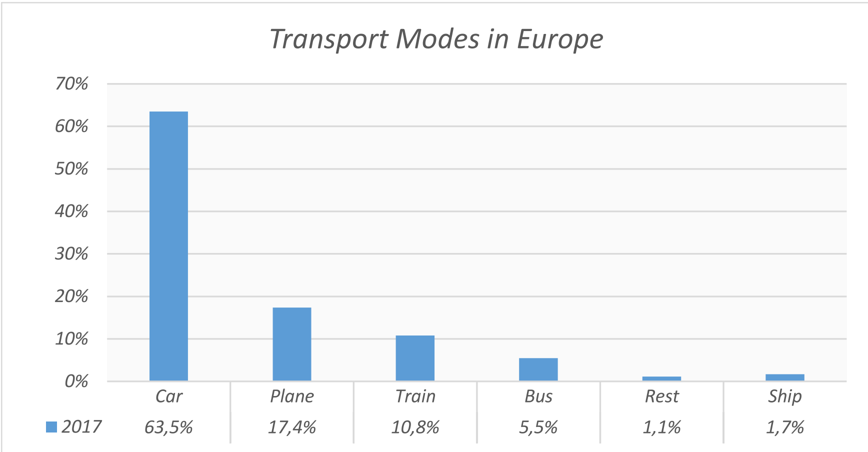

Figure 2.3: *Share of transport modes of European citizens 2017 (Palen and Dimitrakopoulou (2019))*

Recent statistics show a continuous drop in overall numbers, with a small increase during the summer season. It is expected, that in 2022 only 80% of total tourism from 2019 will be reached. For the Austrian tourism and travel numbers are anticipated to rise close to the initially investigated numbers from before the pandemic (i.e. 2019) in the next years.

CHAPTER 3

Methodology

This chapter presents the tools, which will be used for the investigation of environmental, energetic and economic aspects.

3.1 Environmental View

A modern lifestyle requires energy production on a large scale, which always causes unwanted by-products. In this first subsection, the environmental aspect will be explored, with the aim to answer the question, where these dangerous by-products originate from.

3.1.1 Combustion Equation

As a starting point, the general chemical reaction equation for fuels with the chemical formula C_xH_y, is used to describe a complete combustion (Oxygen-Fuel Ratio) (Mukhopadhyay and Sen (2019)):

$$C_xH_y + \left(x + \frac{y}{4}\right)O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O \tag{3.1}$$

This means, that for every C_xH_y mole fuel you need $(x + y/4)$ oxygen for the reaction to occur. Since the air on our planet only consists of about 21% oxygen, 1 mole O_2 has 79/21 N_2 existing at its side. This indicates, that the previous equation has to be extended with this term to get to the Air-Fuel Ratio, although it changes some properties, it is not further considered (Mukhopadhyay and Sen (2019)).

Alkanes, which are the most common fuels used today, belong to the aliphatic hydrocarbons and with the following simplifications:

$$x = n \tag{3.2}$$
$$y = 2(n + 1), \tag{3.3}$$

where n (x and y) is the amount of substance (mole) of a chemical element, the modified chemical reaction is expressed as:

$$C_nH_{2(n+1)} + \Big(\frac{3n+1}{2}\Big)O_2 \rightarrow nCO_2 + (n+1)H_2O \tag{3.4}$$

In Table 3.1 a few chemical elements and prominent chemical chains are depicted, which will be needed in further exemplary calculations in the next section.

H $[g/mole]$	C $[g/mole]$	O $[g/mole]$	H_2O $[g/mole]$	CO_2 $[g/mole]$
1	12	16	18	44

Table 3.1: *Molar mass of selected chemical elements and chemical chains*

3.1.2 Fuels

Nearly every fuel that is used nowadays was once organic matter. A few million years later they turn into crude oil and after refining it under high temperatures and pressure, it separates the hydrocarbon chains, with the lighter parts rising and the denser ones sinking to the bottom, that fuel our world. The products gained from this process are mainly categorised by their aggregate phase, density and carbon concentration, which are (Mukhopadhyay and Sen (2019)):

- Alkanes ($C_nH_{2(n+1)}$)
- Alkenes (C_nH_{2n})
- Alkynes (C_nH_n)

The fuels used in this thesis are shown in the Table 3.2 below (sorted by their density). Since all of them are a mixture of different hydrocarbon chains and other parts, some simplifications will be applied. To illustrate this in a simple matter, all fuels are considered as alkanes and the complete combustion equation 3.4 will be used. The calculation is to be found in Appendix A.1.1.

	n [1]	*Chemical Formula*	*Mass* $[g]$	*Density* $[kg/l]$	*Mass* CO_2 *after Combustion* $[g]$	*ejected* CO_2 $[kg/l]$
Gasoline	8	C_8H_{18}	114	0.79	352	2.285
Kerosene	14	$C_{14}H_{30}$	198	0.80	616	2.489
Diesel	16	$C_{16}H_{34}$	226	0.85	704	2.648
HFO	40	$C_{40}H_{82}$	562	0.99	1760	3.100

Table 3.2: *Alkane simplification for different fuels and ejected CO_2 after combustion (Emission-Factor)*

In Table 3.2 it can be seen that the longer hydrocarbon chains have a higher density and as consequence, the ejected CO_2 is higher as well. For one unit (litre) of fuel, more than one unit

CO_2 is 'produced', because a form of exchange takes place where the light hydrogen is replaced by the heavier oxygen (note Table 3.1). Since fuels are complex mixtures containing more than just alkanes, leads to conclusion that CO_2 is not the only exhausted gas after combustion.

3.1.3 Green-House Gasses and Pollutants

All modes of transportation releases pollutants, however CO_2 is not the only major factor. Further pollutants are:

- Carbon Dioxide (CO_2)
- Carbon Monoxide (CO)
- Methane (CH_4)
- Nitrous Oxide (N_2O)
- Nitrous Gases (NO_x)
- Sulphur Gases (SO_x)
- Particle Matter (PM)

At the *Kyoto Climate Conference, 1997* the gasses CO_2, CH_4, N_2O and hydro-fluorocarbons (HFC) were appointed as greenhouse gasses, which are mainly responsible for the greenhouse effect and climate change, written down in the so called *Kyoto Protocol*. Although the others, CO, NO_x, SO_x and PM, are not considered GHGs they are also hazardous for human and environment.

The *greenhouse effect* is a natural occurring phenomenon, where some rays of the sun are reflected and others are absorbed to heat the earth's surface. If more greenhouse gasses are in the atmosphere, more sun-rays are absorbed to raise temperatures. The distribution of these gasses are shown in Table 3.3[1] (Khan et al. (2013)). Furthermore, these gasses have a different impact on the environment relative to the potential of CO_2 in a period of 100 years, called Global Warming Potential (GWP_{100}) or CO_2-Equivalent (CO_{2e}) (Myhre et al. (2013)), also seen in Figure 3.1.

GHG	*Distribution*	GWP_{100}
CO_2	77	1
CH_4	8	28
N_2O	14	265
HFC	1	12400

Table 3.3: *Distribution of GHGs and their GWP (Khan et al. (2013), Myhre et al. (2013))*

This means that for example 1kg of CH_4 is as potent as $28kg$ CO_2 in 100 years for example. With following formula the CO_2-Equivalent (CO_{2e}) can be calculated:

$$CO_{2e} = CO_2 + 28 \cdot CH_4 + 265 \cdot N_2O + x \cdot HFC \tag{3.5}$$

[1] There are about 20 different hydro-fluorocarbons, which won't be considered any further. CHF_3 is only one example, contained in the table

where x represents the GWP to the respective GHG. This values need to be adjusted from time to time, due to the constant changing atmospheric conditions.

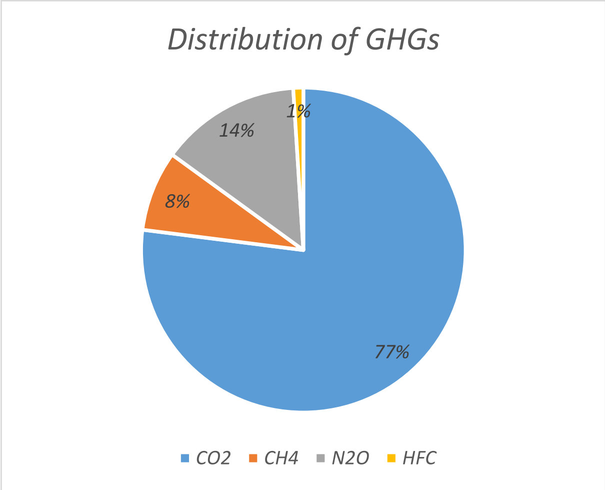

Figure 3.1: *Distribution of GHGs in the earth's atmosphere (Khan et al. (2013))*

3.1.4 Life-Cycle-Assessment

Life-Cycle-Assessment, according to Jensen et al. (1997) dates back to the late sixties and early seventies and can be also called 'Life-Cycle-Analysis', 'Ecobalance' or 'Cradle-To-Grave Analysis'. It considers all kinds of environmental impacts (environmental footprint) during the lifespan of a product, considering the production, the transportation and the usage of the product together with its disposal. The LCA is a tool developed to help process optimization, environmental management and consequently leads to sustainable development and production (Jensen et al. (1997)).
According to Jensen et al. (1997), this tool compromises 4 phases and is also defined in the ISO-Standards 14040:2006:

1 Goal and Scope Definition

2 Inventory Analysis

3 Impact Assessment

4 Interpretation

3.1.5 Well-To-Wheel Emissions

The *Well-To-Wheel* analysis may be seen as a simplified form of the *Life-Cycle Assessment*, since emissions such as building of the needed facilities and *End-Of-Life* are left unregarded. According to Brinkman et al. (2005), fuel-cycle analyses have been performed since the eighties, but gained importance due to the introduction of electricity driven vehicles in recent years. To compare various pathways, which all originate from different primary energy sources, the WtW emissions are separated in *Well-To-Tank (WtT)* and *Tank-To-Wheel (TtW)* emissions. WtT begins with the extraction of the primary energy, ending with the fuel filling the tanks of (combustion) vehicles.

TtW commence right after with the burning of the fuel, to achieve the desired propulsion. Figure 3.2 further illustrates this pathway for conventional technologies (combustion engine, Brinkman et al. (2005)). In this case, this method proves beneficial for the energetic part as well, although in a different manner.

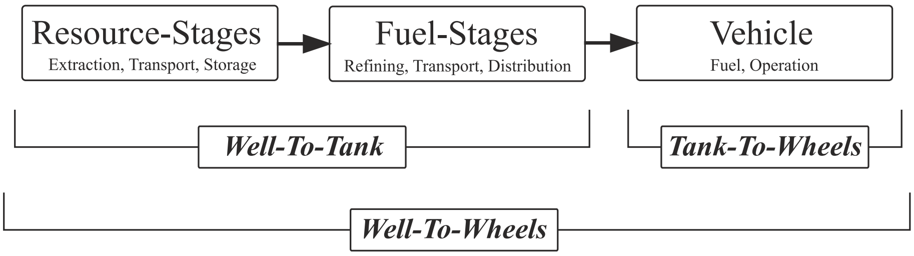

Figure 3.2: *Pathway for conventional vehicles (Well-To-Wheel) (based on Brinkman et al. (2005))*

Resources such as (crude) oil or natural gasses, using various pathways (WtT), are the main origin for today's fuel production, like gasoline or diesel. As result, the engine technologies (TtW) differ as well, promoting the improvement for their efficiencies and further a lower emission exhaustion (Brinkman et al. (2005). This procedure is usable for other primary energy sources and other energy forms as well, the path changes, but the method stays the same. Since only official published parameters and estimations are undertaken, no calculation is presented for this. An exemplary calculation, however, can be seen in Appendix A.2 to illustrate this method.

3.2 Energetic View

Energy is an abstract structure concept to grasp, however it is a necessity that powers everyday life. For lighting a bulb or driving a vehicle, energy has to accomplish a long journey, which will be investigated in the next subsection.

3.2.1 Energy Chain

The general definition of energy is the exceptional ability to do work. As commonly known, energy can not be produced, nor consumed, but it can be converted from one form into another (note Figure 3.3). The different forms of the energy in this aspect are divided in (Krischer and Schönleber (2015)):

1 Primary Energy
This first state of energy, mostly can not be used directly and needs to be reformed[2] to utilize it in any conventional way. After the refining process, some parts of the energy is 'lost' (E_{PtF}) and the result left is called Final Energy. A few examples are: crude oil, coal or the solar radiation.

2 Final Energy
This part may also be called Secondary Energy and is delivered to the costumers. This group contains, for instance, electrical energy or refined organic fuels, like gasoline or diesel.

[2]Reformation could be for example the burning of coal or the refining of crude oil to Gasoline, Diesel and other fuels

3 Useful Energy
After losing some parts of energy (E_{FtU}) again, Useful Energy is the final and desired form. This is for example the conversion of:

- electrical energy to thermal energy
- fuel to kinetic (motion) energy for driving a car

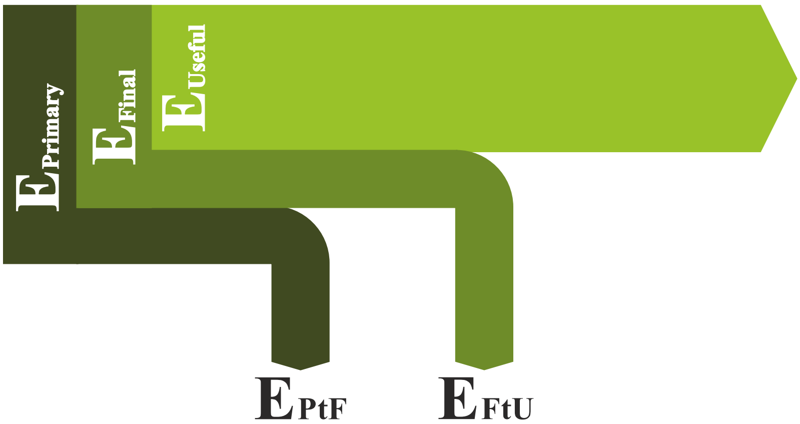

Figure 3.3: *Conversion from Primary Energy to Display Energy ($E_{Primary}$ to E_{Final} to E_{Use} with its 'losses' E_{PtF} and E_{FtU})*

Energy Resources

Energy Resources can be separated in two major categories:

- Renewables (e.g. solar, wind, etc.)
- Non-Renewables (e.g. fossil fuels, nuclear)

For the context of this thesis, the focus is on fossil fuels and renewable energies:

- **Coal**
  Found in the crust (the solid, outer layer) of our earth, it is a rock, formed million years ago from organic matter (trees and vegetation), containing carbon, hydrogen, oxygen and little amounts of nitrogen and sulphur. According to Rao and Gouricharan (2016) it is a widespread source for electric energy generation, that fuels about 41% of the worlds electricity and growing faster than any other (fossil or renewable) energy source.
- **(Crude) Oil**
  Just like coal, crude oil can be found in the earth's crust, being the remnants of organic life form prehistoric times, it is a unique mixture (not exactly matched by any other sample of crude oil) and consists of paraffnic, cycloparaffinic and aromatic hydrocarbons, containing low amounts of sulphur, nitrogen and oxygen according to Dybing et al. (1989). After the refining process, like explained in section **3.1.2-Fuels**, the products listed in Table 3.2 are gained.

- **Natural Gases**
  The natural deposit of natural gases is often connected with the extraction of crude oil, and similarly to crude oil, it is chemical composition differs, depending on its geographic origin (Bakar and Ali (2010)) and consist of Methane (CH_4), Ethane (C_2H_6), Propane (C_3H_8), Butane (C_4H_{10}) and some more (Olivier and Khaled (2010)).

- **Renewables**
  In opposition to fossil sources, renewable energy sources are (nearly) endless origins for energy, with the major deficiency being its reliability, since energy from sun, wind, tides, etc. are not always availability. However, contrary to their fossil counterparts, the losses through conversion and exhausted *GHGs* are considerably less.

3.2.2 Energy Conversion

Figure 3.3 symbolizes the 'losses' of conversions from one energy form to another (Primary Energy > Final Energy > Useful Energy, $[kWh]$), with the ration between these energy forms called efficiency (Krischer and Schönleber (2015)):

$$\eta = \frac{E_{out}}{E_{in}} \leq 1 \tag{3.6}$$

If energy passes multiple conversions $(1 \ldots n)$, the efficiency of the whole chain can be transcribed as follows:

$$\eta_c = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \ldots \cdot \eta_n \tag{3.7}$$

A important aspect to consider is $\eta_c = 1$ being a theoretical value and can practically never be reached. The conversions used in the following chapters, described by Edwards et al. (2014), are depicted in Appendix B.2.

In special cases, for example when utilizing different energy sources, with varying manifestation, a *weighted (average) efficiency* is of notable importance. For a total amount of m sources, the efficiencies $\eta_1, \eta_2, \ldots \eta_n$ and their corresponding weights $w_1, w, \ldots w_n$ are calculated to the weighted efficiency

$$\eta_w = \frac{\sum_{n=1}^{m} \eta_n \cdot w_n}{\sum_{n=1}^{m} w_n} \tag{3.8}$$

3.3 Economic View

Energy, its production and the products of a capitalist society are costly. In the following Section, one way to calculate costs during a products lifespan will be presented, namely the Life-Cycle Costs.

3.3.1 Life-Cycle Cost

In this part, with a focus on economics, the concept of Life-Cycle Costs will be discussed. The idea behind the LCC is, taking all the expenses during its lifespan into account. These can be split in two major categories:

- Capital Expenditures
- Annual Expenditures

The *Capital Costs* C_C are the initial (one-time) costs and consist of building expenses and fees, such as administration (research, engineering, financing, etc.), in the case of Austria (and a combustion engine driven vehicle), the *NoVA* (Normverbrauchsabgabe). In the context of this thesis solely the prime (purchase) price of a product and, if necessary, the respective NoVA will be considered.

The *Annual Costs* C_Y (in a common cash flow series) describe a recurring cash flow over multiple periods of time (Farr and Faber (2019)). These are for example expenses for:

- Admission
- Insurance
- Operation
- Maintenance
- Repair
- Replacement

The Life-Cycle Costs can therefore be described with following formula (Galar et al. (2017)):

$$LCC = C_C + C'_Y - C'_R \tag{3.9}$$

where C_C is the capital cost and C'_Y and C'_R are the projected annual (yearly) costs and the residual value from value time $t = n$ to $t = 0$, respectively. These factors are in Euro and the residual value will not be considered any further ($C_R = 0$).

To calculate a *Future Amount of a Value*, information about interest rate i and a number of years n has to be taken into consideration. Furthermore *Compound Interest*, since it is the paid interest on the capital and the accumulative amount. This can be exemplified by the following equation (Farr and Faber (2019)):

$$A_F = A_P \big(1 + i\big)^n \tag{3.10}$$

With A_F describing the future amount and A_P the present amount of a product.
For a common cash flow series, previous equation can be extended with (Galar et al. (2017)):

$$A_F = A_P \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{3.11}$$

Another factor is the phenomenon of a decrease in purchasing power over time, commonly referred to as *inflation* (Farr and Faber (2019)). The real interest i_r over a period of time can be calculated with the inflation f and the interest i:

$$i_r = \frac{1+i}{1+f} - 1 = \frac{i-f}{1+f} \tag{3.12}$$

And in the context of the projected annual costs the formula 3.11 for a common cash flow series develops, with the real interest i_r (net present value factor i') into the following equation:

$$C'_Y = \frac{(1+i_r)^n - 1}{i_r \cdot (1+i_r)^n} C_Y = i' \cdot C_Y \tag{3.13}$$

Formula 3.9, 3.12 and 3.13 will be used to calculate the total cost projected to $t = 0$ and will be exhibited in the next chapters, while the residual value will not be considered any further ($C_R = 0$). The following notation in this thesis is: C_C are capital cost, C'_I, C'_M, $C'_{R\&R}$, C'_A and C'_O are insurance, maintenance, repair and replacement, admission and operational costs, respectively. The costs for those expenses are in Euro ([€]) and further explained in section 3.4 (taxes are included, fuel intensity/energy costs are contained in the operational costs). They display linear relation, as can be seen in the equation:

$$C_Y = C_I + C_M + C_{R\&R} + C_A + C_O \tag{3.14}$$
$$C'_Y = C'_I + C'_M + C'_{R\&R} + C'_A + C'_O \tag{3.15}$$

3.4 Vehicle Information, Calculation and Limitations

This section focuses on information of the used vehicles, the calculation and limitations with regards to the environmental, energetic and economic perspective.

3.4.1 Environmental View

For the environmental view, the *Life-Cycle Assessment*, particularly the Well-To-Wheel-Emissions will be used. In a complex LCA the released GHGs would be calculated starting the mining process of the needed resources, continuing with the refining of the materials and up to the construction of the finished product. Due to the lack of information (and the subsequently needed estimations) on every composition of the various transport modes the official parameters taken from the Federal Environmental Agency (Emi (2021)), containing parameters regarding gasoline and diesel cars, electric vehicles, national and international buses, electricity and diesel driven trains and short and long distance flights (done by planes) used in this thesis, to gain the best comparability as possible. In case of the cruise ship the emission were chosen according to Gilbert et al. (2017) (TtW_1, using Low-Sulphur HFO), the indirect emissions, were modelled using the data from Chatzinikolaou and Ventikos (2014) (WtT_2, TtW_2, $[gCO_2/kWh]$) assuming a linear relation:

$$WtT_1 = TtW_1 \cdot \frac{WtT_2}{TtW_2} \tag{3.16}$$

To calculate the direct emissions (TtW emissions, $[gCO_2/km]$, or $[gCO_2/kWh]$) the *Emission-Factor* $[kgCO_2/l]$ (note Table 3.2) and the *Fuel-Intensity* $[l/km]$ (consumption) are used:

$$CO_2 = EF \cdot FI \tag{3.17}$$

A multiplication of Formula 3.17 by a covered distance s leads to all exhausted CO_2 ($[kg]$) emissions:

$$CO{*}_2 = CO_2 \cdot s \tag{3.18}$$

Further the CO_2-Equivalent (CO_{2e}) is gained using Formula 3.5. Comparing the total values with each other is not expedient, due to the different data (for example: distance, occupation and lifespan) of the vehicles, a further relation is calculated to gain more comparable parameters.

$$CO_{2eR} = \frac{CO_{2e}}{s \cdot r} \tag{3.19}$$

While CO_{2eR} ($[kgCO_2/km]$) describes the related CO_{2e} to the (yearly covered) distance s ($[km]$) and rate of occupation r ($[1]$). Formula 3.19 can also be applied to the other emissions. An exemplary calculation for the Well-To-Wheel-Emissions can be seen in Appendix A.2 to show the method of this tool.

3.4.2 Energetic View

The energetic perspective will be exemplified by the *Energy-Chain*, starting from the production of the raw material (Oil, Gas, etc.) to the energy needed to move the vehicle. The estimated values, from a realistic point of view, are to be found Table B.3 in Appendix B. In assumption of an energy chain containing extraction η_E, refinement η_R, transport η_T (η_{WtT}) and the efficiency of the engine η_M (η_{TtW}) itself leads, using Formula 3.7, to an overall efficiency of:

$$\eta_c = \eta_{WtT} \cdot \eta_{TtW} = \eta_E \cdot \eta_R \cdot \eta_T \cdot \eta_M \tag{3.20}$$

For a certain Energy-Input E_{in}, an Energy-Output E_{out} ($[kWh]$) with the efficiency η_c of the whole chain is calculated with Formula 3.6:

$$E_{out} = E_{in} \cdot \eta_c \tag{3.21}$$

To calculate the share of the WtT and TtW energies ($E_{S,WtT}$, $E_{S,TtW}$) of the complete chain ($E_{WtW} = E_{out}$) following formula is used:

$$E_{S,WtT} = \frac{E_{WtT}}{E_{WtT} + E_{TtW}} \cdot E_{WtW} \tag{3.22}$$

A similar formula applies for $E_{S,TtW}$ as well[4].

Similar to Formula 3.8, is the following energy consumption ($EC = E_{TtW}$, $[kWh]$), weighted over a certain distance s, called *specific energy consumption SEC* ($[kWh/km]$)

$$SEC = \frac{EC}{s} \tag{3.23}$$

and further related to the rate of occupation (note Formula 3.19).

3.4.3 Economic View

To illustrate the economic perspective in a comprehensive manner, the *Life-Cycle Costs* will be calculated. The initial purchase price of the represented vehicle marks the starting point of this evaluation. Furthermore, annual costs like insurance, admission and more are considered, for the operational costs C_O, calculated in Formula 3.24 (which are annual costs as well, note Formula 3.17), an average consumption together with average fuel prices (FP, $[€/l]$) enter the calculation, according to Formula 3.9, 3.13 and 3.15.

$$C_O = FP \cdot FI \cdot s \tag{3.24}$$

Similar to **3.4.1-Environmental View** the total values are related to their yearly covered distance s, rat of occupation r and lifespan t ($[a]$), due to the major differences between each vehicle:

$$LCC_R = \frac{LCC}{s \cdot r \cdot t} \tag{3.25}$$

The residual value will not be considered. For further information note Appendix C.1.

3.4.4 Vehicle Information

The environmental, energetic and economic aspects are based on following vehicles:

[4] note $E_{WtT} \neq E_{S,WtT}$; $E_{TtW} \neq E_{S,TtW}$; $E_{WtT} + E_{TtW} \neq E_{WtW}$, since $E_{WtT} \cdot E_{TtW} = E_{WtW}$

Passenger Car

Calculations are based on VW Golf sized gasoline and diesel cars and furthermore electric vehicles. The environmental and energetic parameters are taken from Emi (2021) and Edwards et al. (2014) respectively, with an estimated engine efficiency of 30% and 35% for gasoline and diesel engine[5] (the values for the efficiency vary by operation), for electrical engine and Fuel Cell[6] 75% and 60% respectively . For the economic part, the primary (purchase) price, which is around 20000€ for gasoline, 23200 for diesel cars, 32000€ for EVs and 60000€ for FCV (estimation to match the car size), were taken from various online sources[7], the insurance (3% - 7%) from the official UNIQA-Insurance calculation[8], maintenance, repair & replacement are estimated relative to the purchase price, admission cost, 165€, are based on the prices from the official ÖAMTC site[9] and the operational costs using the current fuel prices[10].

Public (long distance) Buses

The Calculations for the environmental and energetic part are based on Emi (2021) and Edwards et al. (2014) respectively. The engine driving the bus is a diesel engine, similar to the private vehicle, although it is assumed to be higher (40%). The purchase price is around 200000€ - 600000€ depending on the type and equipment[11] and was estimated to 250000€. Insurance, maintenance, repair & replacement are estimated relative to the investment, based on private vehicles. The operational costs are the same as for a diesel driven car (1,38€/l, as of January 2022).

Electricity driven Trains

Emi (2021) is used to present the environmental part and Edwards et al. (2014) is used for the energetic part. The electrical engine[12] is higher than the combustion engines and is estimated to be 90%. This initial price (12 million €) is an estimation based on the purchase price for the Railjet[13] from the ÖBB in 2006 and 2007, which marks the base of the calculation. Insurance, maintenance, repair & replacement are estimated based on private vehicles, relative to the purchase price of the train. No information could be obtained regarding the admission costs, so they are not considered. The operational costs are assumed to be the same as for EVs ($15kWh/100km$).

