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Land Use of Urban Public Transport Systems

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Keywords

Public Transport, Land Use, Ecological Footprint, Hinterland, Urban Region, Area Efficiency

Abstract

As the world urbanizes cities all over the globe have been constantly growing. Directly linked to the population growth of cities are increasing traffic and steadily raising land prices. Compared to the increase of many commodities observed during last decades land prices in cities have experienced significantly higher gains, indicating its overall scarcity. One option to cope with increasing traffic and scarce land availability is to strengthen public transport systems, as they are characterized by lower land use and higher transportation capacities. Besides the direct land use within the city borders transportation systems also cause land use in the hinterland, for example for the extraction of raw materials, for energy supply or for the sequestration of emitted carbon dioxide.

The study at hand investigated different land uses of a public transport network taking the case study of Vienna and its three main modes of public transport (subway, tram, and bus). The land uses distinguished were the **direct land use** within the city (for tracks, garages, etc.), the **direct land use in the global hinterland** (to provide energy and resources), and the land needed to sequestrate the CO_2 emissions emitted. For the latter a distinction between the CO_2 emissions from direct energy consumption (**operational energy CO_2 hinterland use**), and from CO_2 embodied in goods and materials (**embodied CO_2 hinterland use**) was made. The overall land use of the public transport system was finally determined and illustrated using an extended ecological footprint (EF) analysis.

The results obtained indicate that the operational energy CO_2 hinterland use, which accounts for the energy consumption, contributes most to the overall land use (550 km²), followed by the embodied CO_2 energy hinterland use (150 km²) and the direct hinterland use (16 km²). The direct land use within the city covers an area of around 6.2 km² (1.5% of city area) which corresponds to 1% of the ecological footprint (EF). Divided by transport mode, the subway has the largest EF (51%) followed by busses 20%, trams 19%, and services 10%. However, calculation of the EF per performance unit changes this ranking: the bus uses round 1.7 times the area per person kilometer traveled compared to subway.

On the basis of these results, the reduction of land use of Vienna's public transport network can be planed. It can be argued that that the knowledge about the mentioned lands and by what degree they are caused by specific inventory categories is essential to find reduction measures. Finally, our findings are essential to ensure sustainable development of the urban public transport.

1. Introduction

Urbanization leads to growing cities, until 2050 the current share of 50% of the global population living in urban areas will further increase to 80% (UN-DESA, 2014). The latter is also responsible for a significant share of cities´ overall resource consumption and CO_2 emissions, which leads to a large land use for providing resources (e.g. energy, construction materials) and sequestrate CO_2. To reduce traffic area, emissions and resource consumption public transport is widely propagated, as it allows transporting more passengers over the same cross section per hour (Whitelegg, 1993) and fewer emissions are emitted per person kilometre travelled (Umweltbundesamt, 2014).

Public transport systems like in Munich, Paris, Shanghai and Vienna comprise mainly busses, trams, subways and railways. Therein, subways have the advantage of requiring less above-ground land within a city (Pfaffenbichler, 2001; Randelhoff, 2014) while providing high transportation capacity at the same time. On the other hand, they require more materials than tramways or bus lines, i.e. for the construction of tunnels (Andrade and D'Agosto, 2016; Lederer et al., 2016a, 2016b; Li et al., 2016), which impact on direct land consumption in the cities' hinterland for the supply of raw materials (e.g. land for gravel pits), goods (e.g. land for cement production plants), and energy (e.g. land for coal mines necessary to supply cement production or power plants to generate electricity for concrete mixing). In addition to this direct land and hinterland consumption, sustainable urban development planning should furthermore consider the compensation of greenhouse gas (GHG) emissions (e.g. CO_2 sequestration by forests). This land requirement can be assessed by means of the so-called "ecological footprint", which should always be set in context with the overall life-cycle emissions as specified in several frameworks and studies (e.g. (European Commission, 2013; Matthews et al., 2008; Wackernagel and Beyers, 2010). Several studies (e.g. (Barrett and Scott, 2003; Bhandari et al., 2014; Chi and Stone, 2005; Lederer et al., 2016b; Tuchschmid, 2009)) have already assessed the contribution from public transport systems or partial transport modes to the emissions of a region or urban area. However, none of these studies have analyzed the contribution to the overall direct land use and the different land uses in hinterlands of each transport mode.

