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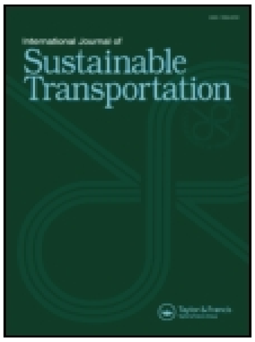

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The life cycle energy demand and greenhouse gas emissions of high-capacity urban transport systems: A case study from Vienna's subway line U2

Jakob Lederer[a,c], Christian Ott[a], Paul Hans Brunner[a], and Markus Ossberger[b]

[a]Institute for Water Quality, Resource, and Waste Management, Vienna University of Technology, Vienna, Austria; [b]Wiener Linien, Vienna, Austria; [c]CD Laboratory for Anthropogenic Resources, TU Wien, Vienna, Austria

ABSTRACT

This article calculates the impact of three measures in order to reduce the global warming potential (GWP) and cumulative energy demand (CED) of Vienna's subway line U2. Results show that the increase of the train occupancy rate has the highest reduction impact (−30%/−30%), followed by new rolling stock (−26%/−34%), and a change in energy mix (−8%/−4%). The total reduction to be achieved with all measures combined is around −55% for GWP and CED, leading to a GWP of 91 [g] and 1.653 [MJ] per passenger kilometer traveled (PKT). With all these measures applied, the subway has lower GWP and CED than other modes of transport presented in the literature.

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CED; energy demand; GHG; global warming potential; greenhouse gas emissions; subway

1. Introduction

Transport and traffic are among the main consumers of energy and main producers of greenhouse gas (GHG) emissions in the urban anthropogenic metabolism, contributing 27% to the final energy consumption and 15% to the anthropogenic GHG production in the world in 2008 (International Energy Agency [IEA], 2010; Organisation for Economic Co-operation and Development [OECD]/International Transport Forum [ITF], 2010). More than half of these transport emissions are caused by petroleum-based diesel and gasoline fuels passenger transport, mostly induced by urbanization and large urban agglomerations (Baccini & Brunner, 2012; IEA, 2009). This combustion of fossil fuels and subsequent energy consumption and GHG production, expressed as the global warming potential (GWP), correlates with the most important emissions in the urban transport sector, such as NO_X, CO, and particulate matter, making them the most important indicators for a brief assessment of environmental sustainability in the sector (Huijbregts et al., 2006).

Sustainable urban development seeks a reduction of GWP and fossil fuel consumption in all modes of urban transport, but particularly in fossil-fueled private passenger transport. Suggested measures are sound urban planning with regard to short transport distances, transition to more sustainable energy sources, higher energy efficiency, and a shift in the modal split from private to public transport (May, 2012; OECD/ITF, 2010). For cities of a certain size, this public transport function can most likely be achieved by rapid transit systems such as subways and commuter rails. However, their construction is often an issue of public and scientific discussion due to the GWP and energy demand during the construction phase, particularly through the excavation of tunnels (Bekesi, 2005; Melanie, 2010; Rönkä, Ritola, & Rauhala, 1998).

In the view of these discussions, decision makers, urban planners, and transport companies require a sound knowledge base on (1) the cumulative life cycle energy demand (CED) and GWP of rapid transit systems compared to other modes of transport and (2) which measures are the most promising to reduce GWP and CED. This is particularly the case in urban regions that are about to extend their existing subway system such as the Austrian capital of Vienna (Wiener Stadtwerke, 2008).

Thus, the objectives of this article are to calculate the CED and GWP of newly built subways, assess them in comparison to other modes of transport, and evaluate and discuss the effect of particular policy measures to reduce both indicators. By doing so, a contribution to the aforementioned claim of expanding the knowledge base on urban transport systems should be made herein for the case study of the city of Vienna.

A number of studies on the energy demand and GWP of urban transport systems are already available for various urban regions in the world, but not for Vienna. Eriksson, Blinge, and Lövgren (1996) compiled a Life Cycle Impact Assessment (LCIA) of the road transport sector in Sweden, taking into account private cars and transport of goods, but excluding public road passenger transport and nonroad passenger transport. Baumgartner et al. (2000) performed a LCIA on the Swiss Metro, a thus-far-not-realized underground high-speed railway network in Switzerland connecting the main urban centers of the country. The study concludes that 21% of nonrenewable cumulative energy demand (CED) comes from the construction of the tunnels and the vehicle. The nonrenewable CED per passenger is similar to that of other high-speed trains, but only because of the different passenger occupancy rates (load factors), which are assumed to be twice as high for the Swiss Metro.

CONTACT Jakob Lederer jakob.lederer@tuwien.ac.at Institute for Water Quality, Resource, and Waste Management, Vienna University of Technology, Karlsplatz 13/226, A-1040 Vienna, Austria.

Schmid et al.'s (2001) LCIA on transport services along particular travel routes in the German region of Baden Wurttemberg considers the CED, GWP, and other emissions. Results show far lower GWP for commuter rails than for private cars, explained by the high nuclear power and low fossil fuel proportion for the electricity consumed by the trains. As a result, the CED of gasoline-fueled cars was ten and of diesel-fueled cars six times higher than the one of commuter rails. However, figures for the commuter rails are only for peak hours, not off-peak hours. Unfortunately, results are also not given in a comparable functional unit such as passenger kilometer traveled.

A special focus on the ecological design of metro trains is presented by Struckl and Wimmer (2007), who carried out a LCIA case study for the production and operation of the so-called Greenline Metro train in Oslo. For this special case, they conclude that although materials of a high specific GWP and CED value such as aluminum are used to build the trains, the emissions and energy demand is dominated by the operation phase. Therein, a remarkably high share can be assigned to cooling and particularly heating of the trains, which shows the high relevance of the geographical conditions.

Chester and Horvath (2009) compare the results of their LCIA of different long distance and urban transport systems in the United States, finding the CED and GWP highest for urban diesel buses during off-peak hours. However, during peak hours, urban diesel buses perform best compared to other modes of transport. Gasoline cars consume a CED between 3 and 5 MJ per passenger kilometer traveled (PKT) and emit 230 and 415 g CO_2-equiv./PKT of GWP, while commuter rail and light rail systems consume between 1.4 and 1.9 MJ/PKT CED and emit 100 to 140 g CO_2-equiv./PKT GWP. As a major finding, they claim more attention for the emissions and energy demand during the construction phase of rail systems in particular (Chester & Horvath, 2009).