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[5] https://de.wikibooks.org/wiki/Motoren_aus_technischer_Sicht/_Vergleich_zwischen_dem_Otto-_und_dem_Dieselmotor, accessed January 2022

[6] https://www.enbw.com/energie-entdecken/mobilitaet/brennstoffzellenantrieb/

[7] Gasoline: https://www.autobild.de/artikel/vw-golf-8-basismodell-2020-preis-einstieg-grundaussattung-life-16783239.html; Diesel: estimated 16% more expensive; EV: https://ecomento.de/2019/08/29/vw-e-golf-4000-euro-guenstiger-ab-31-900-euro/; FCV: https://www.handelsblatt.com/mobilitaet/elektromobilitaet/wasserstoff-autos-welche-hersteller-autos-mit-brennstoffzellen-anbieten/27306932.html, all accessed January 2022

[8] https://www.uniqa.at/versicherung/kfz/uebersicht.html, accessed January 2022, including the relevant engine-power fee

[9] https://www.oeamtc.at/thema/autokauf/kfz-zulassung-in-oesterreich-16187062, accessed January 2022

[10] The current prices (January 2022) are gasoline: 1,40€/l; diesel: 1,38€/l; energy (EV, Train): $15kWh/100km$; H2: $1kg/10km$

[11] https://ecomento.de/2019/02/18/verband-bemaengelt-lieferbarkeit-und-preise-von-elektrobussen/ and https://de.wikipedia.org/wiki/Reisebus, accessed February 2022

[12] https://www.volkswagen.de/de/elektrofahrzeuge/elektromobilitaet-erleben/elektroauto-technologie/einfach-effizienter-wirkungsgrad-von-elektromotoren.html, accessed January 2022

[13] https://www.hochgeschwindigkeitszuege.com/oesterreich/railjet.php, accessed January 2022

Aeroplanes

The Boeing 767-300ER, designed as a middle- to long-distance aircraft was taken as examination object. Due to the fact, that this aeroplane is part of Austrian Airlines fleet, Emi (2021) can be used as base for the environmental part. Edwards et al. (2014) is used for the energetic part, with an engine efficiency[14] of around 40%. The purchase price[15] is estimated to 200 million €. Insurance, maintenance, repair & replacement are estimated relative to the initial price. Similar to trains admission costs are not considered, since no information was obtained. The operational costs are assumed to be 33.8 ct/l, with a consumption of 3 $l/100km$ per passenger[16].

Cruise Vessels

As cruise ship, the AIDAblu is chosen. The environmental part is calculated using Formula 3.16 and the data of Gilbert et al. (2017) and Chatzinikolaou and Ventikos (2014). Edwards et al. (2014) is used for the energetic part, with an efficiency for the diesel engine (used as a generator) of 45% (marginally higher than the standard diesel engine, due to specialisations) and an electrical engine of 90%. The purchase price[17] is 350 million €, the insurance, maintenance, repair & replacement and admission are estimated relative to the initial price. For the operational cost the consumption was estimated to $20t/100km$ with a fuel price for HFO of $350€/t$[18].

[14] https://www.kfz-tech.de/Biblio/Alternative_Antriebe/Strahltriebwerk.htm, accessed February 2022

[15] https://www.fliegerweb.com/de/news/Airliner/Boeing+gibt+neue+Listenpreise+bekannt-13694, accessed January 2022

[16] https://www.lufthansagroup.com/de/verantwortung/klima-umwelt/treibstoffverbrauch-und-emissionen and https://utopia.de/ratgeber/kerosinpreis-ermitteln-so-viel-kostet-der-liter-flugbenzin/, accessed January 2022

[17] https://www.cruiseturtle.com/cruise-ships/aidablu, accessed January 2022

[18] https://shipandbunker.com/prices, accessed January 2022

CHAPTER 4

Transport Modes in Tourism

In this chapter, the relevant data concerning touristical behaviour of the Austrian population is used as benchmark to analyse information regarding the transportation used for travelling.
As in chapter **2.4.1-Tourism in Austria** presented, the following transport modes will be discussed and compared, judged by their environmental, economic and energetic parameters:

- Private Vehicles
- Public (long range) Buses
- Electricity driven Trains
- Aeroplanes
- Cruise Vessels

For the investigation of the environmental perspective, the emissions will be split in direct (WtT – *Well to Tank*) and indirect (TtW – *Tank to Wheel*) emissions, while the direct emissions cover (almost) all released gasses during their activity and the indirect emissions contain the ejections which are generated during production. All necessary parameters were taken from the official publications from the *Austrian Federal Environmental Agency* (Emi (2021)) and measure all values related to Austrian vehicles.

The energetic perspective will be considered via the afore mentioned, energy chain and the efficiencies of every energy conversion will be evaluated.

The economic perspective will be considered by using the previously discussed Life-Cycle Costs, which will be restricted to comparability.

4.1 Passenger Cars

Starting with the most widely used means of transportation, private vehicles, *gasoline* and *diesel* powered combustion engines will be introduced and divided into the following subsections, with the first car in Europe being enrolled by *Carl Benz* in *1886*[1].

4.1.1 Environmental View - Gasoline Cars

In chapter **3.1.2-Fuels** all propellants were assumed to be Alkanes. This will suffice for the environmental perspective as well, since gasoline's properties are very close to the ones Alkane have, although it consists of other components[2], such as Alkenes, Sulphur and more. Formula 3.17 with the emission factor for gasoline (note Table 3.2) and an (average) consumption of 7 l/km, delivers a CO_2 exhaution of 159.6 g/km.

This indicates that every driven kilometre the vehicle exhausts around 160 g/km CO_2, which comprises aforementioned Tank-to-Wheel (direct) emissions. For the Well-to-Tank (indirect) emissions, many vital parts are incorporated to all ejections[3], however their discussion lies beyond the scope of this thesis. An exemplary calculation with the taken parameters for WtT and TtW can be seen in the Table A.7 Appendix A and the distribution of the pollutants can be found in Figure 4.2.

4.1.2 Energetic View - Gasoline Cars

As explained in chapter **3.2.1-Energy Chain**, the transformation of crude oil to kinetic energy that moves a vehicle is one of many possible conversions. The complete chain used here is exemplified by the scheme according to Edwards et al. (2014):

1 Extraction η_E

2 Refining η_R

3 Transportation η_T

4 Engine η_M

Steps 1 to 3 describe the Well-To-Tank and Step 4 describes the Tank-To-Wheel efficiency[4], which is symbolically presented in Figure 4.1, and it is values are to be found in Table 4.1 for Gasoline and Diesel. With and engine efficiency (TtW) of about 30%, this results in an overall efficiency of about 24%. A motion energy around 15kWh[5] gives a needed (WtW) Energy of about 61kWh.

4.1.3 Economic View - Gasoline Cars

For this part, the so-called Life-Cycle-Cost, which were explained in chapter **3.3.1-LCC**, will be used to calculate the costs of owning a private vehicle (disposal and residual value will not

[1] http://www.museum-autovision.de/die-ersten-5-autos-der-welt

[2] According to DIN EN 228, gasoline in the European Union consists of mostly Alkanes, 40 %-Vol, 18 %- Vol Arenes, 1 %- Vol Benzene, 150 mg/kg Sulphur, 2,7 %-M Oxygen and the rest is Methyl Tertiary-Butyl Ether

[3] The most emissions in the production emerge from the bodywork and the chassis, manly in the form of Steel, synthetic material (plastic), the interior fabric and the rubber of the tyres

[4] An average Value was taken for the calculation, although the efficiency varies during operation (depending on the operation point of the engine)

[5] 15kWh conforms the average energy needed for 100km travel distance, which is slightly lower than the values of Girardi et al. (2015) (19 $kWk/100km$)

Fuel	Gasoline	Diesel
Extraction	95%	95%
Refining	90%	92%
Transport	95%	95%
WtT	81.23%	83.03%

Table 4.1: *Energy-Chains for gasoline and diesel*

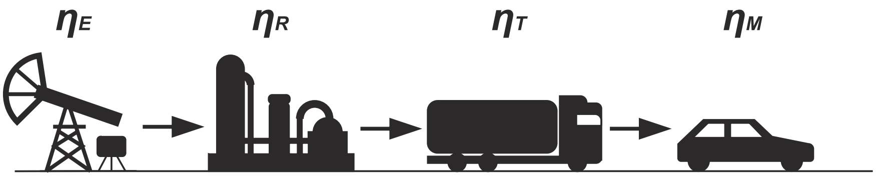

Figure 4.1: *Conversion-Chain for gasoline and diesel cars*

be considered). The following Table 4.2 contains the values for interest and inflation that is required to calculate the future amount of the costs to the present day for gasoline vehicles (with an average lifespan of 12 years).

	Car_{Gas}
i	6%
f	2%
$years$	12
i_r	3.92%
i'	9.43

Table 4.2: *Interest, inflation and duration to calculate real interest and net present value factor*

By using the factors from Table 4.2 all annual costs necessary for the evaluation of the present amount can be calculated. Figure 4.3 depicts the Life-Cycle Costs for gasoline cars, on the present day, with an average purchase price of 20000€, the total amount of expenditures for vehicle is about 53700€, as seen in Table 4.3 (with capital C_C, insurance C'_I, maintenance C'_M, repair & replacement $C'_{R\&R}$, admission C'_A and operational C'_O cost). The calculated values can be seen in Appendix C.1 (see annual costs in chapter *3.3.1*).

Cost (Car)	Gasoline	Diesel
C_C	20 000 €	23 200 €
C'_I	9 428 €	10 936 €
C'_M	9 428 €	10 936 €
$C_{R\&R'}$	3 771 €	4 375 €
C'_A	1 556 €	1 603 €
C'_O	9 517 €	13 115 €
Life-Cycle	53 699 €	64 165 €

Table 4.3: *Life-Cycle Cost for private vehicles (gasoline and diesel)*

4.1.4 Environmental View - Diesel Cars

Diesel driven vehicles use the same principle to get from one place to another as gasoline driven vehicles did formerly. Nowadays, diesel contains more than just the chemicals in this thesis assumed, them being Alkanes[6]. With the calculation, performed with Formula 3.17 and the emission factor for diesel (note Table 3.2) and an (average) consumption of 6 l/km, a value of 159.0 g/km is calculated.

This result is lower than the ones from the gasoline engine, the TtW-Emissions. The exact values for the WtT- and TtW-emissions can be taken from Appendix A.3. In comparison to the gasoline vehicle, the lower emissions, occurring during the refining process of the crude oil are considerable. Figure 4.2 depicts the pollutants released by gasoline and diesel vehicles (logarithmic scaled).

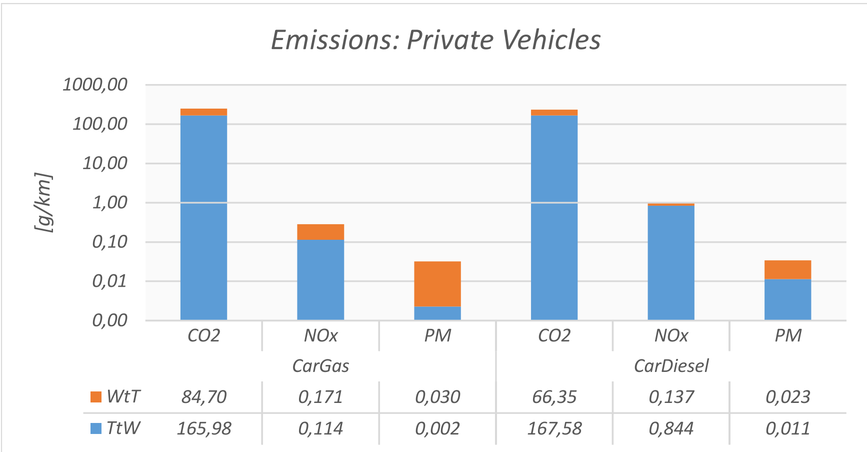

Figure 4.2: *Emissions of gasoline cars (left) vs diesel cars (right) (based on Emi (2021))*

Contrary to the fact that the CO_2-output should be approximately the same as the output from gasoline cars, in this case they are, in fact a little higher, which is attributable to the nature of the used data[7]. The higher NO_x emissions and the lower PM exhausted are mention-worthy as both result from higher temperatures of the combustion process.

4.1.5 Energetic View - Diesel Cars

The same conversion steps, which were previously described for gasoline vehicles apply for diesel driven vehicles as well, as can be seen in Figure 4.1. Nevertheless, there are differences in the refining process (note Table 4.1) and the engine as well (35%). These parameters are in general higher than the ones of the gasoline cars. Doing the same calculation like before (15kWh per 100km), results in about 52kWh for an efficiency of about 29% for the whole conversion process. The used values can be seen in Appendix B.2.

[6]Diesel mainly consists of mostly Alkanes, Cycloalkanes and Arenes (hydrocarbon chains containing 10 to 22 C). The other contents are regulated by DIN EN 590, like Sulphur.

[7]The data presented is an average over cars of standard size (VW Golf) and all engine types. For further Information note Appendix D.1.

4.1.6 Economic View - Diesel Cars

The purchase price for diesel cars is a higher (approximately 16%) than the one for gasoline cars, interest and inflation are the same and can be seen in Table 4.2. Figure 4.3 presents the Life-Cycle Costs for diesel vehicles, broken down in Table 4.3, with an initial purchase price of 23200€. The higher operational costs, in comparison to gasoline cars can be derived from longer distances covered per year and result in 64200€ total. All necessary values for the calcual-tion of the the annual costs, and for the whole life-cycle are contained in Table C.1 in Appendix C.1.

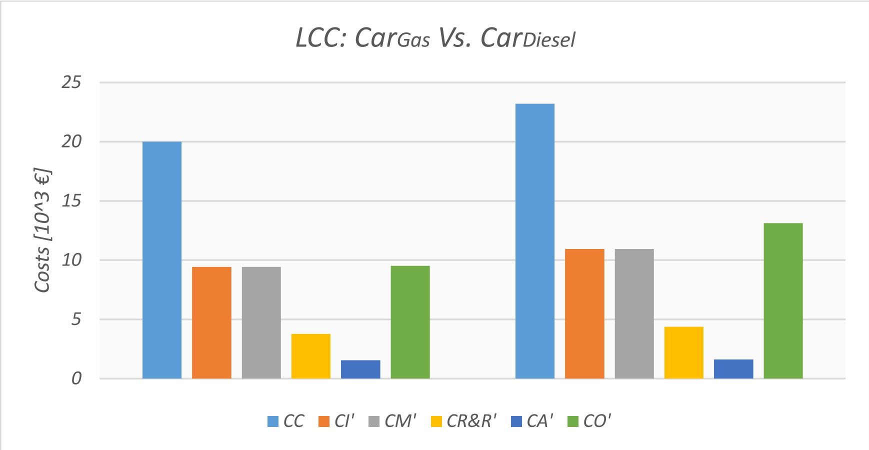

Figure 4.3: *Life-Cycle Costs for gasoline cars (left) and diesel cars (right) in thousand €*

4.2 Buses

A commonly used means of public transportation are buses, with the first bus dating back to around *1662 being pulled by horses in Paris*[8]. The following sections will present an environmental, energetic and economic evaluation of buses.

4.2.1 Environmental View

Buses are mostly powered by diesel and incorporate the same technologies like private vehicles such as a conventional combustion engine. In the context of tourism, only long-distance buses and their exhausted values will be considered, since there is a difference between them and e.g. city buses[9].

Figure 4.4 showcases the emissions of long distance (international) buses, compared to (city) national buses (on a logarithmic scale). The national variant exhausts more than the international for every category. With around 1 $kgCO_2/km$, the emission is about 4 times higher than for private vehicles. NO_x in comparison to gasoline cares is 10 times higher, resulting roughly 2.5 g/km.

[8] https://www.kiwi.com/stories/12-surprisingly-fun-facts-about-buses/

[9] Stop-And-Go usage increases emissions about 22% and due to the different construction the production increases about 16%, which can be seen in the Table A.7 in Appendix A

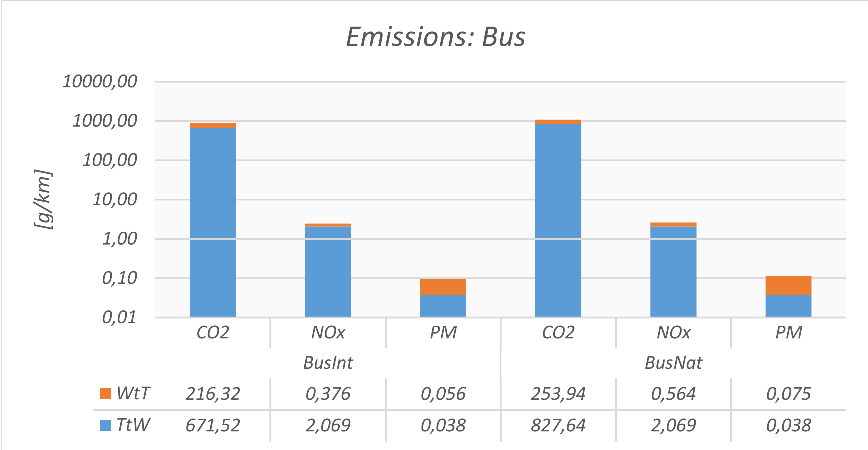

Figure 4.4: *Emission of long-distance buses (left) and city buses (right) (based on Emi (2021))*

4.2.2 Energetic View

As mentioned in the introduction of this chapter, buses are mainly powered by diesel engines, with slightly higher efficiency of the engine (40%). Considering the same efficiency for WtT of 83.03%, as seen in Table 4.1, the result for the whole conversion is about 33%, as seen in Appendix B.2.

4.2.3 Economic View

Inflation and interest stay the same as for gasoline and diesel cars, seen in Table 4.2, however the life time is adjusted to 20 years. With an estimated purchase price of 250000€ and the other values from Appendix C.1, following Figure 4.5 depicts the Life-Cycle Costs for long-distance buses.

Cost	Bus
C_C	250 000 €
C'_I	85 533 €
C'_M	171 065 €
$C_{R\&R'}$	68 426 €
C'_A	68 426 €
C'_O	308 575 €
Life-Cycle	952 025 €

Table 4.4: *Life-Cycle Cost for buses*

Notable are the extraordinary high operational costs C'_O, due to the calculation with current fuel prices for diesel on the market (as of January 2022). Those may vary, since buses are public institutions and expenditures could potentially be way less. The annual maintenance cost result in around 3/4 of the purchase price and can be considered relatively high. All of this adds to nearly 1 million € of expenditures, note Table 4.4.

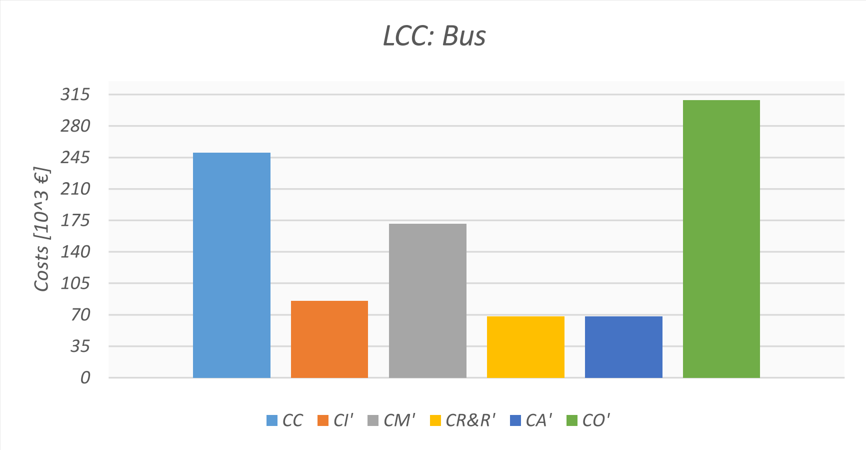

Figure 4.5: *Life-Cycle Costs for long distance buses in thousand €*

4.3 Trains

The next transport mode covered in this thesis will be on rails, with the first one in Europe being steam-powered around *1825 in England* and the first pure electric train by *Siemens 1879*[10].

4.3.1 Environmental View

In this chapter all emissions can be split into WtT- and TtW-emissions, for the purpose of comparing them to the previously discussed modes of transport. In the case of trains the emissions calculated are close to the ones of cars, with some differences concerning the production of the train itself; the used values can be seen in Appendix A.3. Since these are a median over all trains in Austria (81% electric, 19% diesel; Emi (2021)), they have to be treated with caution.

In the following Figure 4.6, direct emissions are included at first, but will be left out later, because the focus will be purely on electric trains (logarithmic scale). For calculating the indirect emissions only the production of the train itself incorporate in the values, although more factors could be considered[11]. The CO_2 and NO_x-emissions amount to around $1 kg/km$ and 2.7 g/km, which are almost the same as the emissions calculated for buses (national and international). The PM is with 0.275 g/km at least double the amount, than their national counterpart.

4.3.2 Energetic View

For trains, the conversion from primary energy to motion energy varies, depending on the primary energy source that is used to move the vehicle. The three researched paths of energy conversion are the following[12], symbolized in Figure 4.7

- from Gas: Extraction – Conversion – Transport – electrical Engine

[10] https://new.siemens.com/global/en/company/about/history/stories/on-track

[11] In difference to cars, where most streets and highways are already constructed, many other factors could be considered, like the roadbed, the supply line and more (de Bortoli et al. (2020))

[12] Extraction η_E, Conversion η_{Cv}, Transport η_T, Engine η_M

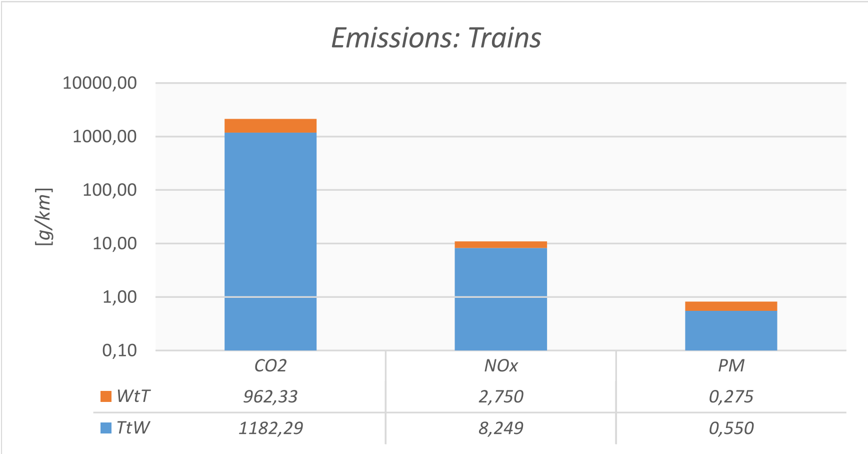

Figure 4.6: *Emissions of trains (based on Emi (2021))*

- from Coal: Extraction – Conversion – Transport – electrical Engine
- from Renewables: Transport – electrical Engine

with a conversion efficiency of 47%, 33% and 79% respectively, with the efficiency for WtT can be found in Table 4.8. The exact values are taken from Appendix C.1. The highest 'loss' in energy , is not in the (electric) engine, but during the conversion processes from the raw energy from to the electric energy (meaning the WtT-efficiency is lower and the TtW-efficiency is higher). The relatively high efficiency of renewables are explicable, due to the not required conversion from primary to final energy.

Electricity	Coal	NG	Renewables
Extraction	91%	97%	-
Conversion	45%	60%	98%
Transport	90%	90%	90%
WtT	36.86%	52.38%	88.20%

Table 4.5: *Energy-Chains for electrical energy driving trains for different energy sources*

4.3.3 Economic View

The following Table 4.6 contains the adapted parameters for interest, inflation and lifetime, needed to evaluate real interest and net present value factor, which depicted in the table.

With an estimated purchase price of $12M€$[13] for a train, with towing, 5 passenger and an end vehicle, the Life-Cycle Costs are represented in Figure 4.8. Compared to the previously presented transport modes, no annual cost stands out considering the long lifespan of trains. Only the primary price stands out as it rises the total costs to 25.8 million €, as Table 4.7 presents.

[13]This price is an estimation based on the purchase price for the Railjet from the ÖBB in 2006 and 2007. The other parameters for the Costs are shown in Appendix C. More details concerning the Railjet are in Appendix D

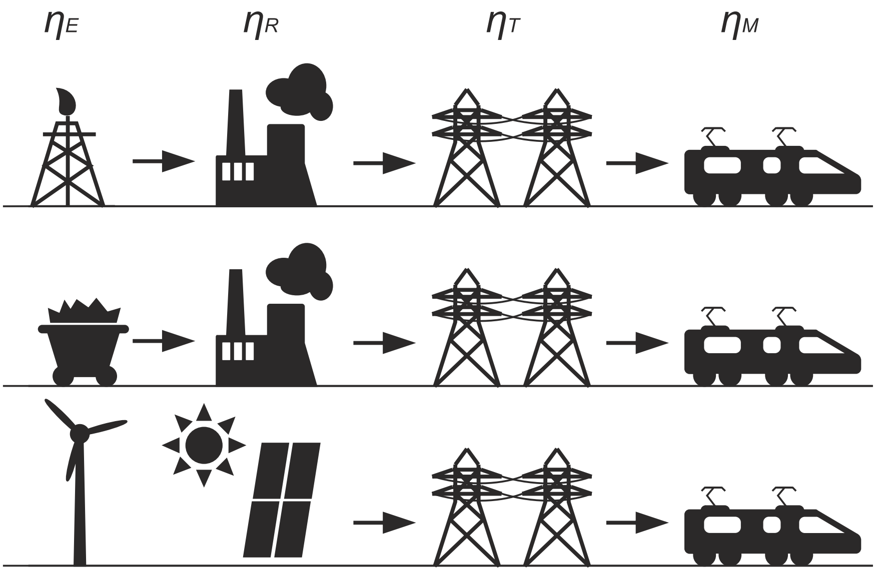

Figure 4.7: *Conversion-Chain for trains, primary energy source from top to bottom: gas, coal, renewables*

	Trains
i	7%
f	3%
$years$	30
i_r	3.88%
i'	17.54

Table 4.6: *Interest, inflation and duration to calculate real interest and net present value factor*

Cost	Train	Plane	Cruise Ship
C_C	12 M€	200 M€	350 M€
C'_I	4.21 M€	35.08 M€	122.78 M€
C'_M	5.26 M€	175.39 M€	153.47 M€
$C_{R\&R'}$	4.21 M€	87.70 M€	153.47 M€
C'_A	-	-	61.39 M€
C'_O	0.05 M€	37.08 M€	66.87 M€
Life-Cycle	25.73 M€	535.25 M€	907.98 M€

Table 4.7: *Life-Cycle Cost for train (Railjet), plane (Boeing 767-300ER) and cruise ship (AIDAblu)*

4.4 Planes

Considered as the far fastest transport vehicle, the plane had its first engine driven flight *1903* under the direction of the *brothers Wright*[14], although early drafts of flying machines had already been designed by *Leonardo Da Vinci*[15] during the late 15^{th} and early 16^{th} *century*.

[14] https://www.space.com/16596-wright-flyer-first-airplane
[15] https://artradarjournal.com/2022/03/01/did-leonardo-da-vinci-invent-the-first-flying-machine/

Figure 4.8: *Life-Cycle Costs for the Railjet in million €*

4.4.1 Environmental View

Using combustion as its main power to generate propulsion, jet engines are different from conventional[16] combustion engines used in cars or to generate electricity. Similar to buses (city traffic – long distance), the emissions differ between national to international flights.