With respect to above mentioned aspects, the overall objective of the study at hand is to provide a detailed analysis of land consumption of an urban public transport system. To fulfill this objective, different land uses of an urban public transport network are investigated. The land uses distinguished were the ***direct land use within the city*** (for tracks, garages, etc.), the ***direct land use in the global hinterland*** (to provide energy and resources), and the land needed to sequestrate the CO_2 emissions emitted. For the latter a distinction between the CO_2 emissions from direct energy consumption (***operational energy CO_2 hinterland use***), and from CO_2 embodied in goods and materials (***embodied CO_2 hinterland use***) was made. The ***overall land use*** of the public transport system was finally determined and illustrated using an extended ecological footprint (EF) analysis.

Vienna's public transport system has been investigated as a case study. Considered is an integrated transport system of one provider operating three different transport modes, yielding a unique set of data. The fact that this type of transport system and operation is prevailing at least in European cities of comparable size (van Egmond et al., 2003) underlines the relevance of the study at hand. For the study, real inventory and energy-consumption data were used.

2. Material and methods

In the case study city of Vienna, the share of public transport of the modal split was 39% in 2013 (Wiener Stadtwerke Holding AG, 2013a). 85% of the overall passenger kilometers traveled (PKT) by public transport was provided by WIENER LINIEN GmbH & Co KG (Österreichisches Institut für Raumplanung (ÖIR), 2014). In the study at hand, only the service covered by this provider is considered. In the reference period from 2012-2013, which was used in this study, the provider operated a network of 5 subway lines, 29 tram lines, and 109 bus lines, characterized by a length of 79 km, 172 km and 700 km, respectively. Additionally, service buildings (e.g. administration) are part of the operators assets (Wiener Linien GmbH & Co KG, 2016) and have been considered in the present study.

The overall land consumption of Vienna´s public transport system has been determined using an extended ecological footprint (EF) analysis approach based on several studies (Borucke et al., 2013; Global Footprint Network, 2009; Rees, 1992; Wackernagel, 1994; Wackernagel et al., 2005; Wackernagel and Beyers, 2010; Wackernagel and Rees, 1996). While most EF studies quantify the overall land required on a global scale, the study at hand distinguished direct land use and the land use in global hinterland. The hinterland is divided in the three categories: direct hinterland use, embodied CO_2 hinterland use, and operational energy CO_2 hinterland use

To calculate the land use categories mentioned, different data were utilized. The direct land use was determined using spatial data processed by a geographic information system (GIS). To assess the hinterland demand, an ecological footprint (EF) calculation was performed. Thereto the software SimaPro and the therein implemented database Ecoinvent was utilized. For the determination of the incorporated land use due to the provision of materials and goods (for the infrastructure of the public transport system), a material inventory was created. Direct land use caused either by material or energy use was subsumed under the category of direct land use. The total land use (ecological footprint) was calculated by combining all four land use categories. Finally, the results obtained were referred to the transport capacity, seat km provided (SKP), and the actual performance in terms of passenger kilometers traveled (PKT). Figure 1 summarizes the method of the study at hand.