Contrary to the aforementioned studies, Harwatt, Tight, and Timms (2011) explicitly deal with policy options to reduce GHG emissions and energy demand, exercised for the greater London region. A combination of market-based (carbon trading) and live-style-based shift (promotion of cycling and walking) shows the highest reduction potential, while the effect of single measures with high capital investment (cleaner technology) or multiple measures formulated by the city government in their action plan are of lower impact.

Most of the studies reviewed do consider private and public transport by car, bus, commuter, and light rails, but not subway systems with extensive tunnel constructions (Chester & Horvath, 2009; Eriksson, Blinge, & Lövgren, 1996). Some studies focus solely on particular aspects of subways such as product design (Struckl & Wimmer, 2007) or even projects not carried out yet (Baumgartner, Tietje, Spielmann, & Bandel, 2000). Others that consider existing subway systems and compare them to other modes of transport show high uncertainties based on sensitive input values such as occupancy rates (peak and off-peak hours), and electricity production mix (Chester & Horvath, 2009; Schmid, Wacker, Kürbis, Krewitt, & Friedrich, 2001). What all of these studies have in common is that they do not aim to investigate the impact of policy measures as a means of implementation of their conclusions. If it has been done, it is only attempted in a prospective way considering policy, corporate, and technological measures aiming to increase passenger numbers by train (occupancy rate) or changing energy mix or energy efficiency, not showing and thus evaluating the effect of measures already carried out (Harwatt, Tight, & Timms, 2011).

In order to provide some new information to both local stakeholders in Vienna's transport system and researchers, the research questions addressed in this work are:

1. How big are the life cycle CED and GWP of a newly built subway system if compared to other modes of transport?
2. To which extent do the aforementioned CED and GWP reduction measures (occupancy rate, energy production mix, and higher energy efficiency of rolling stock) influence the results?

To answer these questions, Vienna's new subway extension line U2 is investigated as a case study. The reason it was chosen is that (1) the U2 was recently built and does provide the data required to carry out the calculations, particularly for provision of infrastructure and buildings, and (2) it is an example of combining measurable attempts of increasing the occupancy rate, changing electricity mix, and investments in new rolling stock.

2. Methods and methodology

LCIA has been developed to analyze the impact of the provision of services and goods along their life cycle, which means from the extraction of raw materials via the production and consumption to the final disposal of residues. Unlike environmental impact assessment, it does not only consider the direct impact of the foreground system, but also the background system in the hinterland, where raw materials are usually extracted. This is particularly important for systems such as subways where both operation and construction phases might be of relevance (Chester & Horvath, 2009).

2.1 *System definition*

The calculation is based on a life cycle approach after ISO 14044:2006 (DIN, 2006), defining first the regarded system, which is the passenger transport function along a particular route within an urban region, namely the travel route of the new subway extension of the U2 subway line of Vienna's subway network, between the existing stop Schottenring and the last stop Seestadt (see Figure 1).

The total length of the extension is 14,820 meters, with a tunnel section of 3,500 meters and an aboveground section of 11,320 meters. The subway line is part of Vienna's public transport network of subway lines, commuter rails, and bus and light rail lines, all operated by the same provider (Wiener Linien). Construction work was carried out between the years 2003 and 2010. The line was opened for the section Schottenring to Stadion in the year 2008, and the section to Aspernstrasse in the year 2010.

2.2 *Life cycle inventory*

The material and energy life cycle inventory (LCI) considers the quantitatively most relevant material and energy flows

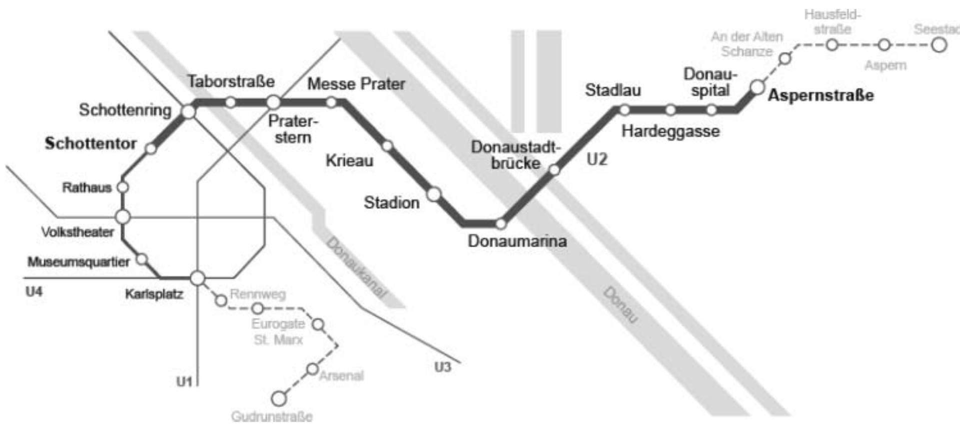

Figure 1. Vienna's U2 subway line extension between the stops Schottenring and Seestadt, adapted from Wiener Linien (2009).

for constructing and operating the infrastructure (Table 1). Cutoff rules defining which flows are considered and which are not is derived from literature and presented later in this section. Values for the infrastructure operation are given in mass or energy unit per year (t/a; MJ/a). In order to integrate the infrastructure provision, the CED and GWP for the construction and production of tunnels, stations, and new rolling stock is calculated and straight-line depreciated through dividing the total lifetime value by the assumed life span of tunnels, stations, and the rolling stock. Therefore, maintenance, demolition, disposal, and recycling of the buildings are not considered because the literature suggests that in rail constructions their contribution to the final result is likely to be negligible (Chester & Horvath, 2009; Rozycki, Koeser, & Schwarz, 2003). The materials and energy consumption for production, maintenance, disposal, and recycling of the old rolling stock are also not taken into account, which is (1) consistent in scenario analysis as applied to all scenarios, and (2) acceptable because their contribution is likely to be negligible due to the high material recycling rates of coaches of around 90% (Chester & Horvath, 2009; Schwab Castella et al., 2009; Struckl & Wimmer, 2007). Table 1 summarizes the energy carriers and materials considered in this study.