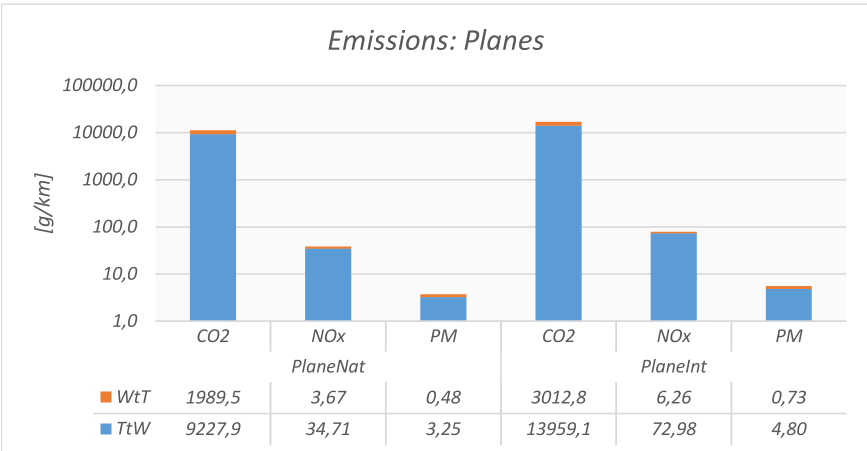

Figure 4.9: *Pollutants of national planes (left) and international planes (right) (based on Emi (2021))*

As can be seen in Figure 4.9 (logarithmic scale), the CO_2-emissions of international flights are around 30% higher (3 and 2 kg/km, respectively) due to the fact, that national flights are generally operated by smaller planes and they usually fly shorter distances (although starting and landing, are the highest contributors and factor in more (Yu et al. (2020))). NO_x and PM for international planes are about double the amount of the national variant, with 2.3 and 0.73

[16]instead of using the combustion to move a cylinder, it is used to generate thrust

g/km, respectively. The usual separation between WtT- and TtW-emissions are considered and presented.

4.4.2 Energetic View

The WtT-efficiency conversing crude oil to kerosene is similar to the one of gasoline, with only a lower efficiency during the refining process (note Figure 4.1). Being able to specify a definite value for the TtW-efficiency is difficult, since more variation than in the case of conventional combustion engines appears, this is further explained in Appendix B. For the purpose of the calculation an average value of 40% was chosen, which results in an efficiency of about 33% for the whole chain. This adds to approximately the same amount that has been calculated for the other conventional driven vehicles (car and bus).

	Plane	Cruise Ship
Extraction	95%	95%
Refining	91%	95%
Transport	95%	95%
Generation	-	45%
WtT	82.13%	38.58%

Table 4.8: *Energy-Chains for the WtT for plane and cruise ship*

4.4.3 Economic View

The parameters interest, inflation and lifespan as well as real interest and net present value factor, are the same as for trains and can be taken from Table 4.6. In this case the purchase price was estimated to be $200M€$[17] for a Boeing 767-300ER, an aeroplane which is part of Austrian Airlines fleet and designed as a middle- to long-distance aircraft. In Figure 4.10 are the Life-Cycle Costs shown. With the projected maintenance costs (C'_M) (about 90% of the initial price), being very high, due to the high service frequency and the repair and replacement ($C'_{R\&R}$) amounting to nearly half of it, all other costs are vanishingly low, the total costs are around 535.3 million €.

4.5 Cruise Vessel

Cruise trips are gaining more and more popularity with vacationist and can be considered as major importance in environmental issues. Transportation by ship is more environmental friendly and efficient than other transport modes, despite the contribution of 3.3% of global CO_2 emissions (Vogler and Sattler (2016)). In the following subsections, key data about cruise vessels will be presented.

4.5.1 Environmental View

Ship engines work in a similar manner to the engines in vehicles like cars and buses, ship-engines are, of course, bigger in size and efficiency as they have to match the used fuel, Heavy Fuel Oil (HFO), which is also called Marine Diesel. Having a higher density and fuel value, the

[17] This price is an estimation based on catalogue price for this type of plane from 2015. All other parameters are taken from Appendix C.1. Further information considering the aircraft can be seen in Appendix D

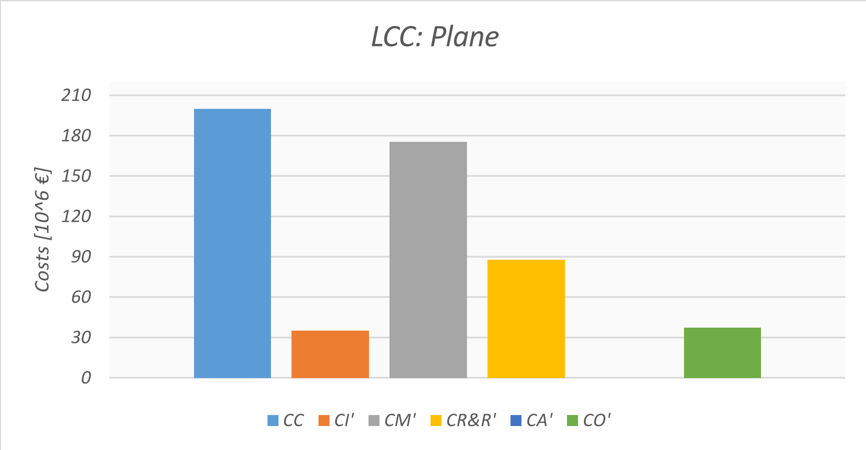

Figure 4.10: *Life-Cycle Costs for the Boeing 767-300ER in million €*

components[18] are listed in Appendix A.1.2. In the previous cases discussed in this thesis, all emissions were limited to CO_2, NO_x and PM, because this was sufficient for their cases. For cruise ships, however emissions will be extended with CO, CH_4, N_2O and SO_x, due to the great coastal concerns they accompany, depicted in the usual way, WtT and TtW-emissions (for the exact values, note Table A.6) separated, in Figure 4.11 (logarithmic scale). Different to every other Graph until now, the emissions are presented in g/kWh (in the upcoming chapter, the emissions will be stated in g/km to compare it with the other results). Another interesting fact concerning cruise vessels is, that the indirect emissions hardly carry any weight, as tehy only constitute about 4% of the direct emissions.

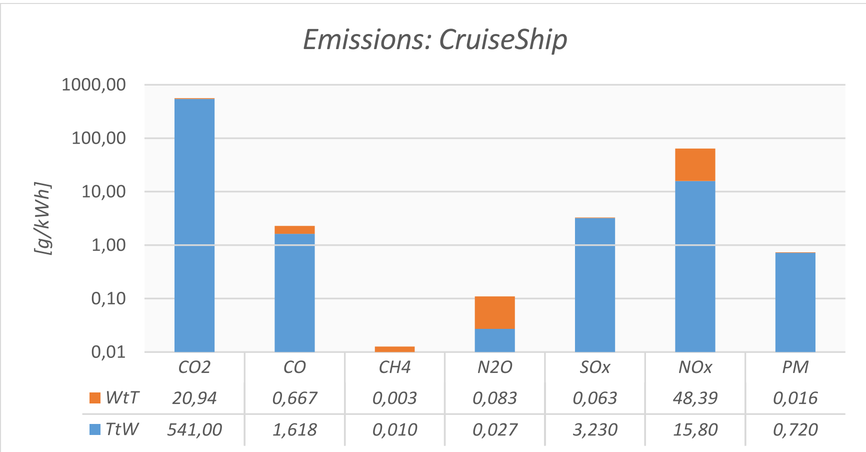

Figure 4.11: *Emissions of cruise vessels*

[18]Marine Diesel is a mixture of mainly Saturates, Aromatics, Resins and Asphaltenes and its contents are limited and regulated by *MARPOL* (International Convention for the Prevention of Pollution from Ships)

4.5.2 Energetic View

As mentioned previously in section **4.5.1**, the usage of HFO has trimmed the engine to have a higher efficiency than the ones of regular combustion engines, with this, marine engine, being around 45%. Mention-worthy in this case is, that newer cruise vessels do not use the combustion to move, but instead use the engine as a generator to power an electrical engine, which drives the propellers[19]. Starting from crude oil, down the energy-chain, to the finished product (HFO, WtT) and subsequent propulsion (TtW) the final efficiency, symbolized in Figure 4.12, for the whole conversion process (with extraction η_E, refinement η_R, transportation η_T, generation of electrical energy η_G and electrical engine η_M) is about 37%, which is significantly higher than all other cases for combustion engines.

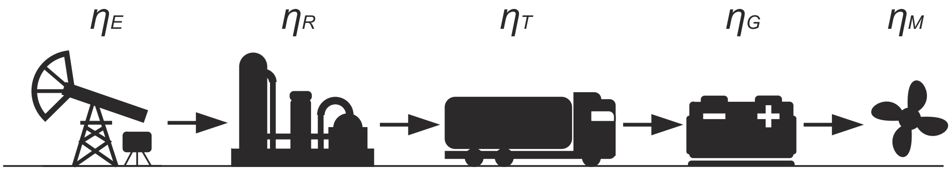

Figure 4.12: *Conversion-Chain for cruise vessels*

4.5.3 Economic View

Inflation, interest, lifetime and the resulting real interest and net present value factor stay unchanged in comparison to trains and plans and are illustrated in Table 4.6. For this part, the AIDAblu[20] is taken as examination object with and purchase price of around $350M€$. The annual cost are depicted in Table C.1 in Appendix C. Figure 4.13 presents the estimated Life-Cycle Costs for the AIDAblu. With no projected annual cost really standing out, maintenance (C'_M) and repair & replacement ($C'_{R\&R}$), besides the primary costs, amount to about 1/3 of C_C and in total to about 900 million € (note Table 4.7).

[19]Due to the high energy demand on the cruise vessel, there are often more generators on the Ship, which power all parts , not only the propulsion.

[20]Further information regarding the cruise vessel can be found in Appendix D.

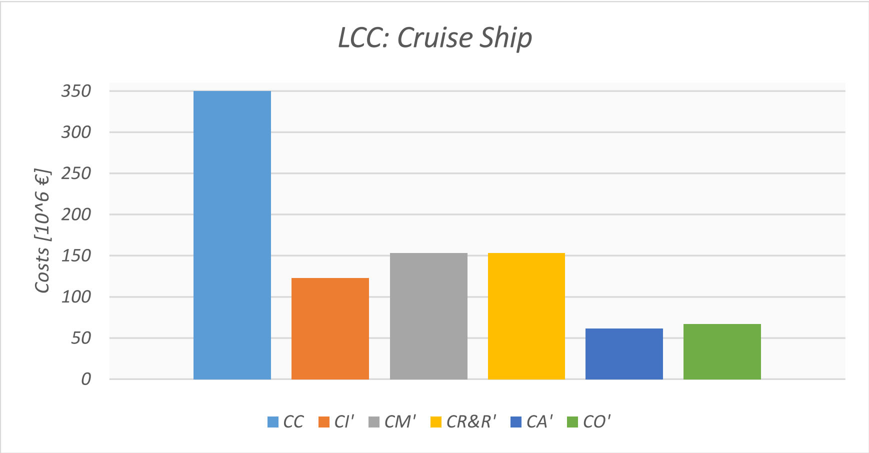

Figure 4.13: *Life-Cycle Costs for the AIDAblu in million €*

CHAPTER 5

Comparison and Alternatives

In this chapter a comparison of conventional transportation, as well as possible alternatives for the previously mentioned vehicles, which usually draw their kinetic (motion) energy from fossil fuels, will be presented.

5.1 Comparison

In this section the presented vehicles from chapter 4 will be compared with each other in the previously introduced ways.

5.1.1 Environmental View

In contrast to the former listing, only the CO_2-equivalent (CO_{2e}) is presented (according to Formula 3.5), additionally the parameters are normalized by their average rate of occupation[1]. The emissions of the cruise ship are estimated with 625 kWh/km.

	TtW *Emissions*	*WtT* *Emissions*	*WtW* *Emissions*
	CO_{2e} $[g/pkm]$	CO_{2e} $[g/pkm]$	CO_{2e} $[g/pkm]$
Car_{Gas}	146.0	80.9	226.9
Car_{Diesel}	149.4	64.7	214.1
Bus	36.2	49.1	49.1
$Train$	-	8.1	8.1
$Plane$	365.6	30.2	395.8
$Cruise-Ship$	223.7	19.0	242.7

Table 5.1: *Emissions of transport modes, normalized by their average occupation*

[1]for cars: 1.14, bus:18.81, train: 274.95, plane: 103.24, cruise ship: 1535.8; with the unit $[g/pkm]$, 'grams per person-kilometre'

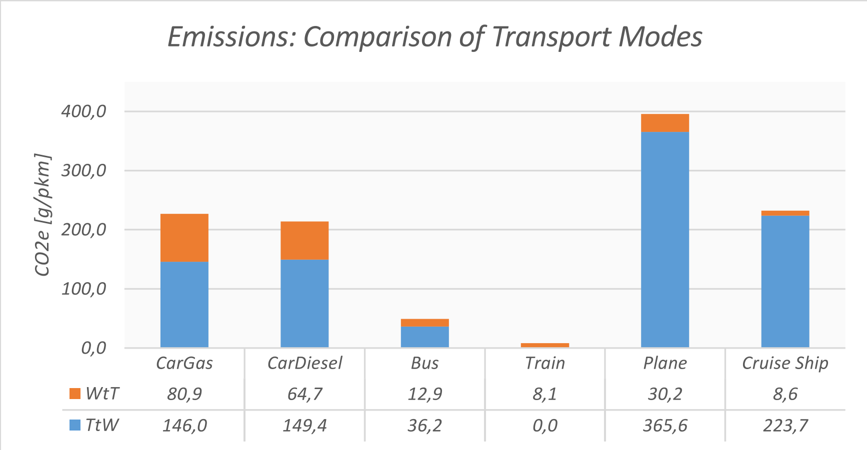

Figure 5.1: *Emissions of transport modes in* CO_{2e} *(David et al. (2021), Pötscher et al. (2014) and Emi (2021))*

Table 5.1 contains all necessary parameters for a general comparison, split into direct and indirect emissions, as well as the combination these two factors (the complete Table can be found in Appendix A.3).
Figure 5.1 presents the evaluated results for common transportation in tourism. Both, gasoline and diesel driven, private vehicles are in the same range and, as one might expect, high in comparison to public transportation, due to the aforementioned average occupation, of 1.14 for cars, 18.81 and 274.95 for bus (values for the international Bus only) and train respectively. The emission for planes (national and international flights combined) overshoot the ones for cruise ships by that much is surprising, but explicable by the recommendation of the *IPCC* (Intergovernmental Panel on Climate Change) to include the *RFI*-Factor (Radiative Forcing Index)[2] for the direct emission (especially for CO_2). The occupation rate are 103.24 and 1535.8 for planes and vessel, respectively[3], which explains the relatively low indirect emission compared to private vehicles.

5.1.2 Energetic View

In this section, the whole conversion-chains for every transportation are compared, according to Formula 3.7. For vehicles such as cars, around $15kWh$ are necessary to move them for 100 km, but since that is not the case for every mentioned means of transportation, a benchmark of $10kWh$ is taken, and calculated using (the transformed Formula 3.6):

$$E_{in} = \frac{E_{out}}{\eta_c} \tag{5.1}$$

[2]A factor to incorporate the great altitudes of air travel and as consequence higher greenhouse effect. In this case, the factor 2.7 was chosen to multiply to Formula 3.5

[3]For the plane a weighted average of national and international flights is taken. For the cruise vessel, the *AIDAblue* is taken as reference (2194 passengers), 70% occupied

Table 5.2 displays the results for the needed *Energy-Input* to achieve an *Energy-Output* of $10kWh$. In the case of trains, different energy sources incorporate in the parameters.

	Well-To-Wheel [kWh]
Car_{Gas}	41.04
Car_{Diesel}	34.41
Bus	30.11
$Train_{Coal}$	30.15
$Train_{NG}$	21.21
$Train_{R}$	12.60
$Plane$	30.44
$Cruise - Ship$	27.28

Table 5.2: *Needed energy-input for transport modes, with 10 kWh energy-output*

Figure 5.2 present the results form Table 5.2, and display the required energy share for WtT and TtW weighted to the overall used energy (note Formula 3.22). As expect, the vehicles using a conventional combustion engine require the most energy to move, with the gasoline driven car needing the most energy, caused by the lowest TtW efficiency compared to the others and followed by diesel powered vehicles. With bus and plane ranging around the same value, the efficiency of the cruise vessel can be considered the highest of the traditional drives, although it has the most numbers of conversions. For the pure electric powered vehicle (train), the origin of the source matters drastically, not only for emissions, but for the needed energy as well. In the case of trains, the sources are coal, natural gasses and renewables. Having nearly the same efficiency as buses and planes, trains driven by coal differ a lot from the others, since natural gasses and renewables use 29.64% and 58.21% less energy, respectively.

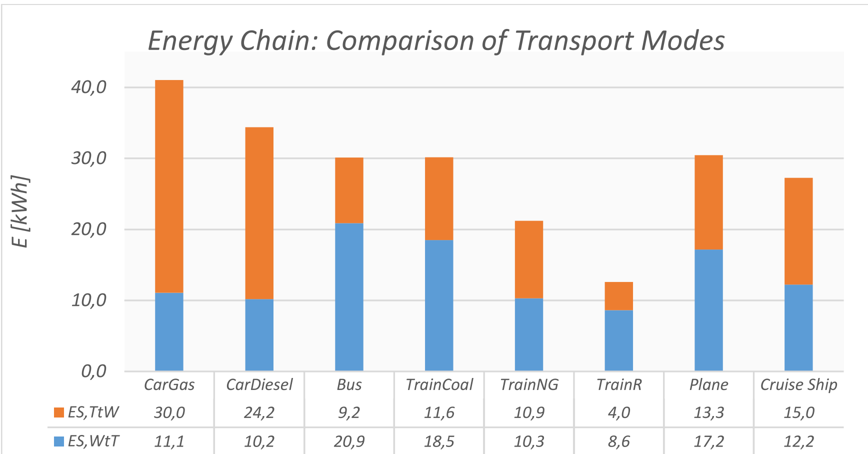

Figure 5.2: *Needed energy-input for transport modes, with 10 kWh energy-output*

5.1.3 Economic View

For the comparison of the *Life-Cycle Costs*, the relative costs will be examined, since it is not reasonable to compare the absolute costs from a simple Car, being about 60000€, and a cruise ship, with total costs of about one billion €.

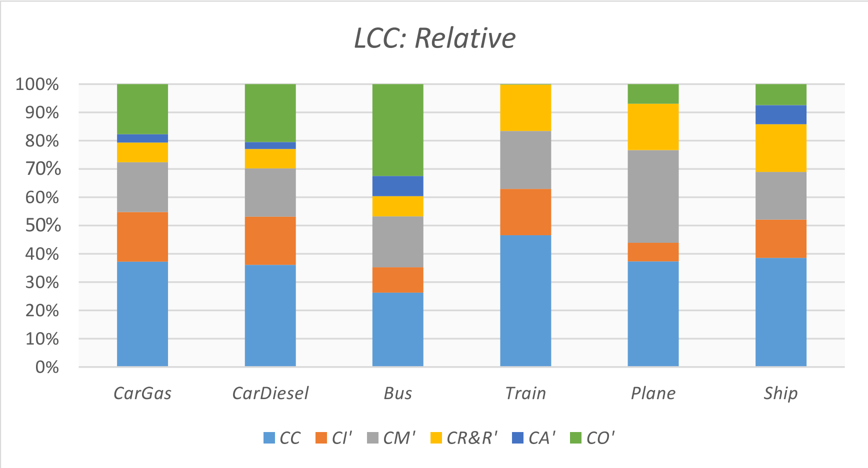

Figure 5.3: *Comparison of the relative Life-Cycle Costs of transport modes*

Figure 5.3 shows the relative LCCs of the means of transport in comparison to each other (note Table C.2 in Appendix C). The first notable marker in the table, is the similarity between the private vehicles and the cruise ship, with an initial purchase price of about 38% and the rest being annual costs, which usually would not be initially assumed. Besides this extraordinary situation, the low primary cost and the high operational costs from buses stand out, however, they could be lower, if the obtained fuel were cheaper for this governmental led transportation. Contrary to the bus, the train has a high starting price and very little costs for the operation, which is promoted by the lower energy price compared to the fuel prices. Towering over all the others are the maintenance costs for planes, explained by the short service intervals, due to safety reasons.

Another way to compare the LCC, is by normalizing the total costs by their occupation, yearly covered distance and average lifespan, as seen in Table D.2 and Table D.3 (note chapter **4-Transport Modes in Tourism**). As presented in Figure 5.4, the public transport modes, train and bus, are the most economic, followed by the plane, with 0.04€, 0.05€ and 0.09€. Private vehicles and cruise ships are at least 3 to 4 times more expensive than the others, with the gasoline driven cars being priciest.

5.2 Alternative Drives

In this section a general overview for alternative transportation is presented, mostly, but not exclusively, concerning the possible changes for *Private Vehicles*.

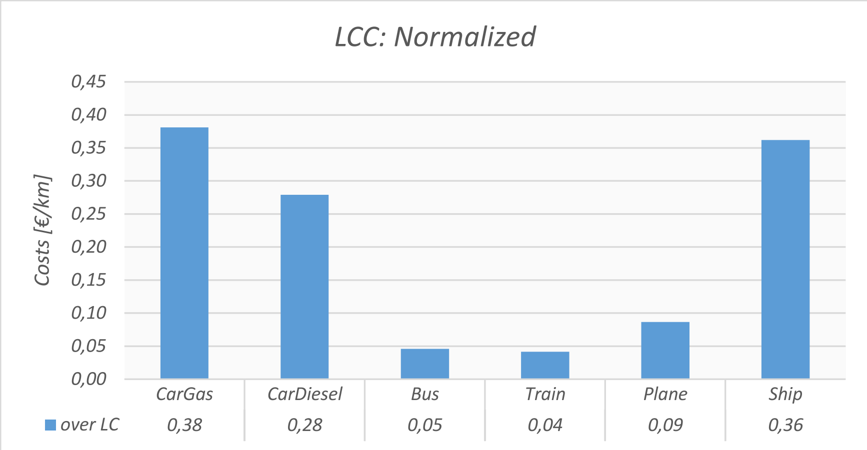

Figure 5.4: *Comparison of the Life-cycle Costs of transport modes, normalized by occupation, average distance and lifespan*

5.2.1 Electric

In this part, the focus will be on the so-called *Electric Vehicles* (*EVs*), driven purely by their on board batteries (Hybrid Vehicles[4] will be left unregarded). In the upcoming subsections EVs will be introduced in an environmental, energetic and economic context.

Environmental View

Again, the occurring emissions will be split into Weel-to-Tank- and Tank-to-Wheel-emissions. The indirect (WtT) emissions depend on the source of the used energy, which in this case will be the *Austrian Energy-Mix* and the *Renewables* (*UZ46*[5]) in this case. As well as the emissions for the generation of the needed energy, the production of the vehicle itself incorporates to the exhaustion too, which are a bit higher than the ones for the conventional combustion engines, due to the elaborate construction of the batteries. Since no fuel is burned during the operation, the direct (TtW) emissions are not present, depicted in Figure 5.5 are the expelled GHGs. Using the *Austrian-Energy-Mix* results in approximately the same emissions as for the conventional gasoline driven car. On the other hand, the utilization of renewables, halves the expelled amount, resulting in 51.87, 0.103 and 0.018 g/km, for CO_2, NO_x and PM respectively.

Energetic View

Similar to the previous chapter, three different energy sources will be considered, with one the energy chain starting with coal, one from gas and the pure renewable path. Since the path starting from renewable origins has the least amount of conversions, the efficiency is, the highest with about 60%, followed by gas with 35% and 25% for coal. The comparison can be seen in Table 5.3.

[4]A Hybrid Vehicle use an internal battery, as well as a combustion engine to drive. A special version is the Plug-In Hybrid, with the possibility to charge the vehicle at charging stations (or at home)

[5]'österreichisches Umweltzeichen', meaning eco-label is a directive for Energy from renewable sources, with a composition of: max 79% from hydropower, at least 1% photovoltaic, the rest consisting of wind power, biomass and others, while 10% of the facilities must not be older than 15 years (Raneburger (2022))

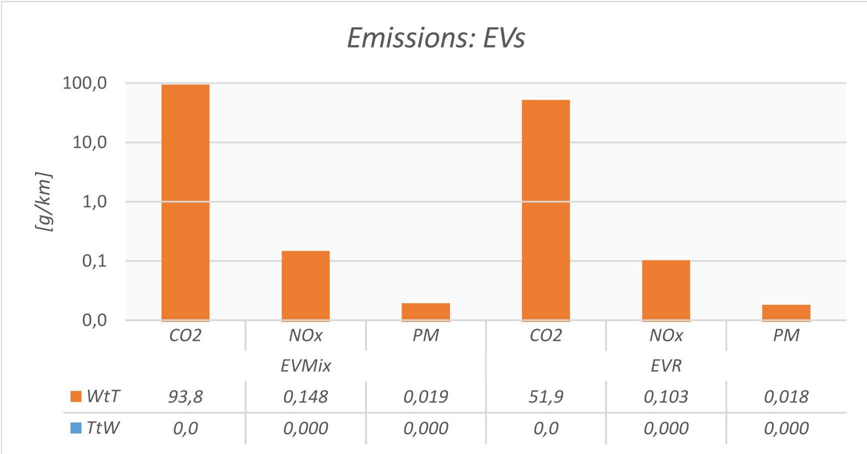

Figure 5.5: *Emissions of EVs with different energy sources: Energy-Mix (left), Renewables (right)*

EV	from Coal	from Gas	from Renewables
Extraction	91%	97%	-
Conversion	45%	60%	98%
Transport	90%	90%	90%
WtT	36,86%	52,38%	88,20%
Charging	90%	90%	90%
TtW	75%	75%	75%
	24,88%	35,36%	59,54%

Table 5.3: *Energy-Chains for EVs from different energy sources*

Economic View

The purchase price for EVs is marginally higher than those of conventional cars, interest and inflation are the same and can be seen in Table 4.2. Figure 5.6 below presents the Life-Cycle Costs for EVs, with an initial purchase price of 25000€. The operational costs are lower due to the cheaper energy price, compared to gasoline and diesel prices and almost the same distances covered per year in comparison to diesel vehicles. All in all the total amount spent to own an electricity driven car is nearly 72000€, which is higher than the other private vehicles, due to the higher maintenance and repair & replacement costs (attributable to the unusual spare parts). All other necessary values considering the annual costs are contained in Table C.1 in Appendix C.