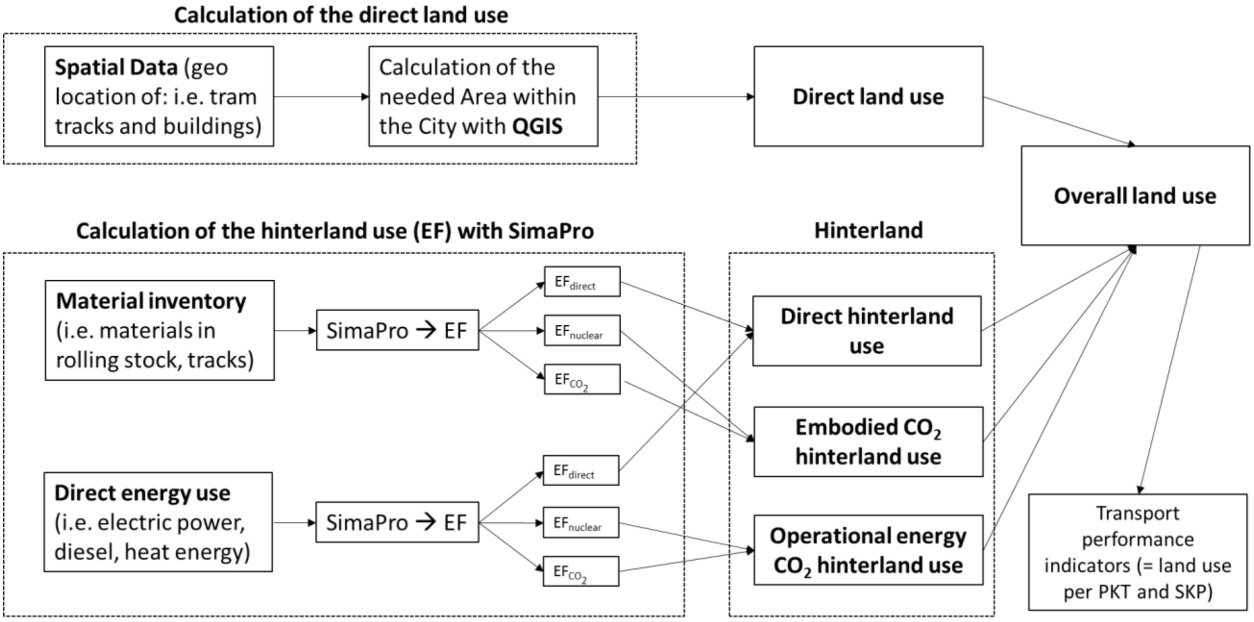

Figure 1: Calculation method and resulting land use categories

2.1. Direct land use

To calculate the direct land use within the city, all surface areas in use by the public transport provider were identified considering the transport modes subway, tram, and bus, including service buildings (depots, garages and administration). Therefore spatial data provided by the city of Vienna (Federal Chancellery and Vienna City Administration, n.d.) and GIS data sets of the operator were used. The data was evaluated and processed using the open source software QGIS (Version 2.16.2). For each transport mode the network was divided into areas in use below and above ground, whereas only the latter were regarded as direct land use. Detailed information which data is used per transport mode is provided below:

- **Tram:** Data from the Municipal Department 28 - Road Management and Construction (MA 28), in detail the so called Straßeninformationssystem (SIS) provides the basis for the direct land use of the tram lines (MA 28, n.d.). The spatial data for buildings (i.e. train depots, engineering rooms, social rooms, and other services) was retrieved from the operator. The stops are on public areas due that reason they are not in that database, the area used is calculated separately on the basis of the number of stops.
- **Subway:** The direct land use for the subway was determined using spatial datasets provided by the operator. The basic data set includes all civil engineering constructive works (tunnels, bridges, elevated track sections).
- **Bus:** The area for the bus network was determined by using vector data for the bus lines from Wiener Linien (Wiener Linien GmbH & Co KG, 2015). Transversal to the vector of the bus lines, a puffer was set to create a raster layer, distinguishing manually between sections where busses travel solely in one direction and those which are used for travel in both directions. According to bus standards, the width of the puffer was chosen at 3.5 m for sections in one direction and 6.5 m for sections used in both directions (MA 18, 2011). The bus stops were calculated separately on the basis of the number of stops.
- **Services:** As some buildings (e.g. main administration building and main garage) cannot be allocated to one single mode of transport, their areas are treated separately in the study at hand. The spatial data is provided by the operator.