2.3 *Cumulative energy demand and greenhouse gas emissions*

The VDI directive 4600 of the Association of German Engineers (VDI 1997) is one of the more commonly used standards for the calculation of the cumulative energy demand (CED), applied in LCIA programs and databases such as Ecoinvent or

Table 1. Infrastructure construction and operation items (materials and energy inventory).

	Item	Materials/energy sources
Infrastructure construction	Structure (tunnels, buildings, stations)	Concrete, steel, copper, aluminum, electricity, heat, fuel (diesel)
	rolling stock	steel, copper, aluminum, electricity, heat, fuel (diesel)
Infrastructure operation	Rolling stock	Electricity (operation, ventilation, heating/cooling of rolling stock)
	Stations, buildings	Electricity, heat (light, ventilation, heating/cooling of stations)

Probas and thus in line with the LCA ISO 2006 standards (Bösch, Hellweg, Huijbregts, & Frischknecht, 2007; DIN, 2006; Huijbregts et al., 2010; Öko-Institut e.V., 2008):

$$CED = CED_H + CED_N + CED_E. \quad (1)$$

Herein, CED_H is the CED for production, CED_N is the CED for operation, and CED_E is the CED for disposal of the investigated good or function. An abbreviated form of the CED is also used in the GEMIS 4.5 LCIA program, which is applied for the LCIA calculation (Öko-Institut e.V., 2008). The expression unit used is mega joule per year (MJ/a).

Greenhouse gas emissions (GHG) are calculated after Grießhammer et al. (2008) and the German Öko-Institut e.V. (2008), converting the greenhouse gases CO_2, CH_4, and N_2O into global warming potential (GWP), expressed as CO_2 equivalent per year (CO_2-equiv./a).

After establishing a material and energy inventory, the inventory data are multiplied by CED and GWP factors per unit of material or energy consumed, taken from the GEMIS 4.5 program database:

$$S_{D,p} = LCI_p * DF^{dm}. \quad (2)$$

Herein, S_D is the damage score to produce the product p, *LCI* is the life cycle inventory, namely the quantity of materials and energy consumed to produce *p*, and DF^{dm} is the damage factor, which in this case is the GWP and the CED per unit.

2.4 *Functional unit*

To compare the results with other transport systems and literature findings, the functional unit is fixed as per passenger kilometer traveled (PKT), meaning that the total result $S_{D,p}$ given as mass or energy per year is divided by the amount of kilometers traveled by all passengers along the new subway extension from the stops Schottenring to Seestadt per year (PKT/a):

$$S_{D,specific} = S_{D,p} \ / \ PKT. \quad (3)$$

Hence, $S_{D,specific}$ is the damage score, thus the CED and GWP per functional unit (PKT).

2.5 *Variation of parameters through selected measures and designing of scenarios*

The second research question requires a variation of selected parameters in order to analyze but also predict the impact of policy and corporate decisions regarding (1) occupancy rate, (2) change in energy production mix, and (3) higher energy efficiency of new rolling stock. Starting with a baseline scenario representing the GWP and CED before the measures have been implemented, the scenarios are further developed and shown, after describing reduction measures and scenarios, in Table 2.

2.5.1 *Measure 1: Higher occupancy rate*

The occupancy rate is a function of the number of passengers transported, which again underlies several assumptions, such as population along the subway line and preferred mode of transport. For both, an increase can be observed in Vienna, as the changes in the modal split and latest population figures show (Deußner & Kovacic, 2010; Schremmer et al., 2011; Wiener Stadtwerke, 2011a). The latter significantly influences urban planning in Vienna, and the city plans to develop the areas along the subway line U2 in order to cope with this population growth (Magistrat der Stadt Wien 2003). Therefore, this scenario considers a continuation of the trend of consumers toward public transport, population growth, and housing development along the subway line U2, applying values for the train occupancy rate for the years 2015 (baseline scenario 0 and scenarios 2, 3, and 5) and 2025 (scenarios considering measure 1—scenarios 1, 4, 6, and 7). The variation of this parameter influences the results from Equation (3) through the increase of the PKT/a.

2.5.2 *Measure 2: Energy production mix*

During the last 15 years, Vienna's main energy supplier Wien Energie made some investments for its energy production. New wind power parks, biomass, and biogas plants have been built, while heating oil for electricity and heat production has been replaced by natural gas (Wiener Stadtwerke, 2011a, 2011b). The objectives of these measures are a reduction of the GWP and CED. These reduction measures are considered in this paper under measure 2. Therefore, the electricity and heat production of the year 2001/2002 is applied to the baseline (scenario 0) and scenarios 1, 3, and 6, and the one of 2011/2012 for the scenarios considering measure 2 (scenarios 2, 4, 5, and 7), which will change the LCI (Equation [2]). The damage score $S_{D,p}$ is again taken from GEMIS 4.5 for each energy mix.

Table 2. Scenarios for no-action alternative and different GHG emissions and CED reduction measures.

Scenario no.	Train occupancy rate	Energy mix (year)	Rolling stock (old/new)
0	7%	2001/2002	U-Wagen (old)
1	10%	2001/2002	U-Wagen (old)
2	7%	2011/2012	U-Wagen (old)
3	7%	2001/2002	V-Wagen (new)
4	10%	2011/2012	U-Wagen (old)
5	7%	2011/2012	V-Wagen (new)
6	10%	2001/2002	V-Wagen (new)
7	10%	2011/2012	V-Wagen (new)

2.5.3 *Measure 3: Higher energy efficiency of rolling stock*

In 2010, the first tranche of the new V-Wagen (V-coach) started its operation. The producer (Siemens) promises a reduction of the energy consumption by this train type compared to the 30-year-old U-Wagen of Vienna's subway system, particularly through the recovery of energy during braking (Siemens, n.d.). According to Wiener Linien, the old coaches could have been used for another 30 years, but due to the high energy demand and lower comfort, they will be replaced by the new V-Wagen until 2019 (Wiener Linien, 2010; Wiener Stadtwerke, 2011a). Therefore, the scenarios considering this measure assume that all rolling stock running at the U2 line is replaced from the U-Wagen (baseline scenario and scenarios 1, 2, and 4) to the newer V-Wagen (scenarios 3, 5, 6, and 7), leading to a lower energy demand, which affects the LCI (Equation [2]). As aforementioned, production, maintenance, disposal, and recycling of old trains are not considered.