5.2.2 Hydrogen

With Hydrogen being the lightest element, it is the first place in the Periodic System of Elements. With a higher energy-density, than any other fuel[6] previously presented, it can be considered a promising alternative and approach to solve environmental issues, because of its diverse possibilities of usage. Since naturally occurring hydrogen is rare, the element has to be artificially produced to utilize it in large quantities. For that matter various ways have been developed:

[6]A comparison of energy-densities can be found in Appendix B.1

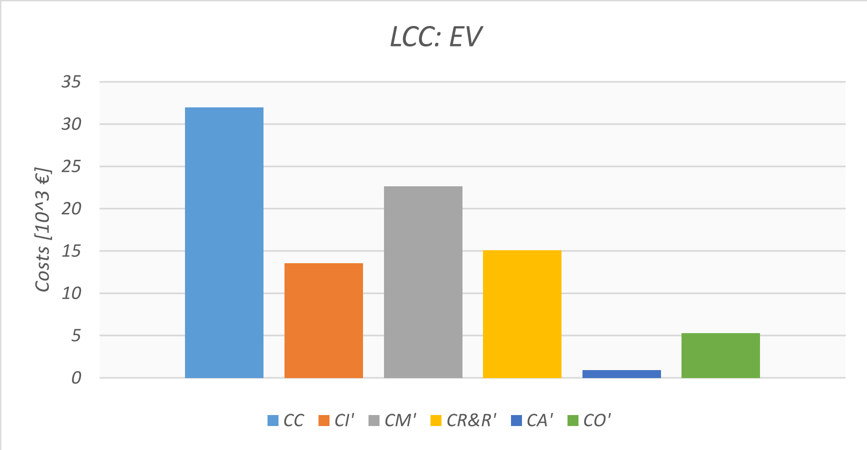

Figure 5.6: *Life-Cycle Costs for EVs*

1 **Gasification**
This way encompasses two main reactions to generate Hydrogen, them being:

- Partial Oxidation (POX-Reaction)
  In this reaction, methane reacts with the oxygen taken from the air, producing Hydrogen and Carbon-Monoxide, which is described in following reaction (Twigg and Dupont (2014)):

$$CH_4 + \frac{1}{2}O \rightarrow CO + 2H_2 \tag{5.2}$$

- Steam Reformation
  Here, the methane reacts with fed steam to provide Hydrogen and Carbon-Monoxide, similar to the POX-Reaction, while generating more H_2, which can be seen in the equation below (Twigg and Dupont (2014)):

$$CH_4 + H_2O \rightarrow O_2 + 3H_2 \tag{5.3}$$

2 **Electrolysis**
Applying electricity to an electrolyser (consisting of Anode and Cathode), forces a reaction[7] where water (H_2O) is split into Hydrogen and Oxygen. Using renewable sources would cut the conversion losses and ultimately lower exhausted GHGs. The reaction can be seen below (Kelly (2014)):

$$2H_2O \rightarrow O_2 + 2H_2 \tag{5.4}$$

The advantage over generated electrical energy is the ability to store the Hydrogen easily, described by Gkanas and Khzouz (2018):

[7]Actually two separate reactions occur on Anode and Cathode respectively

- Compressed Storage (in high pressure cylinders at 40-700 bar)
- Liquid Storage (in cryogenic tanks)
- Solid-State Storage (Hydrogen is absorbed by metals with specific properties)

Hydrogen could be used as substitute for private vehicles, jet-planes and cruise ships, though in a different manner, since there are two different methods to handle propulsion through H_2. One way would be a combustion engine, similar to the conventional combustion engines, or through a Fuel Cell (FC) with an electro-chemical reaction.

Using a combustion engine[8] in combination with hydrogen is a process similar to the ones of conventional combustion, with the difference of burning hydrogen in contrast to the burning of Hydro-Carbons. Due to the lack of carbons in the reaction, no carbon-connections are exhausted (CO, CO_2), the only emissions are Nitrous-Oxides (NO_x) (White et al. (2005)), which is not a GHG, but bad nonetheless like mentioned in the chapter **3.1.3-Green-House Gasses and Pollutants**. The utilisation of a FC is considered as the reversed process of the previously described electrolysis. Permanent supply of fuel generates the electrical energy to drive the vehicle. In this case, the only exhausted gas is steam.

In the upcoming subsections hydrogen powered cars will be introduced in an environmental, energetic and economic context.

Environmental View

As previously explained, the usage of a Hydrogen-Combustion-Engine exhausts[9] some NO_x emissions, but the focus will be on FC-powered vehicles distinguished by their H_2-production (Electrolysis by Austrian Energy Mix and Renewables, Gas reformation). The comparison can be seen in Figure 5.7 and the values are in Table A.8 in Appendix A. If the production is powered by the *Austrian-Mix* the emissions are by far the highest, followed by gas reforming. The best case is achieved by using renewable energy sources.

Energetic View

In this part, three cases of Energy Chains are observed:

- Extraction (Gas) – Reformation – Compression - Transport – FC
- Extraction (Gas) – Conversion – Transport – Electrolysis – Transport – FC
- Renewables - Transport – Electrolysis – Transport – FC

The efficiency of the *Hydrogen Energy-Chain* ie presented in Table 5.4, with extraction η_E, refinement η_R, conversion η_{Cv}, transportation η_T, compression η_{Cp}, electrolysis η_{El} and the engine (FC) η_M. The calculations for each chain result in an overall conversion efficiency of 44%, 17% and 28% respectively, which is, only in the best case (renewable energy), better than a fossil fuel driven car. The additional usage of the combustion engine (instead of a FC) would lower the efficiency of the conversion even more and, therefore, will not be considered. The pathways are symbolized in the Figure 5.8 below.

[8] The efficiency of a hydrogen-fuelled internal combustion engine is up to 40%, similar to a diesel engine (White et al. (2005))

[9] According to White et al. (2005) 0,04 $g/mile$ using a three-way catalyst (TWC)

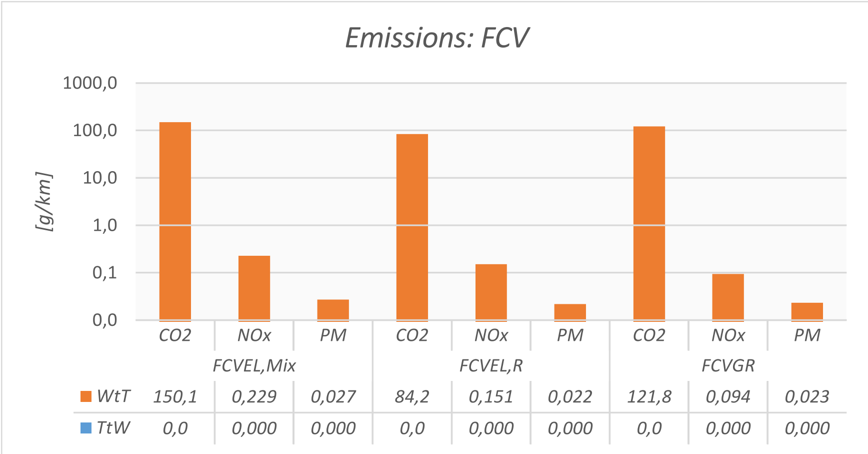

Figure 5.7: *Emission of FCV with a H_2 gained by electrolysis (Mix-left, Renewables-middle) and gas reformation (right)*

Hydrogen	El,NG	El,R	GR
Extraction	97%	-	97%
Conversion	60%	98%	80%
Transport	90%	90%	95%
Electrolysis	70%	70%	-
Transport	75%	75%	-
WtT	27.50%	46.31%	73.72%

Table 5.4: *Energy-Chains for hydrogen, used in a Fuel Cell (electrolysis: natural-gases, Renewables; gas reformation)*

Economic View

Considering the economic view, hydrogen vehicles (*FCV*) are still considered a very exotic means of transportation. With a relative high purchase price of around 60000€ for a standard vehicle[10] the Life-Cycle Costs (interest, inflation, lifespan and net present value factor remain the same as for gasoline, diesel and EVs and can be found in Table 4.2) are also relatively high, albeit the costs of operation are comparatively low. Figure 5.9 displays the Life-Cycle Cost, with a total amount of around 135000€. Meaning, the costs to own a FCV costs is around double of a EV and 2.5 times higher than a gasoline car. Their values found in Appendix C.1.

[10]meaning a VW Golf sized Car, like in the previous examples for Gasoline, Diesel and EVs

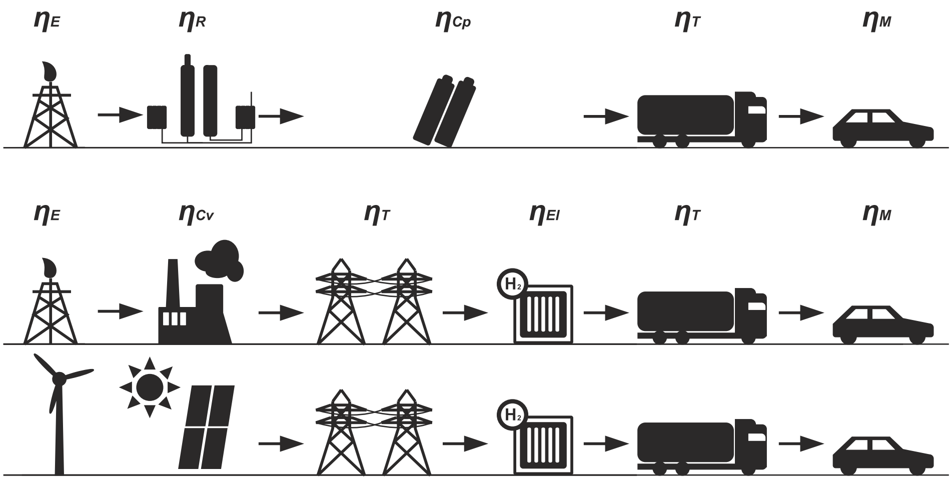

Figure 5.8: *Conversion-Chain for FCV, from top to bottom: gas reformation, electrolysis from natural-gasses and Renewables*

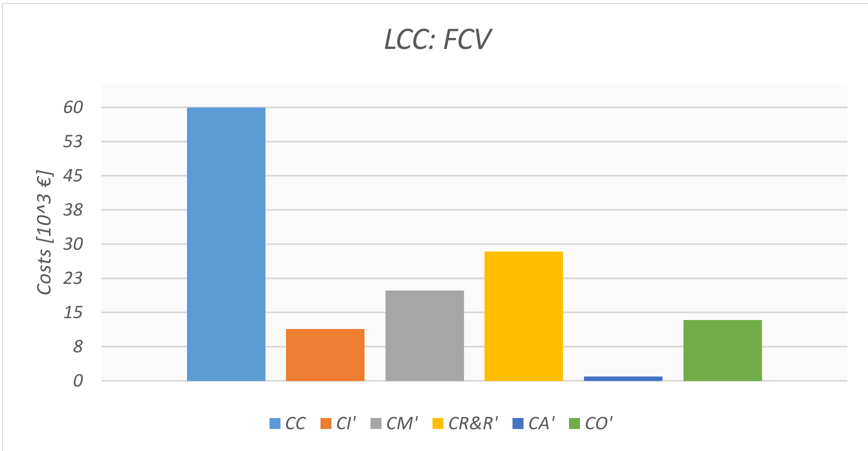

Figure 5.9: *Life-Cycle Costs for FC-Vehicles*

5.2.3 E-Fuels

Another potential alternative to conventional fuels are synthetic fuels, also called 'E-Fuels', which could be used for any of the previously mentioned, fossil fuel driven, vehicle and will be broached in the next few lines (no figures or graphs are presented). The idea behind this method is to bind Carbons (Carbon-Monoxide or Carbon-Dioxide) to Hydrogen to obtain Hydro-Carbon-Chains and achieve similar properties to fuels used in conventional combustion engines[11] (gasoline and diesel) (Hombach et al. (2018)). The major advantage of utilizing these fuels is the ability to use existing technologies, like fuel stations or the engines in the vehicles itself and the fact that no extra CO_2 is released in the atmosphere. The drawbacks of them are the long Energy Chains (similar to the Chain of Hydrogen with the extra step to bind H_2 and C) and the uncirculated technologies, making it very expensive.

[11]The process to receive this synthetic fuel is called Fischer-Tropsch synthesis, named after their inventors Franz Fischer (1947) and Hans Tropsch (19350), two German Chemists

5.3 Conventional Vs. Alternatives

Similar to Section 5.1, the alternatives will be compared to the conventional vehicles, to show the likelihood to become an option of choice. A pure electric drive is only really adaptable as a substitution for private vehicles such as gasoline and diesel driven cars (maybe even buses), if the technology is further refined. Hydrogen on the other hand could be used for every previous vehicle mentioned. For this to take place cars need a combustion engine or a *Fuel Cell*, planes a combustion engine and cruise ships combustion engine or a FC (or even another type of fuel, like Methanol or Liquid Natural-Gases) would be needed. Although they can not be replaced one-by-one, considering the reasons of space, etc. E-Fuels, the way they would be used now, could be substituted easily for any other fossil fuel on the market. Since the alternatives for pure electric and hydrogen were presented for private vehicles already, only they will be compared in the usual way (with all necessary parameters in in Appendix A.3, B.1 and C.1), buses would work in a similar way, planes and cruise ships will not be regarded, due the major unknown factors needed to realise them and to compare them with their conventional counterparts.

Environmental View

The presented GHGs in CO_{2e} shown in Figure 5.10 are the highest for the conventional drives, due to the lack of direct emissions in the alternative vehicles. Just like in the previous sections already explained, it figures, that the EV, as well as the FCV release the lowest emission, if fed by renewable energy sources.

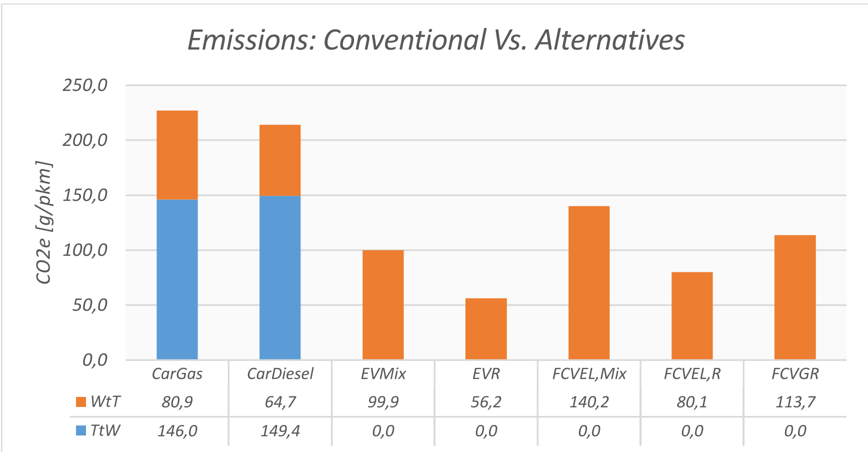

Figure 5.10: *Emissions of conventional vehicles compared with alternatives (pure electric and FC)-Vehicles (David et al. (2021) and Emi (2021))*

Energetic View

The needed energy inputs to reach a desired energy output of $10kWh$ are presented in Figure 5.11, with weighted WtT and TtW energies. With the alternatives being majorly dependent on the energy source, cases like an electric vehicle powered by energy from coal (nearly the same as for a gasoline driven vehicle) or producing Hydrogen from Natural-Gases through electrolysis wouldn't be profitable options. With electric energy from NG or electrolysis using renewables producing nearly the same results, the most effective path is, the FCV with Hydrogen through

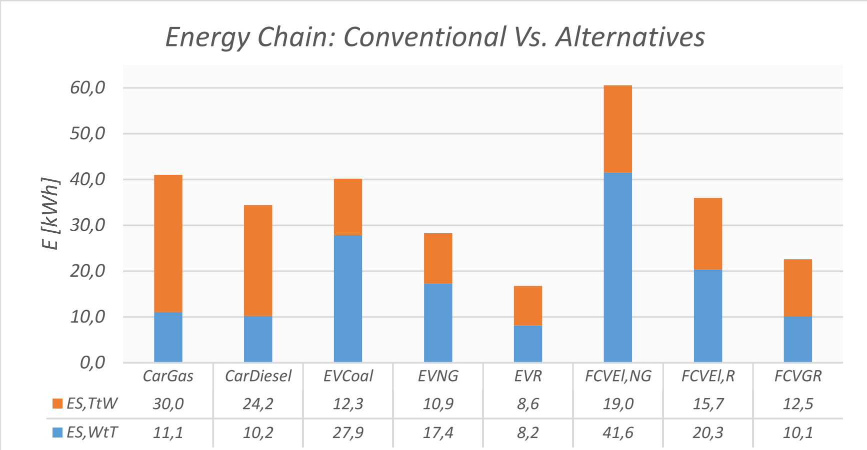

Figure 5.11: *Energy-output for conventional vehicles compared to alternatives, using different energy origins*

gas reformation, closely followed by the vehicle fed by renewable sources.

Economic View

From an economic perspective gasoline and diesel propulsion being nearly the same as the EV, the FC-Vehicle costs about double during its life-cycle, due to the (still) rare technologies and infrastructure (barely any fuel stations in Austria), thus excludes it as possible alternative. Figure 5.12 and Table 5.5 display the results. In every regard (purchase and projected annual costs) the alternatives are more expensive than the conventional vehicles. The chosen base is the diesel driven car, which result in the gasoline car being 16% cheaper, the EV and FCV are 1.39 and 2.08 times more expensive than the conventional counterpart.

Cost (Car)	Gasoline	Diesel	FCV	EV
C_C	20 000 €	23 200 €	60 000 €	32 000 €
C'_Y	33 699 €	40 965 €	73 684 €	57 449 €
Life-Cycle	53 699 €	64 165 €	133 684 €	89 449 €

Table 5.5: *Life-Cycle Cost for private vehicles: conventional vs. alternatives*

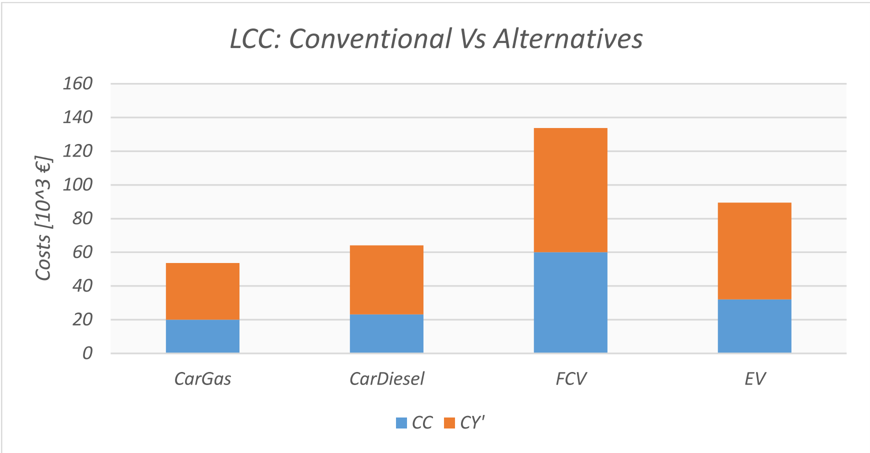

Figure 5.12: *Life-Cycle Costs for conventional vehicles compared to alternative vehicles*

CHAPTER 6

Case Studies - Introduction

This chapter presents three cases, a continental trip, a international flight and a cruise trip. Each case will be introduced separately, the travelling routes and general limiting factors, will be explained by using the data and tools presented in **3-Methodology** and **4-Transport Modes in Tourism**.

6.1 Travelling Routes

6.1.1 Vienna - Berlin

As continental trip, the route from Vienna to Berlin is chosen, due to the presence of an airport (*BER* - Willy Brandt), multiple major train-stations and the many possibilities of alternative ways to travel to the destination. In this case the route is defined by the schedule of the 'ÖBB'[1] and FlixBus as benchmarks for train and bus travel, the roadway is established according to an online navigation site for car and bus[2], and the Austrian Airlines are taken as reference for the flight. Every route is the shortest and fastest possible way, starting in Austria over the Czech Republic to Germany. Although in the case of trains a second instance is examined, representing the most inconvenient way possible, starting in Vienna, over Salzburg and Munich, with a necessary change of trains and ending its trip in Berlin and two planes are compared (obviously on the same route). The different routes shown in Figure 6.1 together, with further information contained in Table 6.1.

	Unit	Train Route 1	Train Route 2	Bus Route 3	Car Route 4	Plane Route 5
code		orange	red	blue	blue	black
time	$[h]$	09:45	08:45	09:25	07:00	01:15
distance	$[km]$	1050	750	660	660	525

Table 6.1: *Relevant Information for the Travelling Routes: Vienna - Berlin*

[1]Österreichische Bundesbahnen - Federal Railroad of Austria

[2]an exact route for the bus could not be identified, but it is reasonable to assume to be the same as for the car

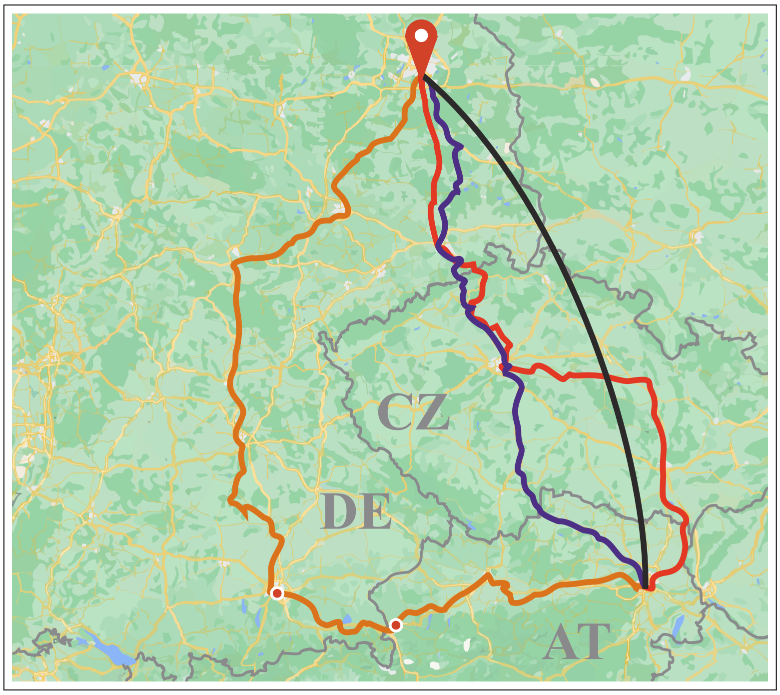

Figure 6.1: *Travelling Routes: Vienna - Berlin*

Route 1 - orange is the longest one, in distance and needed time, with 1050 *km* covered in 9:45 *h*. Representing a common connection between these destinations, the train (Railjet) passes through following cities: *Vienna – Linz – Salzburg – Munich – Nuremberg – Leipzig – Berlin.*
Route 2 - red is also accomplished with a train in a more direct manner, 750 *km* in 8:45 *h*, than the previous one. For a route about 30% shorter than the one before, the needed time to travel appears to be high. An overnight train that covers this distance is the explanation for this, passing through: *Vienna – Brno – Prague – Dresden – Berlin.*
The next distances lead on road instead of rails is *Route 3 - blue*, by bus and *Route 4 - blue* by car. Both of them are fuelled by diesel and travel the same distance of 660 *km*, in 9:25 *h* and 7:00 *h*, respectively. All while passing: *Vienna – Prague – Dresden – Berlin.*
The fastest and most direct way is *Route 5 - black* with a plane covering these 525 *km* in 1:15 *h*. According to Austrian Airlines, 2 different planes are a possible for this distance, namely the *Airbus A320-200* and the *Airbus A321-111* (Pla (2022)).

6.1.2 Vienna - Tokyo

The international travel route from Vienna to Tokyo is analysed by comparing a direct flight, undertaken by Austrian Airlines, and a trip tanking another route. The reason for this detour is the blocked airspace over Russian terrain[3], due to the ongoing conflict between Ukraine and Russia (as of End of March 2022), extending the flight by nearly 50%. In the case of the roundabout route various airlines are chosen (Austrian Airlines and All Nippon Airways), leading from Vienna to Tokyo in Japan. Although Tokyo has two airports, namely Narita - *NRT* and Haneda - *HND*, the landing destination will not be distinguished, since the difference in path does not carry any

[3]https://asienspiegel.ch/2022/02/der-grosse-umweg-von-europa-nach-japan-flugroute\-russland-gesperrt

significant weight over these distances. Figure 6.2 presents the routes and Table 6.2 additional information.

	Unit	Plane Route 1	Plane Route 2
code		red	orange
time	$[h]$	09:45	14:30
distance	$[km]$	9200	13605

Table 6.2: *Relevant Information for the Travelling Routes: Vienna - Tokyo*

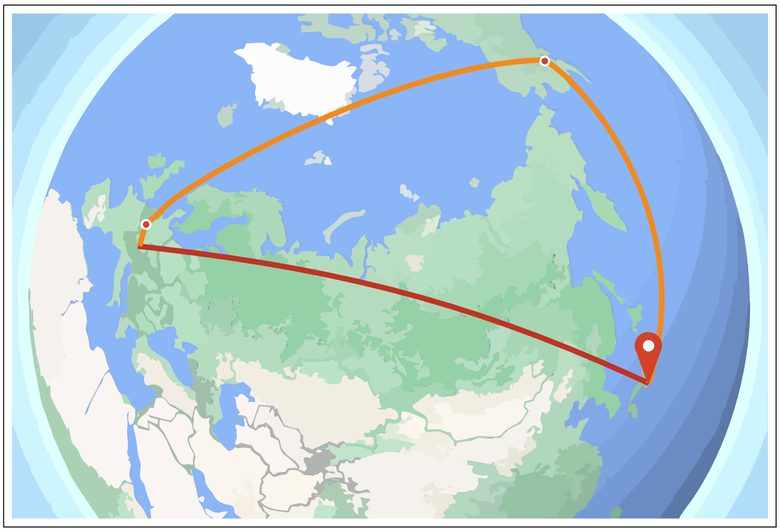

Figure 6.2: *Travelling Routes: Vienna - Tokyo*

Route 1 - red represents the non-stop flight from Vienna to Tokyo, with a flight-time of 09:45 h for 9200 km. Since there is only one possible plane in the repertory of Austrian Airlines (as of March 2022) to cover this distance in one go, the *Boeing 777-200ER* (Pla (2022)) is chosen.
On the other hand *Route 2 - orange* describes the same flight, however a different way. Starting from Vienna over Frankfurt (Germany) and Anchorage (USA), with the possibility to refuel, to Tokyo using the *Airbus A320-200* (Austrian-Airlines) for the first leg and the *Boeing 787-9* (All Nippon Airways) (Pla (2022)) for the second (and if necessary a third).

6.1.3 Cruise Trip

The cruise trip is undertaken with the previously mentioned *AIDAblu*, on a cruise in the Mediterranean Sea. A specific sailing route is defined, based upon the cruise ship company *AIDA*[4]. Starting in Civitavecchia (Rome - Italy), down south to Valletta (Malta), around Sicily, while porting in Catania and Palermo, further to Naples (Italy) and an excursion to Olbia (Sardinia) is made, before ending the trip in Civitavecchia. The whole round-trip is presented in Figure 6.3

[4] https://www.aida.de/kreuzfahrt/ziele/westliches-mittelmeer.19107.html, the trip took place at the end of March 2022, accessed January 2022

and the details in Table 6.3.

Day	Port	arrival	departure	at Port [h]	at sea [h]
	Civitavecchia/Rome (Italy)	-	22:00	-	2
1	*at sea*	-	-	-	24
2	Valletta (Malta)	08:00	19:00	11	13
3	Catania (Sicily)	08:00	18:00	10	14
4	Palermo (Sicily)	08:00	17:00	9	15
5	Naples (Italy)	08:00	18:00	10	14
6	Olbia (Sardinia)	10:00	19:00	9	15
7	Civitavecchia/Rome (Italy)	05:00	-	-	5

Table 6.3: *Deatiled Information for the Cruise Trip of the AIDAblu in the Mediterranean Sea*

Figure 6.3: *Cruise Trip of the AIDAblu in the Mediterranean Sea*

In these 7 days of the trip (151 h to be exact) the cruise ship travels a distance of 1225.46 Nautical Miles[5], or 2270 km (rounded), within 102 h. The rest of the overall time, 49 h, are spent at a port, which gives the travellers a chance to explore the cities and, if necessary, the ship can be refuelled. While in port, the main engines are still powering the ship, meaning that even though no energy is used for propulsion, fuel is burned to generate the electricity needed for hotelling functions on board.