2.2. Calculation of the hinterland

In order to assess direct hinterland use, first the quantity and composition of materials (including goods) consumed were determined. Therefore, data provided by the operator were categorized and a material inventory (see section 2.3) was created. Based on the material inventory, direct hinterland use was calculated using the software SimaPro (version: 7.2.3). In addition, the software was also used to determine the EF for the inventory.

SimaPro uses the Ecoinvent database, which includes not only all preceding chains of materials and energy for manufacturing these materials, but also the associated land uses (Hischier et al., 2010). The method implemented in SimaPro distinguishes three environmental impact categories associated with land use ($EF=EF_{direct}+EF_{CO2}+EF_{nuclear}$). The categories are divided in direct land occupation (EFdirect) and indirect land occupation (EF_{CO2} and $EF_{nuclear}$). The indirect land occupation is related to nuclear energy use (EFnuclear) and to the sequestration of CO_2 emissions from fossil energy use (EF_{CO2}) (Hischier et al., 2010). Contrary to the common application of SimaPro, direct hinterland consumption due to material and associated energy supply is presented separately from the hinterland used to sequestrate CO_2 emissions related to the production of materials. In other words, the total direct hinterland consists of the direct land occupation calculated from materials (and goods) used and the direct land occupation related to direct energy use. The hinterland land use categories are given in global hectares per time [gha/ a]. A normalization was made in categories where materials and goods were used over a longer period than one year. For this reason, the results of the calculation (land use) for these categories were divided by assumed life spans that derive from economic depreciation. The economic life spans were defined by the financial accounts department based on legal regulations and are individual for each asset category.

2.3. Inventory data to calculate the hinterland

To assess direct hinterland use and the embodied CO_2 energy hinterland use, first a material inventory of all used goods and materials by Wiener Linien has to be determined. An overview of the inventory of Wiener Linien, the categories and sources used, is presented in Table 1. Inventory data from the public transport provider were collected, assessed and categorized. Thereby the following data groups were identified: (i.) buildings, (ii.) mobile and immobile assets, (iii.) rolling stock, (iv.) consumer goods, (v.) waste.

The respective quantity of goods within the data groups had to be linked with the material composition of each good. Besides information collected during previous studies (Gassner, 2013; Lederer et al., 2016a, 2016b; Ott et al., 2010), material intensities were taken from literature and the Ecoinvent database. The categorization of goods and its linkage to material intensities was very diverse for each data group due to the available data, but also due to different features. In general, the formulae applied have in common that information on quantities of goods (e.g. section length, number of goods) is multiplied by specific material intensities of these goods (e.g. copper in wire, concrete in buildings).

Due to resource constraints, similar infrastructures and appliances were clustered in joint categories, and representative elements of these categories were analyzed and subsequently the data have been up-scaled to account for all elements of the respective category.

The inventory data was divided wherever applicable into traffic modes and services. For the categories consumer goods and waste, for instance, an allocation to traffic modes was not accomplished. Hence, both are accounted for in the category services. The inventory data contain physical assets like buildings and rolling stock and nonphysical assets like thermal heat or electric power. For the physical assets, the material intensity and material composition were investigated. To calculate the environmental impact of nonphysical assets (power supply) the overall energy mix had to be identified.