2.5.4 *Scenarios*

To assess the impact of the measures, different scenarios are designed that consider each of the measures, but also combinations of them. Therein, the baseline alternative refers to the system before the three measures are implemented (scenario 0). All other scenarios are a mix of the different measures, particularly scenario 7, which considers all three measures to be implemented (Table 2).

3. Materials

3.1 *Functional unit for the baseline*

To calculate the functional unit (PKT), the projected passenger numbers for the year 2015 per section are used and multiplied by the section's length. Passenger number data derives from Deußner and Kovacic (2010). Then the base to calculate the functional unit is 128,940,000 PKT/a for the year 2015, which equals an occupancy rate of about 7% of the total seating and standing passenger capacity (848 seats in total), but 19% if only seating capacity is considered (300 seats in total).

3.2 *Life cycle inventory for the baseline*

3.2.1 *Infrastructure provision*

The quantities of concrete, reinforcing steel, construction steel, and aluminum used in the building constructions were acquired from the bidding documents of the construction project from the tendering party Wiener Linien (2010). Data for copper consumption, which is mainly used in electrical installations and the overhead traction line, were acquired through interviews with Wiener Linien. The same is true for electricity and fuel consumption during the construction phase (Wiener Linien, 2010). Data for the infrastructure operation are given in mass or energy unit per year (t/a; MJ/a). In order to integrate the infrastructure provision, the GWP and GHG for the construction and production of tunnels, stations, and the new rolling stock is calculated and straight-line depreciated through dividing the total lifetime value by the assumed life span of tunnels and stations (100 years) and the rolling stock (30 years) (Struckl, personal communication, 2010; Struckl & Wimmer, 2007; Wiener Linien, 2010).

3.2.2 *Infrastructure operation*

Electricity consumption for the operation (traction current) of the old rolling stock called U-Wagen is 76.32 MJ/train-km traveled (Wiener Linien, 2013). With a total amount of 2,267,000 train-km traveled per year (Ossberger, 2010), the annual electricity consumption is 173,017,440 MJ/a. This value corresponds with data from literature of 155−182 million MJ/a (Brauner, 2009; Kindler et al., 2006). Electricity consumed for operating the stations is 3,600,000 MJ/a for aboveground stops and 2,412,000 MJ/a for subsurface stops (Kindler et al., 2006). This value corresponds with Hong and Kim's (2004) data on electricity consumption of Seoul's subway system. In total, the 16 new stops (four subsurface, twelve aboveground) consume 43,344,000 MJ/a of electricity. The total heating demand of the 16 new stops is estimated at 6,840,000 MJ/a (Wiener Linien, 2010). Finally, the total energy demand for operating the subway system is 222 million MJ/a.

3.2.3 *Energy mix*

The energy mix is crucial for the determination of the GWP and CED. In 2001/2002 Wien Energie, the electricity supplier of Wiener Linien, had a domestic electricity production mix of 91% fossil (86% gas and 5% oil), 8% hydropower, and 1% biomass and wind energy, covering 51% of the electricity demand (Wien Energie, 2003). The residual 49% was imported from the Austrian grid. The final electricity mix, which is used for the calculation of the GWP and CED impact factor through GEMIS, considers this import by using the Austrian energy mix data from GEMIS 4.5 for imported electricity (Öko-Institut e.V., 2008). Heat is consumed from the district heating provided by Wien Energie, covering 100% of the demand and dominated by natural gas, waste, and heating oil (Pölz, 2007). Both values are shown in Table 3.

3.3 *Life cycle inventory for measures 1−3*

3.3.1 *Measure 1: Higher occupancy rate*

Based on the assumptions regarding housing development, population growth, and modal split development, an increase in the average passenger occupation rate from 7% to 10% (19% to 27% if only seating capacity is considered) for the year 2025 is used, which corresponds to 183,996,000 PKT/a (Deußner & Kovacic, 2010). This is still a conservative estimate if compared to literature data, stating figures between 20% and 60% of average train occupancy rate (Brauner, 2009; Chester, 2008).

3.3.2 *Measure 2: Change of energy mix for electricity and heat production*

The production electricity mix of Wiener Linien's electricity supplier Wien Energie in 2011/2012 is still dominated by fossil fuels, but oil was phased out. Therefore, the share of wind, hydropower, and biomass increased (see Table 3). In addition, the self-sufficiency increased, and the share of electricity imported from the Austrian grid decreased from 49% to 47% (Wien Energie, 2012). The changes in the district heating system are established by updating the data of Pölz (2007) with data from Wiener Stadtwerke (2011a, 2011b). These changes include the installation of a new biomass, biogas, and waste incineration plant. The energy mix is presented in Table 3, and the resulting damage factors from GEMIS 4.5 are shown in Table 4.

3.3.3 *Measure 3: Higher energy efficiency through technological innovation*

Unpublished electricity consumption measurements for the operation of the new rolling stock (V-Wagen) show a reduction of 50% compared to the old coaches (U-Wagen) (Struckl, personal communication, 2010). With a total amount of 2,267,000 train-km traveled per year (Ossberger, 2010), the electricity consumption for traction current will reduce to 86,146,000 MJ/a.

3.4 *Damage factors for CED and GHG emissions*

The inventory data is multiplied by emission factors, taken from the well-established and ISO 14044:2006 compliant GEMIS 4.5 database (DIN, 2006; Haapio & Viitaniemi, 2008; Öko-Institut e.V., 2008). As an adjustment, the direct emission factors for diesel and natural gas of 0.068 and 0.055 kg CO_2 per MJ fuel are added to the indirect emission factors from GEMIS (Buchal, 2007).

Table 3. Energy mix for baseline in %. Electricity production mix data derives from Wien Energie (2003, 2011) and the GEMIS 4.5 database (Öko-Institut e.V. 2008), heat production mix data is taken from Pölz (2007) and Wiener Stadtwerke (2011a, 2011b).