[5] $1\ NM = 1.852\ km$

6.2 Calculation Information

The tools presented in **3-Methodology** serve as a base for the calculations in this section and with further explanation will be provided.

6.2.1 Environmental Part

In this section the released emissions of every used vehicle, of any mentioned route are calculated.

Private Vehicle

In case of cars, the values from Table A.8, which are universally acceptable, since there is no difference in geographical location, are used and multiplied by the covered distance, to gain the complete emissions, like described in Formula 3.18. For the calculation a diesel driven vehicle is chosen.

Bus

According to Formula 3.18, a similar calculation is executed and leads to the expelled emissions of buses.

Train

Trains on the other hand, depend majorly on the energy source, where they draw their power from. For this reason the emissions expelled during energy generation, varying by country, are included. These being 220 gCO_2/kWh, 520 gCO_2/kWh and 475 gCO_2/kWh for Austria, the Czech Republic and Germany, respectively (Ele (2022)), used to calculate the direct emissions. The indirect emissions are taken from Table A.8. Formula 3.17 is used to calculate the emissions per kilometre and, again, Formula 3.18 to calculate the complete emission exhausted over the distance.

Plane

Although Table A.7 contains differences between national and international flights, the weighted combination is used to calculate emissions (Formula 3.18), see **5.1.3-Economic View** (note Table 5.1).

Cruise Ship

In the case of cruise ships, as previously mentioned, fuel is burned not only during movement, but in port as well. Thus, the calculation will be based on the hourly fuel consumption for propulsion and hotelling separately, which is estimated using Simonsen et al. (2018). Further, using the combustion equation according to Formula 3.4 and the emission factor contained in Table 3.2 leads to the direct emissions. Taken from Table A.6, the indirect emissions are about 4% of the direct, which are added at the end (but carry hardly any weight).

6.2.2 Energetic Part

To find the needed energy input for a specific energy output is the wanted result in this part.

Private Vehicle

For cars, values for the consumption (in kWh/km) have been published in the article by Girardi et al. (2015) and the application of the calculated efficiency of the engines themselves, leads to the wanted results using Formula 3.21.

Bus

Similarly to cars, the consumption is found in Laizānsa et al. (2016). By utilizing the efficiency of diesel engines for buses and Formula 3.21, the desired result can be calculated.

Train

The fact that trains massively depend on the origin of the energy stays unchanged for this part. Using average consumptions ascertained by Chiara et al. (2017) and the acquainted efficiency of an electrical engine is the first step in this calculation, figuring out the rest of the energy chain marks the second part. Since at least one border will be crossed during the trip, Austria to Germany (or Austria - Czech Republic - Germany for the other route), different weighted efficiencies (note Formula 3.8) to gain the WtT-Efficiency are calculated by using 3.21 and official data of the represented energy mixes of the countries passed through.

Plane

For planes, the phase of flight (Martin (2021)) and the corresponding consumption is the crucial factor, as described by Chiara et al. (2017). Using this method and weighing the consumption over the distance achieves an average for the complete route (note Formula 3.23). Finally, applying the already known and used TtW-Efficiency from Table B.3 and according to Formula 3.7 and Formula 5.1 results in the needed energy input.

Cruise Ship

Similar to the calculation done for the environmental part, the results by Simonsen et al. (2018) will be estimated to match the chosen vessel. As energy is consumed in the port, for hotelling, and at sea, during movement, the calculation is split and with the efficiency of the complete energy chain taken from Table A.6 (note Formula 3.7), the energy input is obtained (Formula 5.1).

6.2.3 Economic Part

A comparison between the costs for the operator and the incurred costs for one traveller are established in in this part by using the already received costs per kilometre from **5.1.3-Economic View** for every vehicle[6]. The prices for the traveller (ticket/cabin) are described separately.

Private Vehicle

The costs for the operator, in the case of cars, are calculated with the average expenditure per kilometre, which is already calculated and contained in Table C.1 and the price with the charges for Diesel according to Formula 3.24 (as of February 2022, before the Ukraine/Russia conflict).

[6]In case of planes, even though the LCC were calculated for a different plane (Boeing 767-300ER), the Airbus A320-200/A321-111 are way cheaper and the Boeing 777-200ER/787-9 are slightly more expensive considering their cost-dimensions. In case for the smaller planes the calculation overshoots, the other are underestimated.

Bus

The calculation for the costs of this vehicle are the same as for cars (note Table C.1), with the only difference that one has to buy a ticket to use the bus.

Train

In case of the ÖBB, the ticket price is bound by rate of occupation and date[7]. The costs for the route are already calculated and to be found in Table C.1.

Plane

The prices for the tickets, change from day to day and airline, are taken from the Homepage of Austrian Airlines. The costs for the airline are calculated by using the values contained in Table C.1.

Cruise Ship

The costs for the shipping company are contained in Table C.1, which are already calculated. The price for a cabin is chosen for one person, replacing the tickets from the previous mentions.

[7]'Sparschine', a made-up word describing an early-bird price

CHAPTER 7

Case Studies - Results

This chapter presents the results from the routes described in detail in **6-Case Studies - Introduction**

7.1 Vienna - Berlin

In this section the various transport modes from the route Vienna - Berlin will be analysed and compared to gain clear results regarding their environmental aspects and further the released emissions. Moreover the energetic and economic point of view will be analysed as well.

7.1.1 Environmental Estimation

Vehicles

As explained in **6.1.1-Travelling Routes/Vienna - Berlin**, the vehicles for this route can be split depending on the used way. On the one hand, there are independent transport modes: car, bus and plane, where the exhausted gasses are the always same no matter what country is passed through. The values from Table A.7 and the distance are used to calculate the released emissions, presented in Table 7.1.

	consumption $[kWh/km]$	distance $[km]$	WtT	TtW $[gCO_{2e}/km]$	WtW	sum $[kgCO_{2e}]$
Car	0.15	660	73.76	170.32	244.07	161.09
Bus	2.5	660	242.65	680.92	923.57	609.56
Plane	30	525	3117.85	37744.54	40862.39	21452.76

Table 7.1: *Accumulated emissions of car, bus and plane (based on Emi (2021))*

The plane has the highest emitted gasses in comparison to the other vehicles (*RFI-Factor* included), with about 35 times the amount of the bus and 133 times higher than the amount of emissions of travelling the route by car.

On the other hand, the calculation of the emissions of a train is dependent on the emissions released via the required energy generation, as explained in **6.2.1-Environmental Part/Train** (According to Ele (2022): Austria 220 gCO_{2e}/kWh, Czech Republic: 520 gCO_{2e}/kWh, Germany: 475 gCO_{2e}/kWh). In accordance to these numbers, the covered distance in the respective countries is estimated. Table 7.2 shows the results of the calculation (note that the WtW-Emissions are the pure addition of WtT- and TtW-Emissions and are not equal to the sum, reason to the different emissions per country).

	cons.	dist.	land-specific distance & emissions						WtT	TtW	WtW	sum
			AT	CZ	DE	AT	CZ	DE				
	$[kWh/km]$	$[km]$	$[km]$			$[kgCO2e/km]$			$[kgCO2e/km]$			$[tCO_{2e}]$
Train R1	20	750	297	-	753	4.4	-	9.5	2.23	13.9	16.13	8.699
Train R2	20	1050	87	387	276	4.4	10.4	9.5	2.23	24.3	26.53	10.799

Table 7.2: *Accumulated emissions of trains for different routes*

Although *Route 2* is, with 1050 km, about 30% longer than *Route 1*, the emissions are only 20% higher (10.8 tCO_{2e} and 8.7 tCO_{2e}), this discrepancy shows that the calculation of emissions is dependent on the respective country and its energy sources in this example. Further the released gasses are about 2 to 2.5 times lower than in the case plane, for the long and the short route, respectively. But the emissions are 14 to 18 times higher than the bus and 54 to 67 times more than the car.

Comparison

The previous calculation of the accumulated emissions for the route is not representative, since size, weight and the capacity differ majorly. To achieve an equal footing, results from Table 7.1 and Table 7.2 are normalized by occupation and further the travelled distance. Instead of only normalizing to the average occupation[1] ($[gCO2e/pkm]$), as seen in Table D.2, a 70% occupation ($[gCO2e/pkm]$) as well as a calculation for every seat (maximum capacity, $[gCO2e/stkm]$) are presented in Table 7.3 (an extension to Table 6.1).

	Unit	Train Route 1	Train Route 2	Bus Route 3	Car Route 4	Plane Route 5
code		orange	red	blue	blue	black
time	$[h]$	09:45	08:45	09:25	07:00	01:15
distance	$[km]$	1050	750	660	660	525
WTW-Emission	$[kgCO2e/km]$	26.35	16.13	0.92	0.25	40.86
avg. Occ.	$[kgCO2e/p]$	39.28	31.64	32.41	141.31	207.80
	$[gCO2e/pkm]$	37.41	42.19	49.10	214.10	395.80
70% Occ.	$[kgCO2e/p]$	36.47	29.38	19.57	46.03	176.13
	$[gCO2e/pkm]$	34.73	39.18	29.65	69.74	335.49
per Seat	$[kgCO2e/st]$	25.53	20.57	13.70	32.22	123.29
	$[gCO2e/stkm]$	24.31	27.42	20.75	48.81	234.84

Table 7.3: *Emissions for the travelling routes: Vienna - Berlin (note Figure 6.1)*

[1] An occupation higher than the average for a touristical context is assumed in this calculation.

Purely considering the WTW-emissions leads to the expected result, that planes are by far the highest GHG ejector, being about 50% higher than the train taking the roundabout way. In contrast, the direct train has 60% less emissions compared than its (longer) counterpart. Buses and cars on the other hand can be considered 'economical', as they exhaust only 1/16 comparing bus and direct train, and further the car expels 1/4 of the bus.

Unsurprisingly the results for car, bus and plane, normalized by the average occupation, are the same as seen in Table A.8. For the train the calculation is different, since the emissions are not exclusively bound to Austrian energy generation. Additionally, travelling becomes more environmentally acceptable with higher occupation rates, with bus and car standing out the most, since their emissions are more than cut in half (2.4 and 4.4 times lower).

However, it needs to be highlighted that public transportation (train and bus) are on the same level of released gasses with higher manning. The exceptions are cars, with about double, and plane with 8.5 to 11 times higher releases compared to bus and train.

7.1.2 Energetic Estimation

Energy Consumption

The consumption of the energy is mostly considered stable in case of car, bus and train, but grow with vehicle size (0.15, 2.5 and 20 kWh, respectively). From Chiara et al. (2017) it becomes apparent, that the average energy consumption of planes, in contrast, is dependent on the covered distance (525 km in this case), due to the greater weight of the energy intensive phases of flight, for example starting and climbing to travelling altitude. On that account, two planes, both part of the fleet of Austrian Airlines, are differentiated and examined.

Firstly, the *Airbus A320-200* with a capacity of 174 people will be investigated. The estimation for the weighted *Specific Energy Consumption*[1] is contained in Table 7.4.

		Airbus A320-200 (Austrian Airlines) with 174 p					
Vienna - Berlin		take off	climb	cruise	descent	approach	sum
Range	$[km]$	10	100	235	75	105	525
EC	$[kWh]$	7000	23000	4230	3000	3675	40905
SEC	$[kWh/km]$	700.00	230.00	18.00	40.00	35.00	
weighted SEC	$[kWh/km]$	13.33	43.81	8.06	5.71	7.00	77.91

Table 7.4: *Weighted specific energy consumption, Vienna - Berlin (Airbus A320-200)*

Applying an occupation of 70% and the maximum possible capacity to the weighted SEC of 77.91 kWh/km, lead to 0.6397 kWh/pkm and 0.4478 $kWh/stkm$, respectively.

Secondly, the *Airbus A321-111*, with space for 200 people, is a suitable alternative for this route. Since this variant has higher capacity than the previous one, it needs to be bigger and subsequently has a higher consumption. The relevant parameters are in Table 7.5.

With a manning of 70% results in 0.6304 kWh/pkm and the maximum capacity to 0.4413 $kWh/stkm$ for 88.26 kWh/km, which is nearly the same as for the smaller plane.

[1]The calculation for a similar plane can be found in Appendix B.11 (Chiara et al. (2017))

Airbus A321-111 (Austrian Airlines) with 200 p **Vienna - Berlin**		take off	climb	cruise	descent	approach	sum
Range	$[km]$	10	100	235	75	105	525
EC	$[kWh]$	7930	26054	4792	3398	4163	46336
SEC	$[kWh/km]$	792.95	260.54	20.39	45.31	39.65	
weighted SEC	$[kWh/km]$	15.10	49.63	9.13	6.49	7.93	88.26

Table 7.5: *Weighted specific energy consumption, Vienna - Berlin (Airbus A321-111)*

Well-To-Wheel

Most of the needed WtT-efficiencies have already been calculated in **5.1.2-Comparison/Energetic View**, so most efficiencies can be found in Table B.3. In case of the train, the different energy origins showcased the dependency, but are not to be considered a representative reflection of reality, because they are supplied by various energy sources and not just one. For this reason, the *Energy Mix* of Austria, the Czech Republic and Germany are taken into account, as these countries are passed through (for further information note Appendix B.3). Table 7.6 present the weighted efficiencies of the aforementioned countries[3].

Austria	Czech Rep.	Germany
71.15%	49.66%	53.02%

Table 7.6: *Weighted efficiencies of European-Energy generation*

Eye-catching is the high percentage of Austrian-Generation, which derives from the high share of renewable sources in contrast to the others, with high ratio of thermal power-plants (long Energy-Chains). Due to the fact, that Austria has a high import rate, the efficiency is further weighted with the efficiency of the Czech Republic and Germany[4], leading to an overall efficiency of 66.30%.

For trains, using the weighted efficiencies for the *Energy Mixes* (according to Formula 5.1), provides the results of the WtT-Efficiency displayed in Table 7.7.

	cons.	dist.	land-specific distance & consumption						sum
			AT	CZ	DE	AT	CZ	DE	
	$[kWh/km]$	$[km]$		$[km]$			$[kWh]$		$[kWh]$
Train R1	20	1050	297	-	753	8959	-	28404	37363
Train R2	20	750	87	387	276	2624	15585	10411	28620

Table 7.7: *Accumulated energy consumption of trains for different routes*

The TtW-efficiencies are all chosen according to Table B.3, and their combination leads to the already presented *Well-To-Wheel-Efficiency* for the whole chain.

[3]For the complete calculation note Appendix B.3

[4]Assuming no trade is present, Germany and the Czech Republic are able to supply themselves. Austria on the other hand needs about 25% imports to cover the overall needs, with 2/3 deriving from Germany and 1/3 from the Czech Republic (according to Ele (2022))

Comparison

Incorporating the already calculated consumption for planes (Table 7.4 and 7.5) and the needed energy (Table 7.7, further including the efficiency of an electrical engine) to supply trains, is further related to the occupation (average, 70% and maximum capacity) and the overall distance (note **7.1.1-Environmental Estimation/Comparison**) to gain a comparable result. By using the overall conversion, as seen in Table B.3, Table 7.8 , the needed energy for the respective energy consumption for each vehicle are calculated.

	Unit	Train Route 1	Train Route 2	Bus Route 3	Car Route 4	Plane Route 5	Plane Route 5
code		orange	red	blue	blue	black	black
time	$[h]$	09:45	08:45	09:25	07:00	01:15	01:15
distance	$[km]$	1050	750	660	660	525	525
consumption	kWh/km	20	20	2.5	0.15	77.91	88.26
Sum	$[kWh]$	41515	31800	4968.08	340.67	124517	141050
avg. Occ	$[kWh/p]$	150.99	115.66	264.12	298.83	1206.09	1366.24
	$[kWh/pkm]$	0.144	0.154	0.400	0.453	2.297	2.602
70% Occ	$[kWh/p]$	140.21	107.40	159.49	97.33	1022.31	1007.50
	$[kWh/pkm]$	0.134	0.143	0.242	0.147	1.947	1.919
per Seat	$[kWh/st]$	98.14	75.18	111.64	68.13	715.61	705.25
	$[kWh/stkm]$	0.093	0.100	0.169	0.103	1.363	1.343

Table 7.8: *Needed energy for the travelling routes: Vienna - Berlin (note Figure 6.1)*

The vehicles are sorted by their 'size' with growing consumption/need, with the car being the lowest and planes by far the highest consumer (the bigger plane, the A321-111, needs more energy, about 13%, than the A320-200). The energy needs of aeroplanes in comparison to trains are about 3 to 4.5 times higher, moreover cars need 1/10 of the energy of buses, which in turn are 6.5 to 8 times lower than the need of buses.

Normalizing them to the respective occupation rates and distance, cuts the related energy need at least by half in the case of planes, less for trains and about 4 times for cars and buses. Filling each vehicle to their maximum capacity of occupation show similar values for the trains and the car, buses on the other hand need about 60% more. The data shows, that the A321-111 has slightly lower consumption per seat and kilometre that the smaller counterpart, but emissions are still about 14 times higher that the values of the trains.

7.1.3 Economic Estimation

For this section the costs for the business are calculated using the figures from chapter **4-Transport Modes in Tourism**, with its values in Table C.1. Further the price per person and distance to travel the route (taken from the respective Websites[6], explained in **6.2.3-Calculation Information/Economic Part**) and the possible revenue are calculated and presented in Table 7.9.

Except for the the car, every other vehicle has variable cost, depending on the day and, in case of the train, rate of occupation. For the calculation, following assumptions are applied:

- for cars: Diesel, 1.38 €/l (as of February 2022), 7.0l/100km

[6] Accessed March 2022

- trains: for the first 55% of passengers, the minimal prices is taken, the maximal price for the remaining seats
- others: the arithmetic average of the minimal and maximal price is taken

	Unit	Train Route 1	Train Route 2	Bus Route 3	Car Route 4	Plane Route 5
code		orange	red	blue	blue	black
time	$[h]$	09:45	08:45	09:25	07:00	01:15
distance	$[km]$	1050	750	660	660	525
over LC	$[€/km]$	0.04	0.04	0.05	0.28	0.09
Cost	[€]	12007.32	8576.66	569.15	210.06	4683.43
Price min	[€]	64.90	69.90	45.00	63.76	75.00
Price max	[€]	220.00	99.00	65.00	-	90.00
Price per km	$[ct/km]$	14.31	11.26	8.33	9.66	15.71
avg. Revenue	[€]	24404.99	20449.94	1034.55	-	8517.30
70% Revenue	[€]	29057.99	22543.79	1713.25	-	10048.50
max. Revenue	[€]	56975.99	35106.89	2447.50	-	14355.00

Table 7.9: *Cost over the Life-Cycle, price and revenue for the travelling routes: Vienna - Berlin (note Figure 6.1)*

As can be seen in the table, if one buys the tickets early, a high quantity of money can be saved, about 20% (plane) to 40%, in the case of the longer train the price rises by 3.4 times.

The price per kilometre (based on the average of minimal and maximal price; except for trains, where they are split according to the previous assumption 55% to 45%) is in close range for every vehicle, with the bus being the cheapest and the plane the most expensive means of transport (double the price). The direct train has nearly the same price as the car, and the roundabout train the nearly same as the plane.

Looking at the revenue, with an average occupation, every transport mode makes a profit in this example (note Table D.2). In these cases profit is made with an occupation of about 35%, 27%, 23% and 33% for the trains, taking route 1 and route 2, the bus and the plane, respectively. Further, instead of taking the plane with higher capacity (A321-111), the profit could be risen by 15%, when resorting to the smaller version. However it is to note, that the direct train has lower capacities, since overnight trains tend to have couchette and sleeping coaches and budget airlines sell their tickets for about half of the estimated minimal price.

7.2 Vienna - Tokyo

This section analyses the two routes from Vienna - Tokyo, introduced in **6.1.2-Travelling Routes/Vienna - Tokyo**, with the aim to compare them regarding their environmental, energetic and economic point of view, while gaining information on the exhausted emissions, needed energy and accruing costs.

7.2.1 Environmental Estimation

For this part, the average emissions of national and international planes are taken from Table A.7. These values incorporate all planes from the Austria Airlines fleet, which include all planes used in this estimation, except the Boeing 787-9, but as it is the newest plane compared to the others in question and has a similar size to the Boeing 777-200ER, it is assumed to have a similar, if not lesser, amount of exhausted gasses.

	Unit	Plane Route 1	Plane Route 2
code		red	orange
time	$[h]$	09:45	14:30
distance	$[km]$	9200	13605
WTW-Emission	$[kgCO2e/km]$	40.86	40.86
direct	$[kgCO2e/km]$	37.74	37.74
indirect	$[kgCO2e/km]$	3.12	3.12
combination	$[kgCO2e/km]$	40.86	40.86
Sum	$[tCO2e]$	375.93	555.93
70% Occ	$[tCO2e/p]$	1.755	3.643
	$[gCO2e/pkm]$	190.77	267.77
per Seat	$[tCO2e/st]$	1.229	2.550
	$[gCO2e/stkm]$	133.54	187.44

Table 7.10: *Emissions for the travelling route: Vienna - Tokyo (note Figure 6.2)*

For the direct flight 375.93 $tCO2e$ are exhausted, for the roundabout way 555.93 $tCO2e$. can be deducted from the table, the longer distance correlates directly with the expelled emissions, making the trip 50% more environmentally unfriendly.

The occupation is adjusted to the planes used in reality, the Boeing 777-200ER with 306 seats and the average of the ones for the other route, the Airbus A320-200 (174 seats) and the Boeing 787-9 (240 seats), with 218 seats. Due to the higher capacity, the shorter trip has, with 1.229 $tCO2e/st$, about half the expelled amount of emissions than the longer one.

The parameters for the rate of occupation in addition to the distance lead to 190.77 $gCO2e/pkm$ and 267.77 $gCO2e/pkm$ for 70% manning for the direct and the detour flight, respectively. For the 50% longer route, 40% more GHG is emitted, reason to the different capacity and distance. The average occupation was left out on purpose, since they would only be linear lower for both examples.

7.2.2 Energetic Estimation

Energy Consumption - Direct Flight

The calculation for the weighted *SEC*, for the Boeing 777-200ER with a capacity of 304 persons, is done in the same manner like explained in **7.1.2-Vienna - Berlin/Energetic Estimation** using and estimation based on Chiara et al. (2017) (note Appendix B.11). Table 7.11 present the results.

Due to the long travelling distance (9200 km), the consumption-peaks don't weigh as heavy as seen in the shorter flights. An occupation rate of 70% and 100%, result in 0.1402 kWh/pkm and 0.0981 $kWh/stkm$ for a weighted *SEC* of 30.02 kWh/km.

Boeing 777-200ER (Austrian Airlines) with 304 p

Vienna - Tokyo		take off	climb	cruise	descent	approach	sum
Range	$[km]$	10	100	8910	75	105	9200
EC	$[kWh]$	9830	32299	225223	4243	5846	277412
SEC	$[kWh/km]$	983.02	322.99	25.28	56.17	55.68	
weighted SEC	$[kWh/km]$	1.07	3.51	24.48	0.33	0.64	30.02

Table 7.11: *Weighted specific energy consumption, Vienna - Tokyo (Boeing 777-200ER)*

Energy Consumption - Detour Flight

Since the alternative route is executed by different planes, reason to the conflict between the Ukraine and Russia, they are examined separately. The first leg, from Vienna to Frankfurt, is assumed to be covered by the same plane as the route Vienna - Berlin was, the Airbus A320-200 from Austrian Airlines. Adjusting the distance leads to the result, displayed in Table 7.12.

Airbus A320-200 (Austrian Airlines) with 174 p

Vienna - Frankfurt		take off	climb	cruise	descent	approach	sum
Range	$[km]$	10	100	315	75	105	605
EC	$[kWh]$	7000	23000	5670	3000	3675	40905
SEC	$[kWh/km]$	700.00	230.00	40.00	40.00	35.00	
weighted SEC	$[kWh/km]$	11.57	38.02	9.37	4.96	6.07	69.99

Table 7.12: *Weighted specific energy consumption, Vienna - Frankfurt (Airbus A320-200)*

Compared to the results presented in Table 7.4, a pattern can be observed. If the flight distance grows (to 605 km, 15%), the energy heavy segments of the flight, like the take off and the climb to the travelling height, carry less weight. This leads to a weighted SEC of 69.99 kWh/km and further applying a relation to the occupation (70%, 100%) delivers 0.5746 kWh/pkm and 0.4023 $kWh/stkm$, which are lower, than the results on the route Vienna - Berlin.

The second leg, the way from Frankfurt to Tokyo, is separated into two parts, the distance from Frankfurt to Anchorage (7500 km) and from Anchorage to Tokyo (5500 km). Both are covered by the Boeing 787-9 by All Nippon Airways. The first part can be seen in Table 7.13.

Boeing 787-9 (All Nippon Airways) with 240 p

Frankfurt - Anchorage		take off	climb	cruise	descent	approach	sum
Range	$[km]$	10	100	7210	75	105	7500
EC	$[kWh]$	8982	29513	166533	3850	4716	213594
SEC	$[kWh/km]$	898.23	295.13	23.10	51.33	44.91	
weighted SEC	$[kWh/km]$	1.20	3.94	22.20	0.51	0.63	28.48

Table 7.13: *Weighted specific energy consumption, Frankfurt - Anchorage (Boeing 787-9)*

As seen before, long distances tend to shrink the weighted SEC. In this case 28.48 kWh/km, further an occupation of 70% and 100 % results in 0.1695 kWh/pkm and 0.1187 $kWh/stkm$, respectively.

The second part, Anchorage - Tokyo, the plane is assumed to be unchanged and presented in Table 7.14.

Boeing 787-9 (All Nippon Airways) with 240 p							
Anchorage - Tokyo		take off	climb	cruise	descent	approach	sum
Range	$[km]$	10	100	5210	75	105	5500
EC	$[kWh]$	8982	29513	166533	3850	4716	213594
SEC	$[kWh/km]$	898.23	295.13	21.88	51.33	44.91	
weighted SEC	$[kWh/km]$	1.63	5.37	21.88	0.70	0.68	30.44

Table 7.14: *Weighted specific energy consumption, Anchorage - Tokyo (Boeing 787-9)*

With a shorter flying distance than before, the weighted SEC is a bit higher, 30.44 kWh/km and with 70% and 100% capacity leads to 0.1812 kWh/pkm and 0.1268 $kWh/stkm$, which are higher as well, since the same plane was taken.

Weighing the results of the three segments delivers a overall SEC of 31.12 kWh/km and with an average occupation of 218, 0.2039 kWh/pkm and 0.1427 $kWh/stkm$.

Comparison

When putting the direct and the detour flight into perspective, it is to be expected for the longer way to have a way higher energy consumption. Table 7.15 present the accumulated energy consumption, as well as the needed energy over the whole energy conversions (32.85%), according to Table B.3 in Appendix B.2.