Table 1.Inventory Data Wiener Linien – Data categories and sources

Data Category	Transport mode	Description	Source Material intensity and mass
General buildings	Tram, subway, bus, services	Storage buildings and administrative buildings	(Hoffmann et al., 2011; Kellenberger et al., 2007)
Subway construction	Subway	Subway constructions, inkl.104 metro stations	(Lederer et al., 2016a).
Tram Tracks	Tram	Own calculation on the basis of the single-track standard cross-section.	(Wiener Linien GmbH & Co KG, 2012a)
Mobile and immobile assets	Tram, subway, bus, services	Allocation to the mode of transport with cost categories. In total around 36,500 assets are in use within the company. An ABC-analysis was performed to exclude non relevant assets. In total 18,000 assets were finally merged to **162 different categories.**	The 162 categories have subsequently been evaluated for their composition using literature data, own calculations or expert interviews.
Rolling stock	Subway	700 subway trains, three different types (types V, U, and T)	(Bomardier, n.d.; Siemens AG, 1998; Struckl, 2007; Wiener Linien GmbH & Co KG, 2012b; Wiener Stadtwerke Verkehrsbetriebe, 1985)
Rolling stock	Tram	525 tram cars that divide into three types (A, B, and E)	(Pamminger and Adamek, 2010; Siemens AG, 2004a, 2004b; Spielmann et al., 2007; Wiener Linien GmbH & Co KG, 2013; Wiener Stadtwerke Verkehrsbetriebe, 1984)

Rolling stock	Bus	Three different types of busses are in operation, namely 223 low-floor normal buses, 234 low-floor articulated buses and 12 low-floor battery-powered buses (2-door).	(Gassner, 2013; Siemens AG, 2012; Wiener Linien GmbH & Co KG, 2013)
Consumer goods	Services	The purchasing department provided data on low-value assets and consumer goods. An ABC-analysis was performed and around 46,000 various articles remained. For all remaining goods, their mass was calculated. In general, the consumer goods can be allocated to a few main material groups. For instance, the majority of maintenance materials like screws, bolts and track wheels were made of steel. **64 consumer good material categories** were identified.	Each type were allocated to an Ecoinvent process (e.g. Rainforced steel, paper, motor oil etc.)
Waste	Services	The annual amounts of waste arising were grouped by the type of waste. Each type of waste is defined by a waste code. 63 different types of waste were generated by Wiener Linien in the year 2012.	Each type were allocated to an Ecoinvent processes.

To assess the operational energy CO_2 hinterland use, first the total operational energy demand has to be determined. The respective data, which comprises the electricity for the subway and tram operations, fuel for busses, heat for the subway stations and electricity for buildings and services, was retrieved from the operator (c.f. Table 2). In the second step, data on the energy mix for the production of operational energy was obtained.

The electricity supplier of the transport provider “Wien Energie” reported the overall energy mix for electric power in 2012 as follows: 46.62% hydropower, 44.99% natural gas, 3.74% wind and solar power, 0.08% power from renewable sources, 3.62% biomass energy, and 0.94% biogas (Keuschnig, 2014). The energy mix for the district heating was: 5,8% biomass energy, 14,3% waste heat (from industry), 17,8% waste incineration, 62,1% combined heat and power generation (natural gas) (Wiener Stadtwerke Holding AG, 2013).

By inserting this data in SimaPro, the operational energy CO_2 hinterland use was calculated, the operational energy CO_2 hinterland use is given in global hectares for one year [gha/a].

Table 2.Total energy consumption 2012 Wiener Linien in Megawatt hour (MWh); own representation based on data from Wiener Linien - (Rumpeltes and Reeps, 2013) and (Keuschnig, 2013).

Energy and Fuels	Megawatt hour (MWh/a)
Electric power consumption	426,647
District heating heat consumption	67,537
Liquid Petroleum Gas (LPG)	191,927
Natural gas	5,082
Diesel	7,518
Gasoline	215

2.4. Calculation of Transport performance indicators

The results were normalized to the transport performance. The total land use per year were divided by the amount of kilometers travelled (PKT) by all passengers of the public transport system. In order to consider not only the PKT but also the transport capacity offered by the operator, another normalization was performed using the seat kilometer provided (SKP). The data about the transport performance was taken for PKT (Österreichisches Institut für Raumplanung (ÖIR), 2014) and for SKT (Österreichisches Institut für Raumplanung (ÖIR), 2013).