	Supplier (GEMIS code)	Translation	Base scenario (year 2001)	Measure 2 (year 2011)
Electricity production	Kohle-KW-DT-EU-Import-2010	Coal	4.2	2.1
	Braunkohle-KW-DT-AT-2000	Lignite	1.3	0.7
	Öl-schwer-KW-DT-AT-2000	Heating oil	3.8	0.7
	Gas-KW-GuD-AT-2010	Natural Gas	50.3	55.3
	Müll-KW-DT-AT-2000	Waste Incineration	1.7	1.0
	Wasser-KW-gross-AT	Hydropower	38.2	38.1
	Bio-KW-DT-EU-2010	Biomass	0.2	1.1
	Wind-KW-Park-groß-DE-2010	Wind	0.2	1.1
Heat production	Öl-schwer-Kessel-AT-2005	Heating oil	15	9
	Müll-HKW-DT-DE-2000-th/el-mix	Waste to energy	24	26
	Gas-HKW-GT-AT-2005-th/el-mix	Natural gas	61	61
	Holz-HS-Waldholz-HKW-10 MW-th-AT-2005	Biomass-fueled	0	4

Table 4. Emission factors for energy and materials provision for the baseline.

No.		Unit	GWP factor (kg/unit)	CED total (MJ/unit)
1	Electricity (baseline—2001)	MJ	0.089	1.846
2	Electricity (measure 2—2011)	MJ	0.080	1.764
3	Heat (baseline—2001)	MJ	0.095	1.787
4	Heat (measure 2—2011)	MJ	0.086	1.841
5	Diesel	MJ	0.147	2.137
6	Natural Gas	MJ	0.122	2.150
7	Concrete	kg	0.174	1.085
8	Steel	kg	1.499	20.361
9	Copper	kg	3.977	50.945
10	Aluminum	kg	17.601	186.070

Source: GEMIS 4.5 database (Buchal 2007; Öko-Institut e.V. 2008).

4. Results

4.1 Results for life cycle GHG emissions and CED of the U2 subway line before implementation of different measures

Under the given conditions, the total baseline results for the regarded system are 26 million kg GHG emissions and a CED of 381 million MJ per year. Transferred into per person kilometer traveled, the result is 199 g CO_2-equiv/PKT for the GWP and 3.676 MJ/PKT for CED. The operation of the infrastructure (rolling stock and stations) generates 78% of the total GHG emissions and consumes 88% of the total CED. Provision of the infrastructure (19% and 10%) and the rolling stock (3% and 2%) contributes to a significantly smaller portion (Figure 2a and 2b). These results are comparable to the 79% contribution of infrastructure operation given by Baumgartner et al. (2000), but higher than Chester and Horvath's values (2009), where infrastructure operation is about 50%–60% of CED and 40%–50% of the GWP. This is remarkable, given that Chester and Horvath consider rail systems that do not require tunnels and hence should have a supposedly lower energy demand in the construction phase (see Figures 2a and 2b). A further breakdown shows clearly that the electricity for

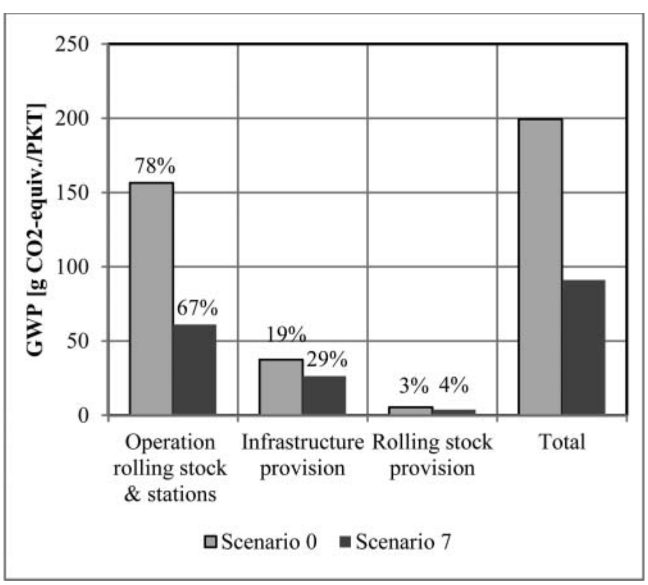

Figure 2a. Baseline (scenario 0) and applying all reduction measures (scenario 7) results for the GWP.

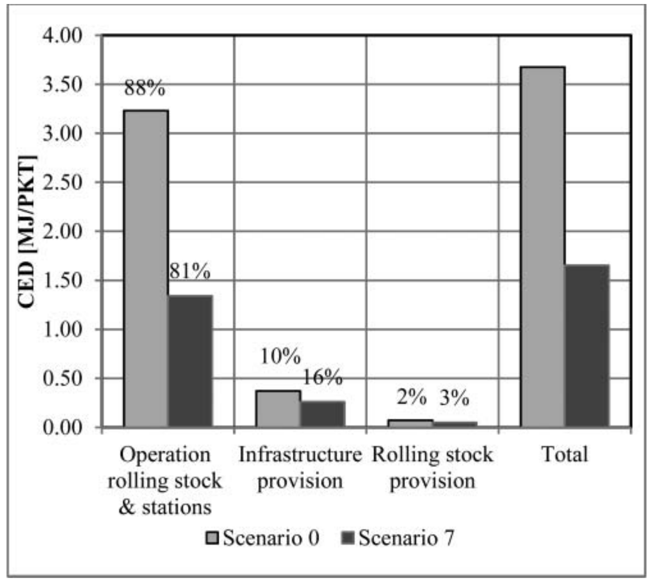

Figure 2b. Baseline (scenario 0) and applying all reduction measures (scenario 7) results for the CED.

operation of rolling stock (60%) and the stations (15%) are dominating the results for the GHG emissions. Other items of relevance are materials provided to construct the infrastructure (concrete—12%; steel—5%) and heat to maintain the stations, while all other items are of much smaller relevance (Table 5).