	Unit	Plane Route 1	Plane Route 2
code		red	orange
time	$[h]$	09:45	14:30
distance	$[km]$	9200	13605
weighted SEC	$[kWh/km]$	30.02	*variable*
Sum	$[kWh]$	276199	423338
Sum (η_C)	$[kWh]$	840763	1288660
avg. Occ	$[kWh/p]$	8143.77	12482.17
	$[kWh/pkm]$	0.8852	0.9175
70% Occ	$[kWh/p]$	3925.13	8444.69
	$[kWh/pkm]$	0.4266	0.6207
per Seat	$[kWh/st]$	2747.59	5911.28
	$[kWh/stkm]$	0.2987	0.4345

Table 7.15: *Needed energy for the travelling route: Vienna - Tokyo (note Figure 6.2)*

For the detour route, being a little less than 50% longer than the direct one (13605 km to 9200 km), about 50% more energy is needed, 1288.66 GWh to 840.76 GWh. Involving the rate of occupation in this calculation, rises the difference to 2.15 times, due to the lower capacity (304 to 218 seats), except for the average, and keeps the relation of slightly more than 50%. Further putting the distance into the ratio results in 0.4266 kWh/pkm and 0.6207 kWh/pkm for 70% occupation, moreover 0.2987 $kWh/stkm$ and 0.4345 $kWh/stkm$ for the maximum possible manning, for the shorter and longer flight, respectively. This leads to a 45% higher consumption per seat. Using the average leads to an approach of the values, which was expected, because of the linear relationship of the weighted *SEC* and the relation to the occupation and distance.

7.2.3 Economic Estimation

Like previously (note section **7.1.3-Vienna - Berlin/Economic Estimation**) explained, the costs for the business itself are provided. In addition the price[7] per kilometre for one person to travel the distance, as well as the revenue for the establishment are calculated.

	Unit	Plane Route 1	Plane Route 2
code		red	orange
time	$[h]$	09:45	14:30
distance	$[km]$	9200	13605
over LC	$[€/km]$	0.09	0.09
Cost	[€]	82071.57	121367.79
Price min	[€]	500.00	500.00
Price max	[€]	950.00	1800.00
Price per km	$[ct/km]$	7.88	8.45
avg. Revenue	[€]	74849.00	118726.00
70% Revenue	[€]	155295.00	175490.00
max. Revenue	[€]	221850.00	250700.00

Table 7.16: *Cost over the Life-Cycle, price and revenue for the travelling routes: Vienna - Tokyo (note Figure 6.2)*

By using the same values for the *LCC* leads to the same costs per kilometre for the planes travelling the routes and to overall costs of 82071.57 € and 121367.79 € for the direct and the roundabout flight, respectively. These are, just like the distance, 50% higher.

These higher costs have to be compensated somehow and when looking at the price, the longer flight has a higher maximum, nearly double, than the shorter one. Averaging the minimal and maximal price over the distance leads to results in close range to each other with 7.88 ct/km and 8.45 ct/km (only 7% more).

For an average occupation (note Table D.2), both flights suffer losses. About 9% and 2% for the direct and the detour flight. Only if the manning becomes higher, a profit is made, which in case of the direct route for 70% and full capacity is 1.9 and 2.7 times the costs, respectively. For the roundabout way they result in 1.4 and 2 times the costs, being lower the its counterpart, as one might expect.

7.3 Cruise Trip

This section examines the route, introduced in **6.1.3-Travelling Routes/Cruise Trip**, cruising the Mediterranean Sea. Using the results of Simonsen et al. (2018) lead to estimations needed to compare the trip regarding environmental, energetic and economic aspects.

[7] The prices were taken from January 2022 and March 2022, for the direct and detour flight

7.3.1 Environmental Estimation

The mean consumption for the cruise ship, separated for port and sea, since the average utilization is different for these two consumption profiles, are estimated to 2302 kg/h and 3526 kg/h for the *AIDAblu*. Using the *Emission-Factor* of 3.1 kg/l for HFO, calculated in **3.1.2-Environmental View/Fuels** (note Table 3.2), leads to the burned fuel and expelled CO_2 emissions, as displayed in Table 7.17.

Day	Port	time at Port [h]	time at sea [h]	fuel burned at Port [kg]	fuel burned at sea [kg]	CO_2 released at Port [t]	CO_2 released at sea [t]
	Rome (Italy)	-	2	-	7053	-	21.84
1	*at sea*	-	24	-	84630	-	262.07
2	Valletta (Malta)	11	13	25524	45841	79.04	141.96
3	Catania (Sicily)	10	14	23204	49368	71.85	152.88
4	Palermo (Sicily)	9	15	20883	52894	64.67	163.80
5	Naples (Italy)	10	14	23204	49368	71.85	152.88
6	Olbia (Sardinia)	9	15	20883	52894	64.67	163.80
7	Rome (Italy)	-	5	-	17631	-	54.60
sum		49	102	113698	359678	352.09	1113.81

Table 7.17: *Burned fuel and CO_2-emissions for the cruise trip of the AIDAblu in the Mediterranean Sea (note Figure 6.3)*

For a duration of 49 h at port 113.70 t fuel are burned for hotelling functions on board, without even moving the ship, while releasing 352.09 t CO_2 into the air. During the travel from port to port, a total of 102 h are spent at sea, burning 359.68 t of fuel and releasing 1113.81 t CO_2. As explained previously in **6.2.1-Calculation Information/Environmental Part**, including the indirect emissions, raises the overall amount about 4%. Further, the emissions occurring in the ports are added to the others, raising the overall exhausted gasses about 31%, and related to their occupation and distance to gain the results contained in Table 7.22. Moreover, to obtain the CO_{2e} about 2% are added, according to the relation, seen in Table A.6.

Occupation	direct Emission [$kgCO_2/p$]	direct Emission [gCO_2/pkm]	Overall GHGs [$kgCO_{2e}/p$]	Overall GHGs [gCO_{2e}/pkm]
70%	725.23	319.48	1002.59	441.67
100%	507.66	223.64	701.81	309.17

Table 7.18: *Emissions for the cruise trip per person and kilometre of the AIDAblu in the Mediterranean Sea (note Figure 6.3)*

For a rate of occupation of 70% and 100% (this could be considered as every 'seat' from the previous examples), the released CO_2 purely during the cruise segment results in 725.23 $kgCO_2/p$ and 507.66 $kgCO_2/p$ for the trip, respectively. Further relating these to the distance (2270 km) leads to 319.48 gCO_2/pkm and 223.64 gCO_2/pkm.

Incorporation the emissions in port and the other released gasses to gain the CO_{2e} results in 1002.59 $kgCO_{2e}/p$ and 701.81 $kgCO_{2e}/p$ for 70% and maximum capacity, moreover 441.67 gCO_{2e}/pkm and 309.17 gCO_{2e}/pkm normalized by the distance.

7.3.2 Energetic Estimation

Following the same pattern as before, two separated energy consumptions, the one at port and the other at sea, are estimated to an average of 8750 kWh/h and 16250 kWh/h (note Table B.12). Further using the calculated energy conversions for the whole chain(36.65%) as seen in Table B.3. The results can be seen in Table 7.19.

Day	Port	time at Port [h]	time at sea [h]	energy consumed at Port [kWh]	energy consumed at sea [kWh]	energy needed at Port [kWh]	energy needed at sea [kWh]
	Rome (Italy)	-	2	-	32500	-	88670
1	*at sea*	-	24	-	390000	-	1064039
2	Valletta (Malta)	11	13	96250	211250	262599	576355
3	Catania (Sicily)	10	14	87500	227500	238727	620690
4	Palermo (Sicily)	9	15	78750	243750	214854	665025
5	Naples (Italy)	10	14	87500	227500	238727	520690
6	Olbia (Sardinia)	9	15	78750	243750	214854	665025
7	Rome (Italy)	-	5	-	81250	-	221675
sum		49	102	428750	1657500	1169761	4522167

Table 7.19: *Consumed and needed energy for the cruise trip of the AIDAblu in the Mediterranean Sea (note Figure 6.3)*

During the accumulated 49 h stay at port 428750 kWh are consumed for hotelling functions on board, resulting in a needed energy of 1169761 kWh. While travelling form one destination to the other, spending an overall time of 102 h at sea, 1657500 kWh are consumed, corresponding to 4522167 kWh of needed energy. Overall 5691928 kWh are needed in total for the whole 7 days. Relating the consumed and needed energy to the occupation and the covered distance leads to the results shown in Table 7.20.

Occupation	Energy Consumed at Port [kWh/p]	Energy Consumed at sea [kWh/p]	Energy Consumed at sea [kWh/pkm]	Overall Energy Needed [kWh/p]	Overall Energy Needed [kWh/pkm]
70%	279.17	1079.24	0.475	3706.17	1.633
100%	195.42	755.47	0.333	2594.32	1.143

Table 7.20: *Consumed and needed energy per person and kilometre for the cruise trip of the AIDAblu in the Mediterranean Sea (note Figure 6.3)*

With an occupation of 70% and 100%, the consumed energy at port is 279.17 kWh/p and 195.42 kWh/p for hotelling functions, at sea 1079.24 kWh/p and 755.47 kWh/p are consumed. For the cruise alone (excluding the port), related to the distance, 0.475 kWh/pkm and 0.333 kWh/pkm needed.

Adding the values of port and at sea together and applying the conversion efficiency, lead to 3706.17 kWh/p and 2594.32 kWh/p for 70% and maximum capacity, respectively. Further relating these results to the covered distance result in 1.633 kWh/pkm and 1.143 kWh/pkm.

7.3.3 Economic Estimation

Again, like in section **7.1.3-Vienna - Berlin/Economic Estimation** before, the occurring costs for the business, using the already ascertained LCC (note Table C.1), are calculated. The price per person[8] for the whole trip is computed, as well as the potential revenue, which is presented in Table 7.21.

Cost [€]	Price [€]	avg. Revenue [€]	max. Revenue [€]
1261326.07	898.00	1379148.40	1970212.00

Table 7.21: *Cost over the Life-Cycle, price and revenue for the cruise trip of the AIDAblu in the Mediterranean Sea (note Figure 6.3)*

The overall costs add up to 1261326.07 € an with a price of 898.00 €, the average revenue (70% capacity, as assumed for the LCC) is 1379148.40 € and the maximum possible revenue 1970212.00 €. For average (70%) and full capacity the revenue is 1.09 and 1.56 times the costs, respectively, meaning profit is made with an occupation rate of 64%, or 1405 passengers.

Occupation	Cost		Price	
	[€/p]	[ct/pkm]	[€/p]	[ct/pkm]
70%	821.28	36.18	1282.86	56.51
100%	574.90	25.33	898.00	39.56

Table 7.22: *Cost for the business and price for the cruise trip per person and kilometre of the AIDAblu in the Mediterranean Sea (note Figure 6.3)*

Having a manning of 70% and 100% the costs amount to 821.28 €/p and 574.90 €/p, being 1.56 times lower than the price, with 1282.98 €/p and 898.00 €/p, respectively. Moreover relating them to the covered cruise distance leads to 36.18 ct/pkm and 25.33 ct/pkm, which is obviously the same result for the average capacity as previously calculated and shown in Table C.1), for the costs and 56.51 ct/pkm and 39.56 ct/pkm for the price.

[8]The price is per cabin, accessed February 2022

CHAPTER 8

Discussion

This chapter provides a discussion of the used tools, general results and the various case studies presented in this thesis. Since there is no documentation uniting environmental, energetic and economic aspects into one, it was challenging to reconcile them for the examined vehicles.

For the environmental part, I mainly looked at the CO_2 emissions, which originate form combustion and a calculation with the *combustion equation* (on molar levels) for fuels, and further the CO_{2e} (CO_2-*equivalent*) which incorporate all other released *GHGs*, such as Methane, Nitrous Oxides and Hydro-Fluorocarbons, declared by the Kyoto Protocol in 1997 was presented. Moreover, emissions not only emerge during operation, but in the course of the production as well. For this reason, the *Well-To-Wheels*-Emissions were chosen (similar to an *Life-Cycle Assessment*), because they can be separated into the emissions appearing during the operation, called direct emissions or *Tank-To-Wheel* emissions, and the emissions occurring during production, called indirect emissions or *Well-To-Tank* emissions. In this particular case only an exemplary calculation was done, since the basic information for nearly every vehicle would have to be guessed, consequently making all the results very uncertain. To bypass this problem the official data from the Federal Environmental Agency of Austria was taken to gain a maximum of comparability (Emi (2021)).

It is a similar case for the energetic part, where the origin of the energy is of high importance. All starting with the first form of energy, a mostly impractical form for the needs of human society, the raw energy or *Primary Energy*, like (crude) oil first need to be reformed, in this instance refined, to become something applicable for our engines in the transport sector. In this context gasoline, diesel, kerosene and HFO, is the next stage in the conversion of energies, called secondary energy or *Final Energy*. Nevertheless, this is not the final stage, as the secondary form has to be used in a way to, for example, move the vehicle, leading to the ultimately desired kind (here: motion energy), called *Net Energy*. This is not the only way to move wheeled transportation, since electrically driven vehicles are nowadays used as well and gain even more popularity, due to continuous debates considering the environmental issues. The factor of the energy source (raw energy form) is most convincing, reason to the different *efficiencies* of the individual conversions, as for example a power plant burning coal to gain electric energy has a worse efficiency than a the ones burning natural gas. Adding up all conversions lead to *Energy Chains*, which are separable in *Well-To-Tank* and *Tank-To-Wheel* efficiency, thus making the comparison meaningful. For instance, the refining process from oil to a fuel is considered 'short' and more efficient than the one to gain electricity, but the electrical engine is compensating for this with an excellent effectiveness compared to a combustion engine. Edwards et al. (2014), who analysed the pathways of various energy-forms was of immense help in this part.

Very little documentation was found for the economic part. Finally the *Life-Cycle Costs* were chosen to gain comparable results, starting with general separation into *Capital-* and *Annual Costs*, like admission insurance, repair & replacement and operation. Using the LCC delivers the costs of the whole duration of an objects lifespan, projected to the day of the purchase, incorporating interest and inflation needed for the future values. Most problematic posed the variability of the vehicles and their prices and the uncertainty of the annual costs. Almost all initial prices were estimated to be as realistically as possible based on list prices and various other sources. For the annual expenditure the car was used as baseline to estimate the costs for the other vehicles, relative to their purchase price. Thus making the results reasonable, but vague down to the very core. This method proves its usefulness even more for reliable parameters of official documents.

Using the touristical aspect as baseline for the examination of the vehicles leads of the following transport modes: *car*, *bus* for conventional combustion engines, *trains* as alternative, since they are (mostly) driven by electrical engines, *planes* using turbines, a variety of combustion and a *cruise vessel* powered by a generator and driven by electricity. The grave difference between these transportation is that car, bus, train and plane are used to cover distances from small to large ranges and the cruise ship is the adventure itself, making the travelled distance secondary (and convenient).

Except for private vehicles, where various engine technologies are prominently used (gasoline, diesel engine and further electric and hydrogen vehicles), but having nearly the same baseline and therefore are on equal footing, every other transportation varies greatly in almost every aspect. Hence bringing them on a similar ground is a necessity. This is done applying the before mentioned CO_{2e}, due to the difference in the used fuel and their composition and in the case of the plane the travelling altitude. Comparing the presented results with other reports, leads to compliant results, due to the nature of the data. Since they are officially published or the estimated values are based on these values (in the case of Cucinotta et al. (2021) and Chatzinikolaou and Ventikos (2014) for cruise vessels) a precise comparison is unrewarding and will not be separately listed. Only in the case of trains, insight is gained examining the report by de Bortoli et al. (2020), with the conclusion that the needed infrastructure (rail-network) for trains is a carbon heavy undertaking.

A comparison between the vehicles, as shown in **5.1.1-Comparison/Environmental View**, is conducted with a relation to their respective average occupation. Vehicles with higher occupation fare better in this comparison, leading to the understanding that the public transportation, like bus and (electricity driven) train, outclass the private vehicles by far, as they only expel about a fifth to 1/30 of emissions, respectively. Without the *IPCC* recommended *RFI-Factor* even planes would do better in an environmental context, but incorporating it makes it the means of transportation with the highest carbon footprint than any other presented transportation, exhausting about 8 times more than a bus and 50 times more than a train. While cruise vessels are in the same range as cars, it has to be noted again that these results are related to the average occupation, the case studies go into further detail and could ultimately give more insight.
Taking a sole look at the conversion chains, like done in **5.1.2-Comparison/Energetic View** is not favourable for conventional driven vehicles, meaning combustion engines and turbines, and especially the gasoline engine perform poorly compared to the others, where the generally

low efficiency of these engine types (TtW-Efficiency) is mainly responsible. On the other hand is the refining process to gain the fuels needed for each conventional vehicle relatively high (WtT-Efficiency), which were nearly perfected over time. Contrary to this, trains have very efficient electrical engines but heavily depending on the the different energy sources, symbolized by the origins *Coal*, *Natural Gasses* and *Renewables* solely to show the dependency. These are further analysed using a mixture of the energies in the respective countries in the case study and the needed energy to move the corresponding vehicle, which was left unregarded until this point was incorporated.
A look at the vehicles from a businesses point of view and using the LCC to calculate the costs for the 'owner' is presented in **5.1.3-Comparison/Economic View** and public and private vehicles are compared in two ways. Firstly, they are compared to each other, leading to similar results for each vehicle due to the fact that the car is used as baseline for the annual costs. The varying durations of the lifetime and the subsequent differences in interest and inflation were accounted for. The high operational costs for buses, which apply to private businesses and could be less for public institutions were compared, the very little fuel costs for train, plane and cruise ship, or the lack of admission costs for trains and plans, due to missing information. Another assumption are the short service intervals of planes, due to safety reasons in the case of planes. Secondly, comparing the overall costs and further relating them to their average occupation, yearly covered distance and average lifespan leads to the conclusion that the public transport modes are the most economic, what one might have expected. On the contrary, private vehicles are more expensive being in the same range as cruise vessels.

The first case study, introduced in **6.1.1-Travelling Routes/Vienna - Berlin**, examines various vehicles (two different routes for the train, bus, car and two planes, for the energetic) and the subsequent variation of the taken routes for the same starting and endpoint. Again, as described the general analysis and when using the same values as in the general part, the emissions as well as the needed energy depend heavily on the rate of occupation. Since it is difficult to estimate the average occupation in a touristical context, 70% and the maximum capacity are assumed. This leads to the knowledge, that the public vehicles exhaust nearly the same amount of GHGs, cars release about twice as much and planes 10 times more.
The energetic view leads to nearly the same results, with the energy mixes in the countries travelled through and an estimation for the energy consumption of planes according to the phases of the flight, with train, bus and car needing nearly the same and 1/10 of the examined planes. Although the planes chosen are different in size and based on this need more energy for the flight, the occupation rate equalizes the otherwise very different vehicles.
To evaluate the costs, the LCC described in the general part is applied on the distance, further ticket prices are used from the official businesses and the resulting revenue is calculated, according to the occupation (excluding the private vehicles). The system of ticket prices is more or less the same for the public transportation, if one buys the ticket early (early-bird or 'ÖBB Sparschine') the price is cheaper in general. In the case of planes, it further depends on the day of purchase.

In the second case, **6.1.2-Travelling Routes/Vienna - Tokyo**, two routes were introduced, a direct flight and a roundabout flight, considering the conflict between the Ukraine and Russia (started 24th February; ongoing as of March 2022). The emissions are linearly dependent on the travelled route and with a 1.47 times longer way to go, 1.47 times more GHGs are expelled. Only the occupation influences the results of the routes, because the maximum capacity is different.
This is contrary to the energetic aspect, since the direct flight is covered by a single plane and the roundabout flight by two (or three) planes separating the route into two (or three) parts. Due to the longer flight-distance the weighted energy consumption is lower than the one calculated for

the first case study. The total weighted consumption for the longer flight is lower than one might expect. But the occupation rate dissociates the results by far.
Higher costs arise due to the longer flight duration, subsequently to this higher prices for tickets have to be set, mostly to compensate the greater expenses.

The third and final case examines a round trip done by a cruise vessel, introduced in **6.1.3-Travelling Routes/Cruise Trip**. Since fuel is consumed not only during the travel from port to port, but at the stay itself, a separation is undertaken. Nevertheless, more fuel is burned when travelling, about thrice as much. Due to the linear connection between fuel and GHGs, while at sea 3 times more emissions are exhausted.
This properties are similar for the energy, in port and at sea energy is needed. Again, the required energy travelling is higher than the one in port by about 4 times. This relation remains valid for the needed energy before the chain of conversions.
For the economic part only the price for the cabin was taken into account. The results showed that at least a certain rate of occupation needs to be met to make it lucrative and generate a profit. Further costs for the landing of the ship in a port were unheeded. Moreover, from a passenger point of view, entertainment and every other product, such as food is not included in the price of the cabin. This rises the costs for the traveller.

After all of this, what transport mode should be taken, what would be the best solution?
A benefit of the private vehicles is, that it is only in motion if necessary. Every other (public) vehicle is covering distances even if one is not on-board, or if the rate of occupation is lower than average, thus pushing their relatively good carbon footprint down. Further it is mostly dependent on other decisive factors, for example when a (large) distance is covered, one could drive at a time when the traffic is sparse, which makes the car more environmentally acceptable. Moreover, with public transportation a schedule is present which should be adhered to. So everything stands and falls with the occupation, since the costs for cars (that are mostly operational) can be shared in accordance to the travellers.

Although, if the distance is too long for a private vehicle, it will become very inconvenient (considering foreign lands in case of affliction). As presented in the second case study (Vienna - Tokyo), only a plane is a viable option. These surpasses every other transport mode in every category (environmental, energetic and economic).

The factor *time* was not considered in the case studies. The majority of humans behave like the electric current and tend to use the way of the least resistance, which makes them perceive the shortest route as the most attractive one. Especially for medium to longer distances, the chances are very high one will take the shortest time needed to travel to the desired destination, due to the convenience a decrease in time brings. Looking back at the first case study illustrates this perfectly. Taking a flight (only considering the travelled time) takes 1:15 h and in comparison taking a train takes 8:45 h (or 9:45 h for the other route), prolonging the time spent to get to the destination at least 7 fold. Even taking the car usually is faster than the train (assuming a lack of traffic jams), with the additional advantage of freedom to go anywhere at any time.
Further time is limited, especially in the context of vacations. If one needs 2 days to travel to the destination and then back as well the faster means of transportation will be preferred, even if it is more expensive.

Except for the overall duration, the downtime one has if a change of transport mode is perceived as a bothersome segment of the travel. This mostly concerns trains and planes, in contrast trains are mostly affected less then the counterpart in the air. This could be solved by providing more frequent transportation, so the schedule is of lesser importance.

Problematic for this aspect is the opposing nature of having more transportations available to shorten latency between eventual changes to make public travel more attractive is problematic as the rate of occupation makes travel most efficient and shrinks the carbon footprint.

Moreover, a flight is in most cases cheaper than a train, due to budget airlines and spontaneous offers. Going by car, with the possibility to share the operational costs (price for fuel), makes it ultimately the most economic transportation. This leads to the second important aspect, aside from time, is the *financial* factor for a travelling person.

This factor is even more important than the prior one, due to different financial situations depending on the traveller. The promotion of public travel in a economic sense can either be done by making it cheaper, or the private vehicles (to travel with) more expensive.
Sooner or later the fuel prices for the private transport will rise, considering the ongoing conflict in eastern Europe this could happen in the near future. Further, the prices for Kerosene are really low, due to the lack of taxation of the fuel, thus making flight tickets relatively cheap. Other forms of transportation, or to be more precise other energy forms to propel the vehicle may produce relief with regards to prices.

The alternatives presented in **5.2-Alternative Drives** could be a solution for these problems. Since the private vehicle is most prominent and the least expensive transport mode (excluding the cruise vessel), if shared, an alternative for conventional engine technologies, could provide viable. Most of the technology is already present, but still rare and not widely spread, thus making them pricey. *EVs* from today's perspective can be considered the most promising, with the biggest downside being the possible range, the subsequent charging, which takes a lot of time (or consume more energy in case of quick-charge stations) and the geographic positioning of the charging-stations.
Hydrogen driven vehicles, operating via a *Fuel Cell*, are also a possible choice with the same direct emission like EVs, namely zero, and about double indirect emissions, depending on the method of *H2* production. On one hand the energetic aspect and on the other hand, however, prove problematic the economic aspect. Due to the long energy chains, most of the production methods are relatively inefficient compared to the pure electric counterpart. The engine, or more widespread the FC, have about the same efficiency as the conventional engines and about the same range to travel. The price-tag of the *H2-Vs* is considerable, being about double the price of an EV, which is in turn about 20% more expensive than a conventional. Most of the infrastructure is already present, although not in its final form. Petrol stations could undergo a transformation, since Hydrogen needs to be treated a bit more carefully than electricity of other fuels, since it is highly flammable.
In consideration of the infrastructure I would promote *E-Fuels* as best alternative. Since these synthetic fuels are made to have the same properties as Gasoline and Diesel, the engines and petrol stations would stay the same. Carbon out of the air, or expelled by other industrial businesses could be captured, stored and further used to bind them with Hydrogen to gain these fuels. Although they would expel about the same amount as the proven fuels the carbon would be in balance. Energetically E-Fuels are even worse than for the H2-Vs, since Hydrogen has to be generated and further bound with carbons.

All of these alternatives are heavily dependent on the origin of the energy, just like in the case of trains. This means, that their carbon footprint is only acceptable if the source is low on emissions as well, even though their GHGs released during production are higher than the ones of conventional vehicles with gasoline or diesel engines. Clearly renewable energies could fulfil this criteria, and although the availability remains questionable, the costs for them shrunk in the last decade to a third (for wind energy) to a tenth (for solar energy) of it is original price, thus making them a contestant for the established energy sources (especially coal). Another technology to come into question could be nuclear fusion, which uses a similar process like the sun in our solar system, which releases immense quantities of energy with relatively little 'combustible' material. Whilst this technology is known since 1950 it is still not ready to go into mass production. Power plants are already under construction, most prominently in the *USA* and *France*. With this 'overproduction' of energy all of the alternatives could prove viable, making it reasonable to expect a mixture of them, or even other technologies, which have not been considered yet. It is also to be expected, that already proven technologies are getting more efficient with ongoing time.

In summary, one may say money is the most driving factor to change, meaning the alternatives should have the same, or even a bit higher, costs than the established transportation, or making the proven technologies many times more expensive, could also force a change.
These two different approaches have actually already been implemented. The countries of northern Europe applied the strategy years ago to make the alternatives more attractive than the conventionals, which started years ago. While *Austria* is planning on banning the selling of combustion engines starting 2030, with most of the *EU* following 2035 - 2040, the northern countries do as well, but having around 8 out of 10 new registrations for cars being electrically driven vehicles an easier endeavour. These numbers are relatively high, due to the funding from the countries governments, like paying a bonus or excluding the tax when buying an EV. Further the infrastructure in these countries is very good, with high availability of charging stations, consequently making the decision to use a vehicle with an alternative drive easier.

All in all, a change is needed and coming, but the alternatives should be promoted to motivate people to change and not force them. Similar to the renewable technologies wind and solar, it is to expect a analogical development and subsequent drop of the costs in the near future. Making the alternatives cheaper motivates more people to do so by investing in them, which spreads the technology and reduces the price, thus motivates more people to choose them.

Since money has the power to move people it could be applied to transportation in tourism as well, to lead passengers to use more environmental friendly means. Applying the same method and subsidizing trains would shrink ticket prices, thus making them more attractive. This could be done by providing good offers, cheap ticket prices or paying a bonus at the end of the year if the vacation was taken using vehicles with a smaller carbon footprint than the conventionals (at the tax equalization). The most important would aspect is to raise awareness that there are more factors than money which play a part in travel and mobility in general.