4.2 Reduction potential through higher occupancy rate, new energy mix, and higher energy efficiency of the rolling stock

If all measures to reduce the impacts of the U2 are applied, the GWP drops to a level of 91 g CO_2-equiv/PKT and the CED to 1.653 MJ/PKT, which is around −55% for both. Consequently, the impact of the operation on the results drops to 66% for the GWP and 81% for the CED (Figures 2a and 2b, Table 5). This is due to the fact that the implemented measures target the operational phase, and the relative contribution to GHG emissions and CED of materials for building and construction will increase. Finally, the highest contribution to the result is through the electricity demand for train operation, followed by steel and concrete for the provision of infrastructure. All others are of lesser relevance (Table 5).

From the single reduction measures, scenario 2—the transformation in the energy mix toward more gas-fired power plants, hydropower, and biomass—has the lowest reduction potential, reducing the GWP by about 8% and the CED by about 4%. The new rolling stock (scenario 3) has a higher reduction potential on GWP (−26%) and CED (−34%). The increase in the passenger number and thus average occupation rate from 7% to 10% (scenario 1) has the highest single reduction effect of about 30% for the GWP, and the second-highest for the CED with −30%. Based on this result of each reduction measure, it is clear that an increase in occupancy rate and the new rolling stock is the most effective binary combination for reducing the GWP and CED (scenario 6), with −51% for the GWP and −54% for the CED. The reduction that can be achieved with this combination is only slightly below scenario

Table 5. Results for scenario 0 (baseline, before applying any measure) and scenario 7 (applying all reduction measures). (1) Units for energy are given in GJ for the inventory total and GJ/year for the inventory per annum (p.a.); (2) Units for mass are given in tons for the inventory total and tons/year for the inventory per annum (p.a.).

			Results baseline scenario (before applying measures)									Scenario 7 (after applying all three measures)								
				DF_{GWP}	DF_{CED}	GWP			CED total				DF_{GWP}	DF_{CED}	GWP			CED total		
Category	Item	Inventory total	Inventory p.a.	t/unit	GJ/unit	t/a	g/PKT	%	GJ/a	MJ/PKT	%	Inventory p.a.	t/unit	GJ/unit	t/a	g/PKT	%	GJ/a	MJ/PKT	%
Energy for operation	Electricity traction[1]		173,017	0.089	1.846	15,399	119.4	60	319,390	2.4770	67	86,509	0.080	1.764	6,921	37,6	41	152,601	0.8294	50
	Electricity stations[1]		43,344	0.089	1.846	3,857	29.9	15	80,013	0.6205	17	43,344	0.080	1.764	3,468	18.8	21	76,459	0.4155	25
	Heat stations[1]		9,720	0.095	1.787	923	7.2	3.6	17,370	0.1347	3.7	9,720	0.086	1.841	836	4.5	5.0	17,895	0.0973	5.9
Energy and material infra-structure provision	Electricity[1]	360,360	3,603	0.089	1.846	321	2.5	1.2	6,652	0.0516	1.4	3,604	0.089	1.846	321	1.7	1.9	6,652	0.0362	2.2
	Diesel[1]	183,272	1,832	0.080	2.137	146	1.1	0.6	3,916	0.0304	0.8	1,833	0.080	2.137	146	0.8	0.9	3,916	0.0213	1.3
	Concrete[2]	1,701,570	17,015	0.174	1.085	2,967	23	12	18,469	0.1432	3.9	17,016	0.174	1.085	2,967	16.1	18	18,469	0.1004	6.1
	Steel[2]	87,681	876	1.499	20.361	1,315	10.2	5.1	17,853	0.1385	3.8	877	1.499	20.361	1,315	7.1	8	17,853	0.0970	5.9
	Aluminum[2]	201	2	17.601	186.070	35	0.3	0.1	374	0.0029	0.1	2	17.601	186.070	35	0.2	0.2	374	0.0020	0.1
	Copper[2]	1,330	13	3.977	50.945	53	0.4	0.2	678	0.0053	0.1	13	3.977	50.945	53	0.3	0.3	678	0.0037	0.2
Energy and material rolling stock provision	Electricity[1]	16,365	545	0.089	1.846	49	0.4	0.2	1,007	0.0078	0.2	545	0.089	1.846	49	0.3	0.3	1,007	0.0055	0.3
	Heat[1]	39,564	1,318	0.095	1.787	125	1	0.5	2,357	0.0183	0.5	1,319	0.095	1.787	125	0.7	0.7	2,357	0.0128	0.8
	Gas[1]	3,681	122	0.068	2.150	8	0.1	0.0	264	0.0020	0.1	123	0.068	2.150	8	0.0	0.1	264	0.0014	0.1
	Steel[2]	1,282	42	1.499	20.361	64	0.5	0.2	870	0.0067	0.2	43	1.499	20.361	64	0.3	0.4	870	0.0047	0.3
	Aluminum[2]	754	25	17.601	186.070	442	3.4	1.7	4,678	0.0363	1.0	25	17.601	186.070	442	2.4	2.6	4,678	0.0254	1.5
	Copper[2]	75	2	3.977	50.945	10	0.1	0.0	128	0.0010	0.0	3	3.977	50.945	10	0.1	0.1	128	0.0007	0.0
Total						25,715	199.4		474,018	3.6762					16,759	91.1		304,200	1.6533	

Table 6. Reduction potential of all scenarios.

Scenario	Description	GWP (g/PKT)	CED (MJ/PKT)	Reduction GWP	Reduction CED
0	before applying any measure	199	3.676	0%	0%
1	increasing occupancy rate	140	2.576	−30%	−30%
2	new energy mix	184	3.543	−8%	−4%
3	new rolling stock	148	2.438	−26%	−34%
4	increasing occupancy rate + new energy mix	129	2.483	−35%	−32%
5	new rolling stock + new energy mix	130	2.359	−35%	−36%
6	increasing occupancy rate + new rolling stock	98	1.708	−51%	−54%
7	applying all three measures	91	1.653	−54%	−55%

7, which considers the implementation of all reduction measures. To reach a level of around 100 g CO_2-equiv/PKT or below for the GWP, only scenario 6 and 7 are effective, as can be seen in Table 6 and Figure 3.

However, this figure must again be seen in the light of a further possible improvement. An even higher occupancy rate from 27% as in measure 1 toward Vienna's average of over 30% related to seating passenger capacity in subway trains will further reduce this figure (Ossberger, 2010). The influence of the passenger occupation rate is shown in Figure 4, also distinguishing whether it is related to the capacity based on seated or standing passengers.

4.3 *Comparison of scenario 0 and scenario 7 to other modes of transport*

If compared to individual transport with passenger cars, the subway shows generally lower GHG emissions. This is the case for both average German car fleet and average U.S. car fleet (Chester & Horvath, 2009; Öko-Institut e.V., 2008). Urban diesel buses require much less energy and emit less GHG during peak hours, but not so during off-peak hours, as data by Chester and Horvath (2009) suggests. Assuming that 60% of the movements are during peak and 40% during off-peak hours, the average GWP of 190 g/PKT are twice as high as the emissions for the subway of scenario 7. The lower emissions and CED in the bus system due to less required infrastructure is challenged by the relative inefficiency of the diesel engine compared to a grid-bound transport system. The maximum emissions of the subway are higher as light rails from the United States, due to the necessity of tunnel infrastructure (Chester & Horvath, 2009). After applying the reduction measures (scenario 7), the emissions become lower, despite the construction of tunnels. The reason, therefore, is the different electricity mix in parts of the United States. The electricity mix is also the reason for the relatively high CED for the subway not directly translating into GHG emissions, because the bulk of electricity is due to hydropower. Figure 5 shows the comparison of the results to other modes of transport from literature studies.

5. Discussion

One of the major arguments against subway systems in the urban public transport networks is the relatively high impact on the environment during the building and construction phase. However, the results of this investigation, expressed in Figures 2a and 2b (section 4.1) show that the operational stage is of higher relevance than the construction phase. This, of course, changes slightly when operations become more efficient. The relatively low relevance of the construction compared to the operation phase is due to the huge number of passengers who can be transported, and the longevity of the buildings and rolling stock, which reduces the figures significantly. However, the result also shows that the longevity of the rolling stock is challenged through the increase in energy

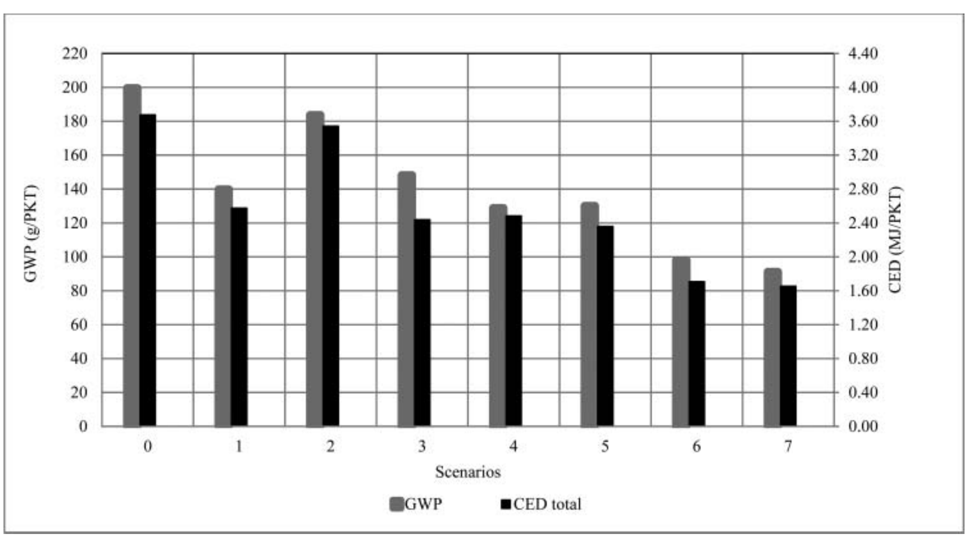

Figure 3. Results for different scenarios: scenario 0—no-action alternative (before implementing measures); scenario 7—after implementing all measures; a detailed description of scenarios can be found in Table 2.

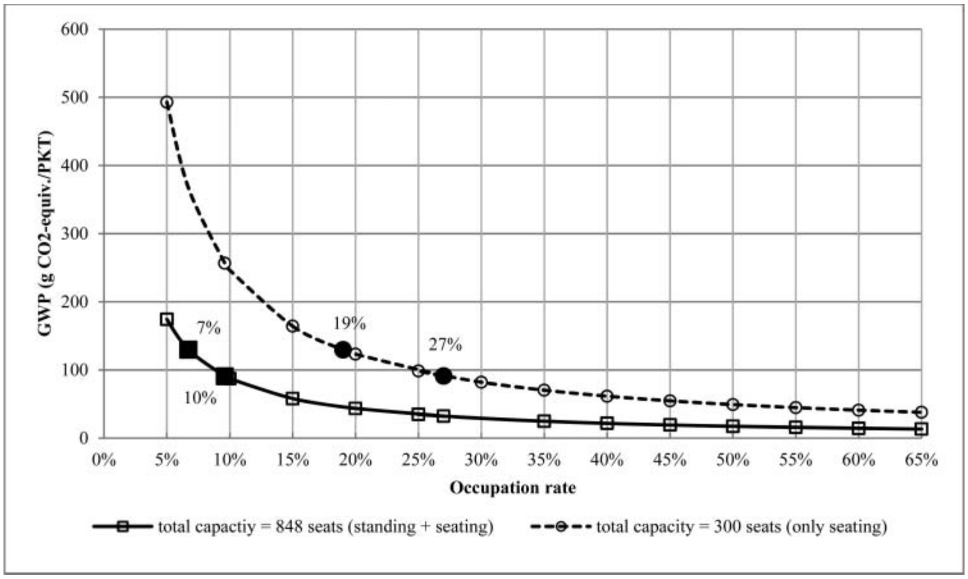

Figure 4. Influence of train occupation rate on the GHG emissions for the combined measures calculation.

efficiency of the new rolling stock, which can reduce the GWP and CED significantly. For instance, recent figures from Wiener Linien (2013) show that by replacing almost half of the old rolling stock with new, the energy demand for train operation (traction current) dropped by 23% from 76 to 59 MJ/train-km traveled. Therefore, it makes sense for transport companies to replace their old trains if more efficient technology is available, because it is also the one measure probably easiest to implement.