All of these assumptions are based on the results calculated in this thesis. Due to the taken liberties, provided by the chosen estimations (especially for the economic part), it could be of interest to further examine each part.
The environmental part was evaluated using the official parameters from the *Federal Environmental Agency of Austria*, which leaves the exact parameters out, but is sufficient for this case. Trying to calculate all of these yourself could lead to even more inaccuracy overall. Moreover not only emissions for the direct and production process could be calculated, but the GHGs related to energy supply as well.
For the energetic part it is a similar situation. Although the report was officially published by the *European Commission* it may be a bit outdated, since progress does not sleep. Taking more precise values would lead to more exact results, but the general scheme of it would stay unchanged.
In the economic part the most liberties were taken. Basing all annual costs on private vehicles and further relating these on their purchase price incorporates some kind of inaccuracy. While

working on this thesis the prices for fuel changed multiple times (the prices from January 2022 were taken), making the combustion engine driven vehicles more expensive than calculated.

Most publications in this field of work link environmental and energetic aspects together, but further combining them with economic aspects is relatively rare if not existent, due to the difficulty of linking these principles together. This challenge is the reason this thesis may be one of the first of its kind. Although no straight answer can be given in this thesis, it lays the groundwork for possible future papers, with its comprehensible methods to calculate meaningful data and the detailed case studies. Further works could specify the used vehicles more, especially for the economic parts, or restrict the examination to fewer vehicles.

In a touristical outline the most environmentally friendly, most efficient and most economic to this date would be not to have a vacation at all, but this is obviously out of the question. Due to the relevancy of this topic, I was already involved and interested in this subject before this thesis began and gained the conclusion, that the quantity makes the poison and finding the perfect balance amongst these cornerstones is the challenge in itself. Although ultimately every person chooses for oneself, asking the question: How much are you willing to pay?

CHAPTER 9

Conclusion

The usage of transportation in tourism is a natural behaviour of man. A general separation into the major factors is reasonable. Them being the environmental, energetic and economic aspect, further divided by the vehicles taken.

With the diesel driven car, the most common private vehicle in Austria, as baseline the *Well-To-Wheel Emissions* (combined emission) show, for an average rate of occupation, that gasoline cars exhaust 1.06 times, cruise vessels 1.13 times, planes 1.85 times more. On the other side of the spectrum are buses and train, releasing 4.36 and 26.34 times less than the diesel vehicle.

Looking at the conversions from raw energy to (a fixed) motion energy, accumulated in the *Energy-Chain*, and using the diesel car as baseline and an average occupation again leads to the results, in which gasoline driven cars need 1.19 times more and the plane about the same energy. Showing the importance of the energy origin, with coal, Natural Gasses and renewables, trains require 1.14, 1.62 and 2.73 times less energy, respectively. Further buses and cruise ships demand 1.14 and 1.26 times fewer energy.

Using the *Life-Cycle Costs*, which incorporate the purchase price and the annual costs over the lifetime, projected to the present day, result, with the average occupation and further relating them to the yearly distance and the diesel as base, in gasoline cars being 1.35 and cruise vessels 1.28 times more expensive per kilometre. Train, bus and plane are 7, 5.6 and 3.1 times cheaper.

With battery powered *EVs* having zero emissions during operation and *H2-Vs*, utilizing hydrogen through a FC with water and electric energy as result, possible alternatives are already present. Compared to diesel driven cars, these alternatives indirectly 'release', in the best case, 3.81 and 2.67 times less GHGs. Further they require 1.98 and 1.51 times less energy in the optimal case. Moreover are they 1.11 and 2.08 times more expensive.

Comparing (diesel) car, bus trains and planes on various routes from *Vienna to Berlin*, with maximum capacity, result in the plane expelling 4.81 times more emissions than the car. Further exhaust train and bus, 2.01 (1.78, depending on the route) and 2.35 times less GHGs per kilometre. Moreover demand diesel cars 1.44 (1.56), 1.63 and 10.51 (10.35, depending on the plane) times less energy than train, bus and plane, respectively. For the costs are train and plane 1.48 (1.16) and 1.63 times more expensive per kilometre than the car. Only buses are 1.15 times cheaper.

On the intercontinental flight from *Vienna to Tokyo*, with a direct (shorter) route and a roundabout way, 1.40 times more emissions are released, related to the capacity and kilometre. Further needs the longer route 2.15 times more energy and costs 1.07 times more than the shorter one.

During the *Cruise Trip* in the Mediterranean Sea 3.09 times more GHGs are expelled while at sea than at port (on board functions consuming fuel), further is 3.86 times more energy required. With an occupation of 70% instead of 100% leads to 1.43 times higher costs per kilometre.

APPENDIX A

Environmental Additions

A.1 Fuels

A.1.1 Molar Calculation

According to the chemical formula, the weight (note Table 3.1) can be calculated (Gasoline as example, $n = 8$):

$$C_nH_{2(n+1)} = n \cdot C + 2(n+1) \cdot H = \big(8 \cdot 1 + 18 \cdot 12\big)g = 114g \tag{A.1}$$

Applying the combustion equation (Formula 3.4), the expelled Carbon-Dioxide is calculated:

$$CO_2 = n\big(C + 2 \cdot O\big) = 8\big(44\big)g = 352g \tag{A.2}$$

Using the density ρ (Staffell (2011)) and Formulae A.1 and A.2, the exhausted Carbon-Dioxide (factor) results in:

$$CO_2' = \rho \cdot \frac{n \cdot CO_2}{C_nH_{2(n+1)}} = 0.74kg/l \frac{352g}{144g} = 2.28kg/l \tag{A.3}$$

Calculating the relative share of carbon (and hydrogen) is done by following equation:

$$\%C = n \cdot \frac{C}{C_nH_{2(n+1)}} = 8mole \frac{12g/mole}{114g} = 0.842 \tag{A.4}$$

Table A.1 presents the calculated density, mass after combustion, relative C and H parts and the released CO_2 from the chemical formula, using the combustion equation according to formula 3.4,

Gasoline				**Kerosene**			
Mole [1]	Chem. Formula	[g]	Density [kg/l]	Mole [1]	Chem. Formula	[g]	Density [kg/l]
8	C_8H_{18}	114	0.74	14	$C_{14}H_{30}$	198	0.80
after combustion [g]	%C	%H	ejected CO_2 [kg/l]	after combustion [g]	%C	%H	ejected CO_2 [kg/l]
352	0.842	0.158	2.28	616	0.848	0.152	2.49

Diesel				**HFO**			
Mole [1]	Chem. Formula	[g]	Density [kg/l]	Mole [1]	Chem. Formula	[g]	Density [kg/l]
16	$C_{16}H_{34}$	226	0.85	30	$C_{30}H_{62}$	442	0.99
after combustion [g]	%C	%H	ejected CO_2 [kg/l]	after combustion [g]	%C	%H	ejected CO_2 [kg/l]
704	0.850	0.150	2.65	1320	0.853	0.147	3.10

Table A.1: *Calculated CO_2 from the chemical formula using the combustion equation*

for the used fuels. The amount of substance (Mole) for *Kerosene* and *HFO* are assumed, using the knowledge of Kerosene being heavier than Gasoline but lighter than Diesel and HFO being the heaviest suitable fuel for combustion[1].

A.1.2 Components HFO

According to Garaniya and Goldsworthy (2011), HFO analysed with the *SARA*-breakdown[2], consisting of the components shown in Table A.2

	SARA Weight	*Elemental* %C	%H	%S	%N	Sum
Saturates	24.08	85.32	13.17	0.48	0.05	99.02
Aromatics	55.81	83.83	9.92	4.28	0.20	98.23
Resins	6.66	80.03	10.55	2.78	0.82	94.18
Asphaltenes	7.86	83.49	8.03	7.07	0.75	99.34
Rest	5.59	85.17	9.16	4.42	0.24	98.99

Table A.2: *Components of HFO (Garaniya and Goldsworthy (2011))*

A.2 Exemplary Emission Calculation

To calculate the indirect emissions from vehicles (or other things - the LCA can be applied to every produced good), one starts with the raw materials. In this example, a VW Golf is

[1]only oil used as lubricants are heavier and denser
[2]SARA - Saturates, Aromatics, Resins and Asphaltenes fractions

the benchmark. Mainly consisting of steel (45%) and aluminium (15%), synthetic materials (15%), iron (5%), glass (2%) and various other components[3]. According to Fritz et al. (2016), depending on the energy sources the average emission factor for a diesel driven car (including engine) ranges between 2.9 and 8.5 $kgCO_{2e}/kg$ for the vehicle, for the best and worst case, respectively. For the similar car, driven by electric energy, following factors[4] have been discovered by Fritz et al. (2016): for the car a range of 2.7 - 7.0 $kgCO_{2e}/kg$, the electric engine 1.7 - 4.6 $kgCO_{2e}/kWh$, the powertrain about 42 $kgCO_{2e}/kg$ and the battery 48.8 - 94.9 $kgCO_{2e}/kWh$.

	diesel Golf	*electric Golf*	*Unit*
Car	7.0	6.0	$kgCO_{2e}/kg$
Battery	-	85	$kgCO_{2e}/kWh$
Powertrain	-	42	$kgCO_{2e}/kg$
Engine	-	4.5	$kgCO_{2e}/kWh$

Table A.3: *Emission-Factor for Golf diesel and electric (David et al. (2021))*

Entering the calculation with the emission factors, contained in Table A.3 results, for the vehicle with a weight of $1600kg$, as well as 30kg powertrain and $32kWh$ for the electric variant, in total to 11.2 and 14.1 $kgCO_{2e}$, respectively, which are the indirect Emissions. For the calculation of the direct Emission, an average consumption of $4.5l/100km$ for the diesel and 15 $kWh/100km$ for the electric vehicle, with an mean exhausted CO_2 of 2.65 for diesel, per combusted l. The electric, depending on the source[5] releases 220, 450, 50 per kWh, for the Austrian, German and $UZ46$ consumption.

Golf	*diesel*	*electric*	*Unit*
Weight	1600	1600	kg
Capacity	-	36	kWh
Car	11200	9600	$kgCO_{2e}$
Battery	-	3060	$kgCO_{2e}$
Powertrain	-	1260	$kgCO_{2e}$
Engine	-	162	$kgCO_{2e}$
Production	11200	14082	$kgCO_{2e}$

Table A.4: *Emissions released during production of a VW Golf (indirect Emission - WtT)*

Golf	*diesel*	$electric_{Aut}$	$electric_{Ger}$	$electric_{UZ46}$	*Unit*
Consumption	4.5	15	15	15	$l, kWh/100km$
CO_2-factor	2.65	220	475	50	$kg/l, kWh$
avg. Cons	0.119	0.033	0.071	0.008	$kgCO_2/km$

Table A.5: *Direct emissions of a VW Golf (diesel and electric - TtW)*

The detailed results are presented in Table A.4 (indirect Emission) and Table A.5 (direct Emission).

[3]like: rubber, copper, liquids, electronic components, coatings, etc.
[4]split into car, engine, powertrain and battery
[5]the Parameters are taken from Ele (2022), corresponding to the average CO_2-Emissions (observation period of the last February week, including imports) - accessed 28.02.2022

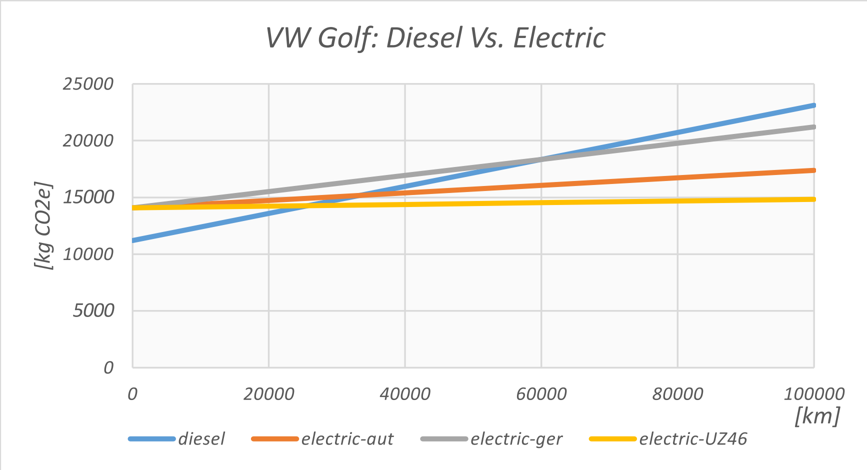

Figure A.1: *Comparison of WtW-Emissions over runtime of a VW Golf: diesel and electric*

Figure A.1 presents the comparison of diesel and electric vehicle. Even though the E-Golf releases about 20% more GHGs during its production, depending on the energy origin they break even after about 30000, 60000 and 25000km. With median yearly driven distance for cars of about 15000km, the break even point will be reached after about 2, 4 and under 2 years, respectively.

A.3 Well-To-Wheel

In Table A.7, the parameters for multiple vehicles are presented, with their respective Units (g/km), which corresponds to the values from the official Site of the Federal Environment Agency[6], multiplied by their rate of occupation, seen in Table D.2. While, the TtW-emissions describe the exhausted amount during the operation, the WtT-emissions contain the production, energy supply and disposal of the transport mode. Furthermore, Table A.6 presents the direct emission according to Gilbert et al. (2017) (using Low-Sulphur HFO), the indirect emissions, estimated using the data from Chatzinikolaou and Ventikos (2014) and their combination (note Formula 3.16), with an estimated consumption of 625 kWh/km.

		CO_{2e}	CO_2	CO	CH_4	N_2O	SO_x	NO_x	PM
TtW	$[g/kWh]$	549.650	541.000	1.618	0.010	0.027	3.230	15.800	0.720
WtT	$[g/kWh]$	46.650	20.941	0.667	0.003	0.083	0.063	48.394	0.016
WtW	$[g/kWh]$	596.300	561.941	2.285	0.013	0.110	3.293	64.194	0.736

Table A.6: *Emissions of cruise vessels (etimated using Gilbert et al. (2017) and Chatzinikolaou and Ventikos (2014))*

Table A.8 presents the emissions of all introduced vehicles, normalized using the average occupation, according to Table D.2. The parameters for FCV were estimated, using the values from the official Site of the Federal Environment Agency (note Table A.7) and the ones determined by Pötscher et al. (2014).

[6] Emi (2021)

	direct Emission (TtW)				indirect Emission (WtT)				combined Emission (WtW)			
	CO_{2e}	CO_2 [g/pkm]	NO_x	PM	CO_{2e}	CO_2 [g/pkm]	NO_x	PM	CO_{2e}	CO_2 [g/pkm]	NO_x	PM
Car_{Gas}	166.44	165.98	0.114	0.002	92.23	84.70	0.171	0.030	258.67	250.69	0.285	0.032
Car_{Diesel}	170.32	167.58	0.844	0.011	73.76	66.35	0.137	0.023	244.07	233.93	0.980	0.034
EV_{Mix}	-	-	-	-	99.86	93.82	0.148	0.019	99.86	93.82	0.148	0.019
EV_{UZ46}	-	-	-	-	56.20	51.87	0.103	0.018	56.20	51.87	0.103	0.018
Bus_{Nat}	837.05	827.64	2.069	0.038	282.15	253.94	0.564	0.075	1119.20	1081.58	2.633	0.113
Bus_{Int}	680.92	671.52	2.069	0.038	242.65	216.32	0.376	0.056	923.57	887.83	2.445	0.094
$Train$	1209.78	1182.29	8.249	0.550	2227.10	962.33	2.750	0.275	3436.88	2144.61	10.998	0.825
$Plane_{Nat}$	25144.02	9227.94	34.711	3.245	2076.99	1989.51	3.669	0.480	27221.01	11217.45	38.379	3.725
$Plane_{Int}$	37999.13	13959.08	72.975	4.796	3148.35	3012.83	6.255	0.730	41147.48	16971.90	79.230	5.525
$Plane_{N+I}$	37744.54	13865.13	71.236	4.749	3117.85	2993.96	6.194	0.723	40862.39	16859.09	77.430	5.472

Table A.7: *Emissions of car, bus, train and plane per kilometre (based on Emi (2021))*

	direct Emission (TtW)				indirect Emission (WtT)				combined Emission (WtW)			
	CO_{2e}	CO_2 [g/pkm]	NO_x	PM	CO_{2e}	CO_2 [g/pkm]	NO_x	PM	CO_{2e}	CO_2 [g/pkm]	NO_x	PM
Car_{Gas}	146.0	145.6	0.10	0.002	80.9	74.3	0.15	0.026	226.9	219.9	0.25	0.028
Car_{Diesel}	149.4	147.0	0.74	0.010	64.7	58.2	0.12	0.020	214.1	205.2	0.86	0.030
EV_{Mix}	-	-	-	-	87.6	82.3	0.13	0.017	87.6	82.3	0.13	0.017
EV_{UZ46}	-	-	-	-	49.3	45.5	0.09	0.016	49.3	45.5	0.09	0.016
$H2_{BzEl,Mix}$	-	-	-	-	140.2	131.7	0.201	0.024	140.2	131.7	0.20	0.024
$H2_{BzEl,UZ46}$	-	-	-	-	80.1	73.9	0.133	0.019	80.1	73.9	0.13	0.019
$H2_{BzGr}$	-	-	-	-	113.7	106.9	0.083	0.020	113.7	106.9	0.08	0.020
Bus_{Int}	36.2	35.7	0.11	0.002	12.9	11.5	0.02	0.003	49.1	47.2	0.13	0.005
$Train$	4.4	4.3	0.03	0.002	8.1	3.5	0.01	0.001	12.5	7.8	0.04	0.003
$Plane_{N+I}$	365.6	134.3	0.69	0.046	30.2	29.0	0.06	0.007	395.8	163.3	0.75	0.053
$Cruise-Ship$	223.7	220.2	6.43	0.293	19.0	8.5	0.07	0.006	242.7	228.7	6.50	0.299

Table A.8: *Emissions of Car (gas, diesel, EV, H2), Bus, Train, Plane and Cruise Ship normalized by the average occupation (Fritz et al. (2016), Pötscher et al. (2014) and Emi (2021))*

A.4 Estimated Fuel Consumption and Emissions

Simonsen et al. (2018) describe a method to estimate fuel consumption for ships, which fails with larger vessels as examination object. Knowing this, another simplified approach is taken using their benchmark, the *MS Finnmarken*. The following Table A contains the mean consumption and the estimation for the *AIDAblu*, for the complete Table note Appendix B.5.

	$[kW]$	Port $[kg/h]$	Sea $[kg/h]$
MS Finnmarken	8280	537	993
AIDAblu	25000	2302	3526

Table A.9: *Fuel consumption of MS Finnmarken Simonsen et al. (2018) and the estimation for the AIDAblu*

With the *Emission-Factor* of 3.1 kg/l from Table A.1, the expelled emissions per hour are gained ($[CO_2/h]$).

A.5 Estimated Emissions for Plane and Cruise Ship related to Cars

Using the (directly) released CO_2 from Table A.7 and the yearly covered distance from Table D.3 for a car, further a flight[7] from Vienna to Tokyo (9200 km) and a cruise trip in the Mediterranean Sea, starting and ending in Rome (duration of 7 days), leads to following results, presented in Table A.10.

Car_{Gas} $[kgCO_2/a]$	$Plane$ $[tCO_2/flight]$	$Cruise-Ship$ $[tCO_2/trip]$
1710	128.42	1465.89

Table A.10: *Estimated emission for gasoline driven cars per year, plane per flight and cruise ship per trip*

Relating these to the car delivers the information, that one flight exhausts as much as *75 cars* and on cruise trip *857 cars* in one year, respectively. Figure A.2 presents these results.

[7]These are the pure emitted CO_2 amounts, excluding the RFI-Factor

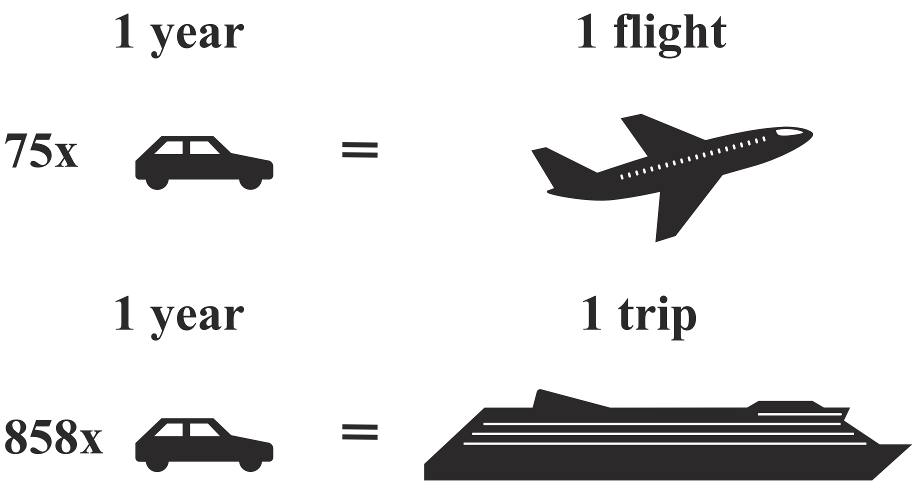

Figure A.2: *Annual released CO_2 emissions of gasoline cars vs. 1 plane flight / 1 cruise trip*

APPENDIX B

Energetic Additions

B.1 Energy Value

Calculation the specific energy value is done in following steps (Gasoline as example).

$$H_i = 44\frac{MJ}{kg} = \frac{44000}{3600}\frac{kWh}{kg} = 12.22kWh/kg \tag{B.1}$$

which corresponds to 81.82 g/kWh (H_i'). Using a typical parameter for η (efficiency, note Table B.2), the specific value is gained:

$$H_s = \frac{H_i'}{\eta} = \frac{81.82g/kWh}{0.30} = 272.73g/kWh \tag{B.2}$$

All energy values, efficiency and specific energy values for fuels are contained in B.2 and for Hydrogen in Table B.1.

Hydrogen

	Fuel Value		η	spec. Value
$[MJ/kg]$	$[kWh/kg]$	$[g/kWh]$	%	$[g/kWh]$
120	33.33	30.00	55	54.55

Table B.1: *Energy value of hydrogen (Staffell (2011))*

Gasoline

	Fuel Value		η	spec. Value
$[MJ/kg]$	$[kWh/kg]$	$[g/kWh]$	%	$[g/kWh]$
44	12.22	81.82	30	272.73

Kerosene

	Fuel Value		η	spec. Value
$[MJ/kg]$	$[kWh/kg]$	$[g/kWh]$	%	$[g/kWh]$
43.5	12.08	82.76	40	206.90

Diesel

	Fuel Value		η	spec. Value
$[MJ/kg]$	$[kWh/kg]$	$[g/kWh]$	%	$[g/kWh]$
42.5	11.81	84.71	35	242.02

HFO

	Fuel Value		η	spec. Value
$[MJ/kg]$	$[kWh/kg]$	$[g/kWh]$	%	$[g/kWh]$
41	11.39	87.80	45	195.12

Table B.2: *Energy value of conventional fuels (Staffell (2011))*

B.2 Energy-Chains

Shown in Table B.3 are all examined pathways from raw material to motion energy, estimated using the official European Report by Edwards et al. (2014) and the *Hydrogen Center Austria*[1]. Displayed are the different forms of:

- extraction: such as mining coal, extracting natural-gases or (raw) oil
- refining[2]: for gasoline, diesel, kerosene and HFO
- conversion: mainly to generate electrical energy (difference in efficiency for power-plants) or the gas reformation for hydrogen
- transport: of fuels via truck or electricity over the (inter-/national) grids
- generation: using a fuel powered generator to generate electrical energy (in case of cruise-ships)
- charging: efficiency to charge EVs
- electrolysis: to gain hydrogen using electrical energy
- transport: incorporation the transport of hydrogen, as well as the necessary storage (e.g. compressed)
- engine/FC: depending on the operation point, the efficiency varies (especially for plane-turbines)

[1]http://www.hycenta.at/, accessed March 2022

[2]in a sense, that every gained type of fuel, has a different efficiency (more energy is needed to obtain Gasoline than Diesel)

	WtT									*TtW*	*WtW*	
	Extraction	Refining	Conversion	Transport	Generation	Charging	Electrolysis	Transport	Sum	Engine/FC	Sum	for $10kWh$
Car_{Gas}	95%	90%	-	95%	-	-	-	-	81.23%	30%	24.37%	41.04
Car_{Diesel}	95%	92%	-	95%	-	-	-	-	83.03%	35%	29.06%	34.41
EV_{Coal}	91%	-	45%	90%	-	90%	-	-	33.17%	75%	24.88%	40.20
EV_{NG}	97%	-	60%	90%	-	90%	-	-	47.14%	75%	35.36%	28.28
EV_{UZ46}	-	-	98%	90%	-	90%	-	-	79.38%	75%	59.54%	16.80
$H2_{BzEl,NG}$	97%	-	60%	90%	-	-	70%	75%	27.50%	60%	16.50%	60.61
$H2_{BzEl,UZ46}$	-	-	98%	90%	-	-	70%	75%	46.31%	60%	27.78%	35.99
$H2_{Bz,Gr}$	97%	-	80%	95%	-	-	-	-	73.72%	60%	44.23%	22.61
Bus	95%	92%	-	95%	-	-	-	-	83.03%	40%	33.21%	30.11
$Train_{Coal}$	91%	-	45%	90%	-	-	-	-	36.86%	90%	33.17%	30.15
$Train_{NG}$	97%	-	60%	90%	-	-	-	-	52.38%	90%	47.14%	21.21
$Train_{UZ46}$	-	-	98%	90%	-	-	-	-	88.20%	90%	79.38%	12.60
$Plane$	95%	91%	-	95%	-	-	-	-	82.13%	40%	32.85%	30.44
$Cruise - Ship$	95%	95%	-	95%	45%	-	-	-	38.58%	95%	36.65%	27.28

Table B.3: *Estimated Energy-Chains for all examined vehicles, including their conversions (using Edwards et al. (2014))*

B.3 European-Mix and their weighted Efficiencies

B.3.1 Austrian Mix

Austria generates its energy mostly from renewables (55% of the overall need), and the rest are thermal power-plants. This accumulates to about 75% of the needed energy, with the rest being imported from neighbouring countries (2/3 from Germany, 1/3 from the Czech Republic according to Ele (2022)). Following the statistics of Urbantschitsch and Haber (2021), the Austrian-Energy Mix from 2018 to 2020 can be seen in Table B.4.

	Inland-Generation [GWh]						
Year	Hydro	Thermal	Wind, PV	Other	sum	Import	Overall Need
2018	41184	19899	7569	46	68698	28076	96774
2019	44206	20960	9137	15	74318	26047	100365
2020	45380	18328	8850	308	72866	24523	97389

Table B.4: *Austrian-Energy Mix from 2018 to 2020 (Urbantschitsch and Haber (2021))*

Including the share of generation[3], leads to weighted *Energy-Chains* η_C, as seen in Table B.5.

2020	E [GWh]	share	Extraction	Refining	Conversion	η_C	η_w
run-of-river	30693	42.12%	-	-	75%	75%	31.59%
pumped-storage	14688	20.16%	-	-	90%	90%	18.14%
NG	10010	13.74%	97%	-	60%	58%	8,00%
Coal	2346	3.22%	91%	-	45%	41%	1.32%
Oil	610	0.84%	95%	95%	60%	54%	0.45%
other	790	1.08%	95%	-	60%	57%	0.62%
BC[4]	4572	6,27%	-	-	60%	60%	3.76%
Wind	6792	9.32%	-	-	45%	45%	4.19%
PV	2058	2.82%	-	-	98%	98%	2.77%

Table B.5: *Share of Austrian-Energy Generation (Edwards et al. (2014) and estimations)*

Using Formula 3.8, leads to the weighted efficiency of Austria (for 2020):

$$\eta_w = \frac{\sum_{n=1}^{m} \eta_n \cdot w_n}{\sum_{n=1}^{m} w_n} = 71.15\% \qquad \text{(B.3)}$$

B.3.2 German Mix

Applying the same algorithms like before, the German-Energy Generation[5] as seen in Table B.6 and share[6] in Table B.7 are used to gain the needed efficiencies.