Overall, the impact of the occupancy rate is still the highest of all regarded measures. This is of particular relevance for the subway U2, because the estimated occupancy rate for 2025 is still below average rates achieved nowadays. However, considering the strong population growth of Vienna of 1% per year between 2001 and 2009 (Schremmer et al., 2011) and the scarcity of building space in most districts, it is likely, as desired and planned by the city administration, that the passenger numbers will increase (Magistrat der Stadt Wien, 2009).

Compared to the two measures, the study shows that the change in the energy mix is of much less relevance. This is surprising, as some major investments have been made in this field. One reason is that the import of electricity from the hydropower-dominated Austrian grid has been reduced; the other reason is that domestic electricity production is still dominated by natural gas. However, it is clear that not only urban transport is affected by this measure, but also all other sectors of energy consumption (industry, housing), which must be considered when evaluating this measure.

In the overall comparison to other modes of transport, the subway shows a relatively low GWP and CED, even with an

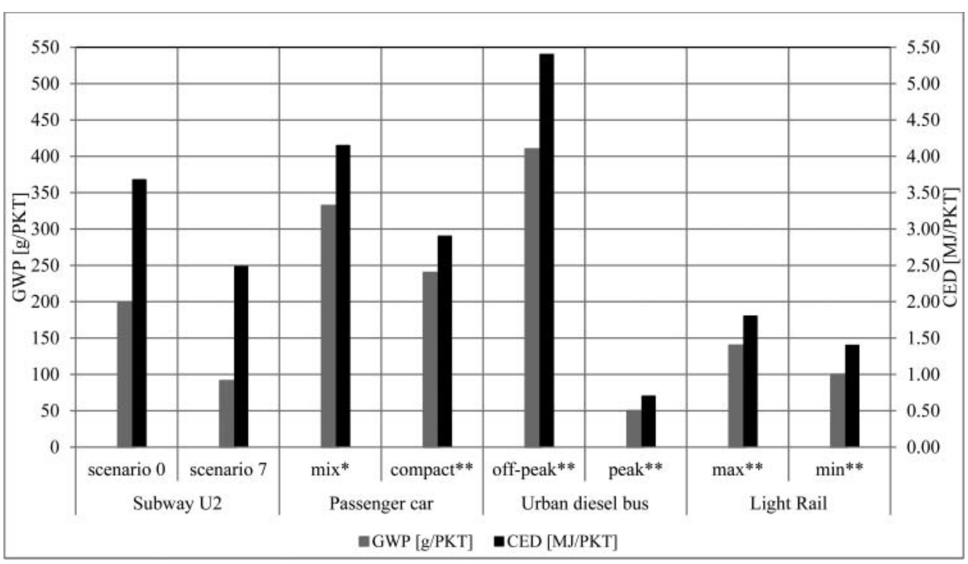

Figure 5. Comparison of scenarios 0 and 7 to other modes of transport, based on literature studies; *data from GEMIS 4.5 for the average vehicle fleet in urban transport in Germany 2010 and an occupancy rate of 1.5 passengers per car (Öko-Institut e.V. 2008); **data from the USA 2008, first for a compact car in urban transport, second for urban diesel bus in peak and off-peak operation hours, and third for two different light rail systems, without declaration of peak-hour, off-peak-hour, or average operation (Chester and Horvath 2009).

old rolling stock, a relatively low occupancy rate, and the old energy mix. This is not a surprise for passenger cars, but more for bus travel. Based on the data of Chester and Horvath (2009), buses have a lower GWP and CED only during peak operation hours. However, it is clear that a functioning public transport system must provide operation even in off-peak hours in order to be a more or less suitable and comfortable alternative to private cars. Therefore, calculations must go beyond peak hours and consider the average occupancy rate during all operation hours (Baumgartner et al., 2000; Chester & Horvath, 2009; Schmid et al., 2001).

This study is based on a technical−environmental assessment and by itself cannot provide sound decision support, which would require more investigations, a bigger number of indicators, and subsequent weighing. What has not been regarded in this research is the aforementioned claim of short travel distances within urban areas to achieve sustainable urban development, as considered, for instance, by Harwatt, Tight, and Timms (2011). Subways and commuter rails are modes of transport designed for longer travel distances, and thus contradictory to the claim of short travel distances, because they may cause and initiate urban sprawl. However, cities of a certain size such as Vienna, with an already high population density and a projected population growth of 12%−85% until the year 2050, will not be able to further densify the old settlement areas in order to cope with this growth (Schremmer et al. 2011). Thus, a measure for more or less sustainable growth is to locate future settlements along main transport axes, providing access to high-capacity public transport lines such as subways or commuter trains.

Finally, most of the data applied in this research was data retrieved from Wiener Linien. Some of the data, like the electricity demand to operate the trains and the stations and the material and energy demand to produce the rolling stock, was primary data in good quality. The data for material and energy demand to construct the buildings was of lesser quality, as it referred to estimates based on the environment impact declaration and the bidding documents. If the data recorded during the construction phase is available, the figures used in this study must be assessed and, if necessary, adjusted. Fortunately, this step will be carried out by the publishing institute in the near future.

6. Conclusions

Provision of high-capacity urban railway transport systems replacing fossil based individual passenger transport is, among other interventions, one option to reduce the GWP and the CED of modern cities. The study shows that subway systems have relatively low emissions and energy demand when compared to other means of motorized transport, even though the building and construction phase is much more important for these emissions. One factor, therefore, is the decision to acquire new technology with lower GWP; another is the policy decision on spatial planning issues, which again influence the number of passengers transported and thus the occupancy rate. Although widely promoted as an important measure to reduce the GWP and the CED in the public transport sector, the change in the energy mix did not influence the result extensively. Therefore, the research provides some valuable information for policymakers and transport companies regarding the efficiency of their measures in reducing their GWP and CED, but it also give some insight into the methodological challenges, among them the relevance of the expression of the occupancy rate.

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Appendix

Abbreviations

CED	cumulative energy demand
CO_2-equiv.	CO_2 equivalent
GEMIS	globales emissions-modell integrierter systeme (global emissions model for integrated systems)
GHG	greenhouse gas emissions
GWP	global warming potential
LCI	life cycle inventory
LCIA	life cycle impact assessment
PKT	person kilometer traveled