[3] https://oesterreichsenergie.at/downloads/grafiken/detailseite/bruttostromerzeugung-in-oesterreich-1, accessed March 2022

[5] https://www.umweltbundesamt.de/sites/default/files/medien/384/bilder/3_abb_bruttostromerzeugung-et_2022-01-17.png, accessed March 2022

[6] https://www.umweltbundesamt.de/sites/default/files/medien/384/bilder/4_abb_stromerzeugung-ee_2021-12-02.jpg, accessed March 2022

Inland-Generation $[TWh]$				
Year	Renewables	Thermal	Others	Sum
2021	237	326	22	585

Table B.6: *German-Energy Mix from 2021*

This leads to an overall weighted efficiency of $\eta_w = 53.02\%$, with the assumption of no energy trade, meaning pure self supply.

2021	E $[TWh]$	share	Extraction	Refining	Conversion	η_C	η_w
Hydro	17	2.96%	-	-	75%	75%	2.22%
PV	46	7.90%	-	-	98%	98%	7.74%
Wind	126	21.39%	-	-	45%	45%	9.63%
Others	48	8.26%	-	-	60%	60%	4.96%
Nuclear	69	11.79%	90%	90%	60%	49%	5.73%
NG	89	15.21%	97%	-	60%	58%	8.85%
Coal (brown)	108	18.46%	91%	-	45%	41%	7.56%
Coal (stone)	54	9.23%	91%	-	45%	41%	3.78%
Oil	6	1.03%	95%	95%	60%	54%	0.56%

Table B.7: *Share of German-Energy Generation (Edwards et al. (2014) and estimations)*

B.3.3 Czech Mix

With the generation and share[7] Table B.8 and Table B.9 are gained.

Inland-Generation $[TWh]$				
Year	Renewables	Thermal	Others	Sum
2021	7.5	70.1	0.2	77.8

Table B.8: *Czech-Energy Mix from 2021*

Under the assumption of pure self supply, the weighted overall efficiency is $\eta_w = 49.66\%$.

B.4 Estimated Energy Consumption for Planes

The values for the specific energy consumption are estimated using Chiara et al. (2017), who calculated a flight from *Milan - Naples* (168 persons), and Martin (2021) for a more precise view in the phases of the flight, them being:

- take off (including the initial climb)
- climb
- cruise

[7] https://de.statista.com/statistik/daten/studie/182188/umfrage/struktur-der-bruttostromerzeugung-in-der-tschechischen-republik/, accessed March 2022

2021	E $[TWh]$	share	Extraction	Refining	Conversion	η_C	η_w
PV	2.1	2.7%	-	-	98%	98%	2.65%
run-of-river	1.2	1.5%	-	-	75%	75%	1.13%
pumped-storage	1.2	1.6%	-	-	90%	90%	1.44%
Wind	0.6	0.8%	-	-	45%	45%	0.36%
others	2.3	3.0%	-	-	60%	60%	1.80%
Nuclear	29.1	37.4%	90%	90%	60%	49%	18.18%
Coal (brown)	27.8	35.7	91%	-	45%	41%	14.62%
Coal (stone)	2.6	3.3%	91%	-	45%	41%	1.35%
NG	6.0	7.7%	97%	-	60%	58%	4.48%
BC	2.5	3.2%	-	-	60%	60%	1.92%
others	2.2	2.8%	95%	-	60%	57%	1.60%

Table B.9: *Share of Czech-Energy Generation (Edwards et al. (2014) and estimations)*

- descent
- approach (including the landing)

		Milan - Naples				650 km	168 p
		take off	climb	cruise	descent	approach	sum
Fuel	$[kg]$	380.3	1872.2	552.6	241.1	287.4	3333.6
EC	$[kWh]$	4571.3	22504.5	6642.4	2898.1	3454.6	40071.0
share	11,41%	56,16%	16,58%	7,23%	8,62%	100,00%	

Table B.10: *Burned Fuel and Energy-Consumption for the Route: Milan - Naples (Chiara et al. (2017))*

Using a relative share of the phases of the flight and the values for the consumed energy from Table B.10, leads to the Table B.11 (energy consumption weighted on the distance), with the estimated *Energy-Consumption* for every phase.

		Phase of Flight				
		take off	climb	cruise	descent	approach
share of time		1%	15%	57%	11%	16%
distance	$[km]$	6.5	97.5	370.5	71.5	104
Energy Cons.	$[kWh/km]$	703.28	230.82	17.93	40.53	33.22
estimated EC	$[kWh/km]$	700	230	18	40	35

Table B.11: *Energy-Consumption during the Phases of the Flight (Milan - Naples, Chiara et al. (2017), Martin (2021))*

The consumption for every phase of flight for planes with higher capacities is estimated using Chiara et al. (2017) and based on the number of passengers. The relation will be to following:

- Airbus A320-200 to Airbus A321-111: 1.133 times more
- Airbus A321-111 to Boeing 787-9: 1.133 times more
- Airbus A320-200 to Boeing 777-200ER: 1.404 times more

For longer distances, only the cruise is changed, every other parameter is kept the same.

B.5 Estimated Energy Consumption for Cruise Ships

Using the same approach for this section, Simonsen et al. (2018) is the benchmark again (note Appendix A.4). The ratio between power and consumed energy is calculated for the MS Finnmarken to estimate it for the AIDAblu, further the burned fuel to consumed energy is calculated.

			Port		Sea	
	$[kW]$	PAX	$[kWh/h]$	$[kg/h]$	$[kWh/h]$	$[kg/h]$
MS Finnmarken	8280	1000	2025	537	4575	993
AIDAblu	25000	2194	8750	2302	16250	3526

Table B.12: *Fuel and energy consumption of MS Finnmarken Simonsen et al. (2018) and the estimation for the AIDAblu*

APPENDIX C

Economic Additions

C.1 Further Information

Table C.1 shows the parameters used for the Life-Cycle Costs and their normalization by occupation, distance per year and lifetime (note Table D.3. The values denoted in *Percent* are in relation to the *Purchase Price*, except inflation f, interest i and real interest i_r, with:

- *Primary (purchase) Price*:
  Collected from various (credible) sources (mostly list prices) and estimated for each vehicle.
- *Insurance*:
  According to the official UNIQA-Insurance calculation[1], the insurance costs for a standard car ranges from 3% to 7% in Austria[2]. The others were estimated based on this information.
- *Maintenance*:
  Estimation, based on cars as well.
- *Repair & Replacement*:
  Estimation, based on the rarity of the components.
- *Admission*:
  In Austria, a yearly inspection to make sure the car is roadworthy. This was estimated for Buses and Ships as well. No information could be obtained, whether this is present for trains and planes, so they were ignored.
- *Operation*:
  The operational costs were calculated, using the current fuel prices[4], an estimated consumption[4] and their yearly covered distance (note Appendix D.1.3)

[1]https://www.uniqa.at/versicherung/kfz/uebersicht.html, accessed January 2022, including the relevant engine-power fee

[2]The standard car is, as with the Emission, a VW Golf sized car. The insurance range from the (cheapest) indemnity insurance to the (most expensive) comprehensive cover insurance, respectively.

[4]The current prices (January 2022) are Gasoline: 1,40€/l; Diesel: 1,38€/l; Kerosene: 0,338€/l; HFO: 350€/t; Energy Price: 0,25€/kWh; H2: 9,50€/kg

[4]Estimated consumption: Gasoline: $7l/100km$; Diesel: $6l/100km$; Kerosene: $3l/100km$ per PAX; HFO: $20t/100km$; Energy (EV, Train): $15kWh/100km$; H2: $1kg/10km$

	Car_{Gas}	Car_{Diesel}	$H2$	EV	Bus	$Train$	$Plane$	$Cruise - Ship$
i	6%	6%	6%	6%	6%	7%	7%	7%
f	2%	2%	2%	2%	2%	3%	3%	3%
$Insurance$	5%	5%	2%	4,5%	2,5%	2%	1%	2%
$Maintanance$	5%	5%	3,5%	7,5%	5%	2,5%	5%	2,5%
$R\&R$	2%	2%	5%	5%	2%	2%	2,5%	2,5%
$Admission$	165€	170€	100€	100€	2%	-	-	1%
$Operation$	1009€	1391€	1416€	559€	22548€	2813€	2114190€	3812844€
C_I	1000€	1160€	1200€	1125€	6250€	240000€	2000000€	7000000€
C_M	1000€	1160€	2100€	1875€	12500€	300000€	10000000€	8750000€
$C_{R\&R}$	400€	464€	3000€	1250€	5000€	240000€	5000000€	8750000€
C_A	165€	170€	100€	100€	5000€	-	-	3500000€
C_O	1009€	1391€	1416€	559€	22548€	2813€	2114190€	3812844€
$years$	12	12	12	12	20	30	30	30
i_r	3,92%	3,92%	3,92%	3,92%	3,92%	3,88%	3,88%	3,88%
i'	9,43	9,43	9,43	9,43	13,69	17,54	17,54	17,54
C_C	20000€	23200€	60000€	25000€	250000€	12000000€	200000000€	350000000€
C'_I	9428€	10936€	11314€	10606€	85533€	4209430€	35078583€	122775039€
C'_M	9428€	10936€	19799€	17677€	171065€	5261787€	175392913€	153468799€
$C'_{R\&R}$	3771€	4375€	28284€	11785€	68426€	4209430€	87696457€	153468799€
C'_A	1556€	1603€	943€	943€	68426€	-	-	61387520€
C'_O	9517€	13115€	13345€	5268€	308575€	49329€	37081394€	66874582€
C_{ann}	33699€	40965€	73684€	46279€	702025€	13729976€	335249347€	557974738€
Sum	53699€	64165€	133684€	71279€	952025€	25729976€	535249347€	907974738€
$avg.Occ.$	1.14	1.14	1.14	1.14	18.81	274.95	103.24	1535.8
km/a	10300	16800	14900	14900	55200	75000	2000000	54469.2
Average	0.38€$/km$	0.28$/km$	0.66$/km$	0.35$/km$	0.05$/km$	0.04$/km$	0.09$/km$	0.36$/km$

Table C.1: *Estimated Life-Cycle Cost and their average for the examined Vehicles*

	Car_{Gas}	Car_{Diesel}	$H2$	EV	Bus	$Train$	$Plane$	$Cruise-Ship$
C_C	37,24%	36,16%	44,88%	35,07%	26,26%	46,64%	37,37%	38,55%
C'_I	17,56%	17,04%	8,46%	14,88%	8,98%	16,36%	6,55%	13,52%
C'_M	17,56%	17,04%	14,81%	24,80%	17,97%	20,45%	32,77%	16,90%
$C'_{R\&R}$	7,02%	6,82%	21,16%	16,53%	7,19%	16,36%	16,38%	16,90%
C'_A	2,90%	2,50%	0,71%	1,32%	7,19%	-	-	6,76%
C'_O	17,72%	20,44%	9,98%	7,39%	32,41%	0,19%	6,93%	7,37%
C'_Y	62,76%	63,84%	55,12%	64,93%	73,74%	53,36%	62,63%	61,45%

Table C.2: *Relative Life-Cycle Cost (note C.1)*

APPENDIX D

Vehicles

D.1 Further Information

D.1.1 Key Data

Table D.1 presents information regarding the vehicles presented in Table A.7. With further information being:

- Direct Emission/Data taken from the air-pollutant inventory 2020
- Indirect Emission taken from Database GEMIS[1]
- due to recommendation from IPCC, a Radiative Forcing Index-Factor of 2.7 was considered
- PM (Particular Matter) $< 10\ \mu$m, exclusive tyre, break and raised dust

D.1.2 Rate of Occupation

Additionally, a rate of occupation[2] can be seen in Table D.2. Furthermore, following assumptions were made for the maximum occupation (possible):

- every car has the same average occupation
- one-storey bus: 32 persons; double-decker Bus: 57 persons
- train: common Railjet from the ÖBB, depending the number of carriages: 404 - 442 persons
- national plane: Airbus A320, 174 persons; Airbus A321, 200 persons
- international Plane: Boeing 767-300ER, 200 - 350 persons
- cruise ship: AIDAblu, 2194 persons

[1]'Globales Emissions-Modell integrierter Systeme', a database containing information regarding: pollutants, GHGs, efficiency, utilization, durability, various resources

[2]taken from the official Site of the Federal Environment Agency: Emi (2021)

Vehicle	*Description*
Car_{Gas}	for cars of standard size (Size of VW Golf and similiar cars); average over all engine sizes; date of build: 2019; consumption: 7,8 $l/100km$; duration 15 years, mileage: 10300 km
Car_{Diesel}	for cars of standard size (Size of VW Golf and similar cars); average over all engine sizes; date of build: 2019; consumption: 7,0 $l/100km$; duration 15 years, mileage: 16800 km
EV_{Mix}	for cars of standard size (Size of VW Golf and similiar cars); date of build: 2019; consumption: 21 $kWh/100km$; duration 15 years, 45 kWh Li-Ion-Battery; Austrian Energy-Mix; mileage: 14900 km
EV_{UZ46}	for cars of standard size (Size of VW Golf and similiar cars); date of build: 2019; consumption: 21 $kWh/100km$; duration 15 years, 45 kWh Li-Ion-Battery; Energy deployment according to directive $UZ46$; mileage: 14900 km
Bus_{Nat}	average traffic (highway, urban, suburban, city); including electric engine (hybrid); consumption Diesel: 33 $l/100km$; consumption Energy: 1,74 $kWh/100km$; duration 15 years, mileage: 56000 km
Bus_{Int}	average taffic (highway, urban, suburban, city); consumption Diesel: 29,6 $l/100km$; duration 15 years, mileage: 55200 km
$Train$	seperation: 19% Diesel, 81% electric; Austrian Energy-Mix
$Plane_{Nat}$	short-term flight: 18t; fuel: kerosene; duration: 30 years; 'mileage': 2000000 km; propeller-driven aircrafts are excluded
$Plane_{Int}$	long-term flight: 40t; fuel: kerosene; duration: 30 years; 'mileage': 2000000 km; propeller-driven aircrafts are excluded

Table D.1: *Information regarding the vehicles presented in Table A.7 (Emi (2021))*

	Occupation		
Vehicle	*average*	*max.*	*relative*
Car	1.14	5	22.8%
Bus_{Nat}	18.81	44.5	42.3%
Bus_{Int}	18.81	44.5	42.3%
$Train$	274.95	423	65.3%
$Plane_{Nat}$	28.22	160	17.6%
$Plane_{Int}$	104.25	320.5	32.5%
$Plane_{N+I}$	103.24	320.5	32.2%
$Cruise-Ship$	1535.8	2194	70.0%

Table D.2: *Information regarding the vehicles presented in Table A.8 (Emi (2021) and estimation)*

D.1.3 Covered Distance and Lifetime

Table D.3 contains the yearly covered distance[3], and an estimated lifetime.

[3]same source as for Table A.7 and an estimated 24 trips per year (of similar length) for the cruise ship á 2270 km

Vehicle	*Yearly covered distance*	*average lifetime*
Car_{Gas}	10300	12
Car_{Diesel}	16800	12
$Car_{EV,H2}$	14900	12
Bus_{Int}	55200	20
$Train$	75000	30
$Plane_{N+I}$	2000000	30
$Cruise - Ship$	54469.2	30

Table D.3: *Yearly covered distance and lifetime of every examined vehicle (Emi (2021) and estimation)*

D.1.4 Share of Vehicles in Austria

As one might expect, the biggest share of private vehicles are fossil based[4]. Figure D.1 presents this, while the rest contains around 1.7% hybrid and 1% pure electric cars.

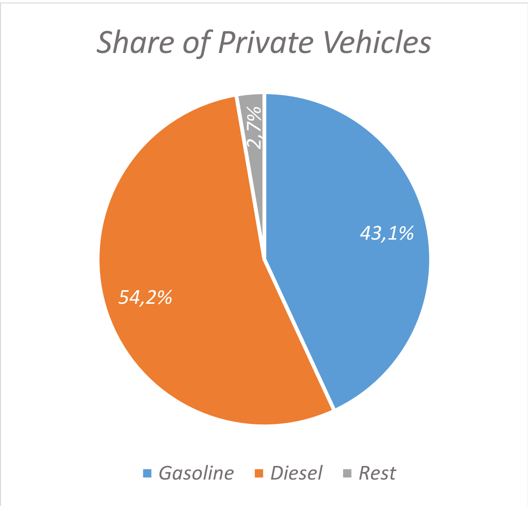

Figure D.1: *Share of Private Vehicles in Austria*

[4]https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/verkehr/strasse/kraftfahrzeuge_-_bestand/index.html, accessed February 2022

APPENDIX E

Tourism

E.1 Further Information

E.1.1 Austria

Vacations

Table E.1 presents the number of vacations Austrians took in 2019 and 2020, also shown in Figure 2.1.

	2019		*2020*	
	Million	%	Million	%
Vacations	21.2		12.62	
inland	11.13	52.5%	9.34	74%
short	9.18	43.3%	6.31	50%
long	1.95	9.2%	3.03	24%
outland	10.07	47.5%	3.28	26%
short	3.71	17.5%	1.39	11%
long	6.36	30.0%	1.89	15%

Table E.1: *Vacations of Austrians in 2019 and 2020 (2020: Wurian (2021); 2019: estimated)*

Destinations

Table E.2 contains the favourite destinations of Austrians in 2019 and 2020, displayed in Figure 2.2.

Vehicles

Table E.3 shows the share of vehicles Austrians took to go on vacation in 2019 and 2020.

Destination	%	2019 Million	2020 Million
Germany	23.5%	4.98	2.97
Italy	21.9%	4.64	2.76
Croatia	7.1%	1.51	0.90
Hungary	5.6%	1.19	0.71
Spain	3.6%	0.76	0.45
Slovenia	3.4%	0.72	0.43
Slovakia	3.0%	0.64	0.38
Switzerland	2.9%	0.61	0.37
Czech Rep.	2.9%	0.61	0.37
France	2.7%	0.57	0.34
Rest (Europe)	17.8%	3.77	2.25
Europe	94.4%	20.01	11.91
Africa	1.6%	0.34	0.20
America	1.2%	0.25	0.15
Asia	2.5%	0.53	0.32
Rest	0.3%	0.06	0.04

Table E.2: *Destinations of Austrians in 2019 and 2020 (Wurian (2021))*

Vehicle	%	%
Car	53%	72%
Plane	31%	13%
Train	8%	10%
Bus	5%	2%
Rest	3%	3%

Table E.3: *Vehicles Austrians took to travel in 2019 and 2020 (Wurian (2021))*

E.1.2 Europe

Table contains the data, vacations as well as transport modes of all members of the EU, as well as the United Kingdom from 2017 (Data from 2020 is present, but was discarded, due to them being incomplete).

	Vacation					*Transportation*						
	overall	inland		outland		by Land	Car	Train	Bus	Rest	by Plane	by Ship
	Million	Million	%	Million	%	%	%	%	%	%	%	%
Vacations	1255	919,92	73,3%	335,09	26,7%	80,9%	63,5%	10,8%	5,5%	1,1%	17,4%	1,7%
Belgium	15,2	3,06	20,1%	12,14	79,9%	65,9%	55,6%	6,6%	3,4%	0,3%	33,3%	0,8%
Bulgaria	5,5	4,74	86,1%	0,76	13,9%	95,3%	76,8%	2,2%	16,2%	0,1%	4,7%	0,0%
Czech Rep.	35,8	29,03	81,1%	6,77	18,9%	94,3%	79,4%	6,3%	8,2%	0,4%	5,6%	0,1%
Denmark	26,5	18,87	71,2%	7,63	28,8%	76,1%	60,0%	8,8%	5,2%	2,1%	21,9%	2,0%
Germany	243,6	151,28	62,1%	92,32	37,9%	79,7%	57,4%	14,4%	5,9%	2,0%	18,9%	1,4%
Estonia	4,6	3,31	71,9%	1,29	28,1%	81,8%	61,6%	4,5%	15,2%	0,5%	13,0%	5,2%
Ireland	14,6	7,59	52,0%	7,01	48,0%	55,4%	48,7%	3,3%	2,9%	0,5%	42,6%	2,0%
Greek	6,2	5,48	88,4%	0,72	11,6%	67,9%	58,7%	1,1%	8,0%	0,1%	15,3%	16,8%
Spain	152,7	138,35	90,6%	14,35	9,4%	88,6%	77,0%	5,7%	5,6%	0,3%	10,4%	1,0%
France	220,8	192,32	87,1%	28,48	12,9%	89,2%	71,7%	14,6%	2,4%	0,5%	10,2%	0,6%
Croatia	4,9	2,97	60,7%	1,93	39,3%	90,6%	70,0%	1,5%	18,7%	0,4%	8,4%	1,0%
Italy	56,4	55,16	97,8%	1,24	2,2%	77,7%	58,4%	11,0%	5,4%	2,9%	20,3%	2,0%
Cyprus	2,8	1,39	49,8%	1,41	50,2%	49,8%	48,0%	-	1,6%	0,2%	49,4%	0,8%
Latvia	4,2	2,94	69,9%	1,26	30,1%	84,8%	66,9%	3,7%	14,0%	0,2%	13,0%	2,2%
Lithuania	4,5	2,49	55,4%	2,01	44,6%	75,7%	60,3%	2,8%	10,7%	1,9%	23,1%	1,2%
Luxembourg	1,8	0,03	1,7%	1,77	98,3%	58,2%	47,8%	6,7%	2,9%	0,8%	41,8%	0,0%
Hungary	18,6	12,11	65,1%	6,49	34,9%	90,5%	75,7%	6,9%	7,4%	0,5%	9,5%	0,0%
Malta	0,8	0,26	32,3%	0,54	67,7%	-	-	-	-	-	63,2%	36,8%
Netherlands	45,1	24,31	53,9%	20,79	46,1%	76,4%	63,5%	8,4%	2,2%	2,3%	22,7%	0,9%
Austria	23,1	11,60	50,2%	11,50	49,8%	81,5%	62,0%	11,2%	6,3%	2,0%	18,3%	0,2%
Poland	57,9	45,97	79,4%	11,93	20,6%	88,6%	67,0%	7,4%	14,0%	0,2%	11,0%	0,4%
Portugal	17,5	15,58	89,0%	1,93	11,0%	89,0%	79,9%	3,3%	4,6%	1,2%	10,5%	0,5%
Romania	17,9	16,83	94,0%	1,07	6,0%	96,5%	66,7%	10,1%	19,2%	0,5%	2,8%	0,7%
Slovenia	4,8	1,80	37,6%	3,00	62,4%	92,0%	85,1%	1,3%	5,3%	0,3%	7,8%	0,2%
Slovakia	10,9	7,05	64,7%	3,85	35,3%	89,3%	67,4%	11,9%	9,8%	0,2%	10,7%	0,0%
Finland	39,5	30,14	76,3%	9,36	23,7%	75,7%	59,7%	9,2%	6,7%	0,1%	15,4%	8,9%
Sweden	59,7	38,45	64,4%	21,25	35,6%	67,5%	51,5%	11,1%	3,2%	1,7%	28,9%	3,6%
UK	159,4	107,12	67,2%	52,28	32,8%	67,3%	50,0%	13,0%	3,8%	0,5%	29,6%	3,1%
Norway	23,3	15,12	64,9%	8,18	35,1%	56,3%	47,0%	5,1%	2,7%	1,5%	40,8%	2,9%
Switzerland	22,1	6,78	30,7%	15,32	69,3%	68,9%	50,0%	-	2,9%	16,0%	30,6%	0,5%

Table E.4: *Vacation and transportation of the EU-27 and the United Kingdom in 2017 (Palen and Dimitrakopoulou (2019))*

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List of Abbrevations

WtT	Well-To-Tank
TtW	Tank-To-Wheel
WtW	Well-To-Wheel
EC	Energy-Chain (Energy-Conversion)
LCA	Life-Cycle Assessment (Analysis)
LCC	Life-Cycle Cost
HFO	Heavy Fuel Oil
LNG	Liquid Natural Gasses
NG	Natural Gasses
GHG	Green-House Gas
GWP	Global Warming Potential
EC	Energy Consumption
SEC	Specific Energy Consumption
EV	Electric Vehicle
FC	Fuel Cell
FCV	Fuel Cell Vehicle
HST	High-Speed Train
ICE	Inter-City Express
TVG	Train à Grande Vitesse
FEA	Federal Environmental Agency
IPCC	Intergovernmental Panel on Climate Change
RFI	Radiative Force Index (commonly 2.7)

List of Symbols

C	Carbon
H	Hydrogen
O	Oxygen
n	Amount of Substance (Mole)
ρ	Density

CO	Carbon-Monoxide
CO_2	Carbon-Dioxide
CO_{2e}	Carbon-Dioxide-Equivalent
CH_4	Methane
HFC	Hydro-Fluorocarbons
H_2O	Water
NO_x	Nitrous Gases
N_2	Nitrogen
N_2O	Nitrous Oxide
PM	Particular Matter
SO_x	Sulphur Gases

C_nH_n	Alkynes
C_nH_{2n}	Alkenes
$C_nH_{2(n+1)}$	Alkanes

r	Rate of Occupation
s	Distance
t	Lifespan

E_{in}	Energy-Input
E_{out}	Energy-Output
$\eta_{(C)}$	Efficiency (of the Chain)

A_F	Future Amount
A_P	Present Amount
C_C	Capital Cost (primary purchase price)
$C_A^{(')}$	Admission Cost (projected)
$C_I^{(')}$	Insurance Cost (projected)
$C_M^{(')}$	Maintenance Cost (projected)
$C_O^{(')}$	Operational Cost (projected)
$C_{R\&R}^{(')}$	Repair & Replacement Cost (projected)
$C_R^{(')}$	Residual Value (projected)
$C_Y^{(')}$	Yearly (Annual) Cost (projected)
f	Inflation
i	Interest
i_r	Real Interest
i'	Net Present Value Factor
n	Duration (Lifetime)

Bus_{Int}	International Bus
Bus_{Nat}	National Bus
Car_{Gas}	Gasoline driven Private Vehicle
Car_{Diesel}	Diesel driven Private Vehicle
EV_{Coal}	Electric Vehicle, driven by electric Energy gained by burning Coal
EV_{NG}	Electric Vehicle, driven by electric Energy gained by burning Natural Gasses
EV_{Mix}	Electric Vehicle, driven by electric Energy provided by the Austrian Energy Mix
EV_R	Electric Vehicle, driven by electric Energy gained through Renewable Energies
$FCV_{EL,Mix}$	Fuel Cell Vehicle, driven by Hydrogen gained by Electrolysis from the Austrian Energy Mix
$FCV_{EL,R}$	Fuel Cell Vehicle, driven by Hydrogen gained by Electrolysis from Renewable Energies
FCV_{Gr}	Fuel Cell Vehicle, driven by Hydrogen gained by Gas Reformation
$Plane_{Int}$	International Plane
$Plane_{Nat}$	National Plane

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