3. Results

Results show that the direct land use within the city of Vienna covers with 620 ha around 1.5% of the city area. Altogether, the three land uses in global hinterland are 115 times larger than the direct land use in the city. Therein, the operational energy CO_2 hinterland use contributes most to overall land use, followed by the embodied CO_2 hinterland use and the direct land use in the global hinterland.

The resulting overall land use calculated was ~72,500 gha per year which equals around 175% of the city area. Vienna has around 1.8 million inhabitants. Hence, the overall land use of public transport per capita is ~300 m²/a. In Figure 2 the overall land use per land use category is presented and set in relation to the number of soccer fields which equal that area.

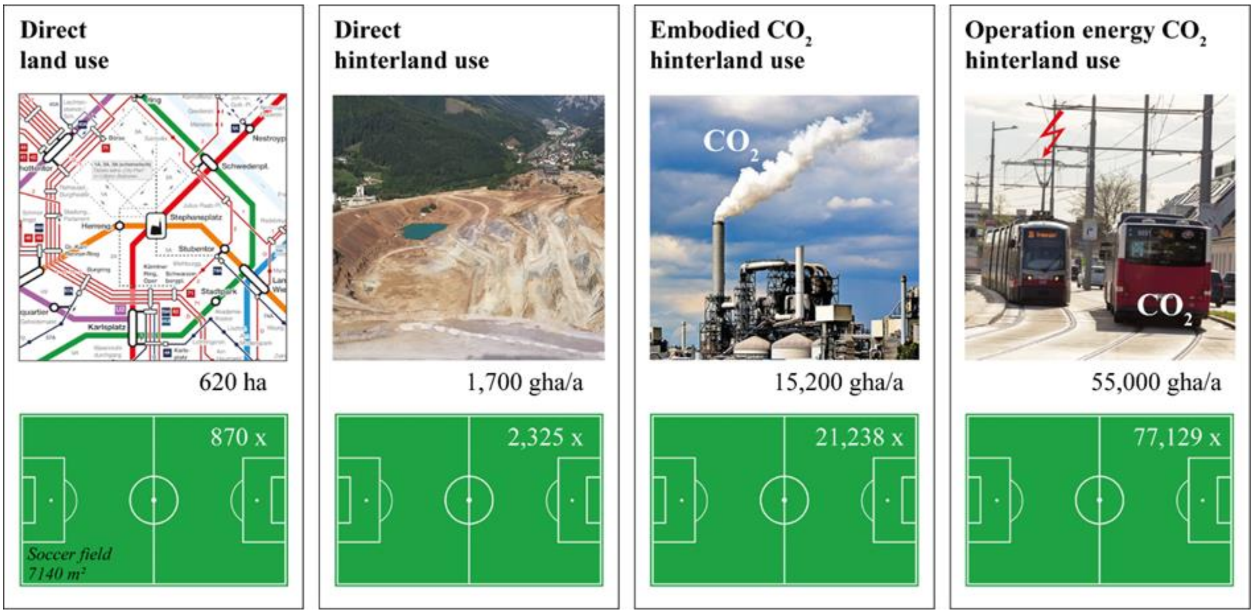

Figure 2: Overall land use divided by land category; size in relation to soccer fields

In Figure 3 the overall land use for the three transport modes are presented. Beside annual land use, the results are presented with respect of the transport performance in m²/PKT and m²/SKP. The comparison of the transport modes shows that the subway requires with 51% the largest share of the overall land use followed by bus (20%), and tram (19%). The remaining 10% are for services (e.g. office buildings) that can't be allocated to one of the aforementioned modes. For services a land use of around 7,000 gha/a was calculated, this number is included in the overall land use of urban public transport of Vienna within the Figure 3.

The results indicate that the subway shows the largest overall land use of all transport modes. However, when considering at land use per performance unit, this ranking of the transport modes changes. Due to the high transport performance of the subway and tram, both perform better than the bus. The transport mode bus needs around 1.7 times the area per PKT and 2.5 times the area per SKP compared to the subway.

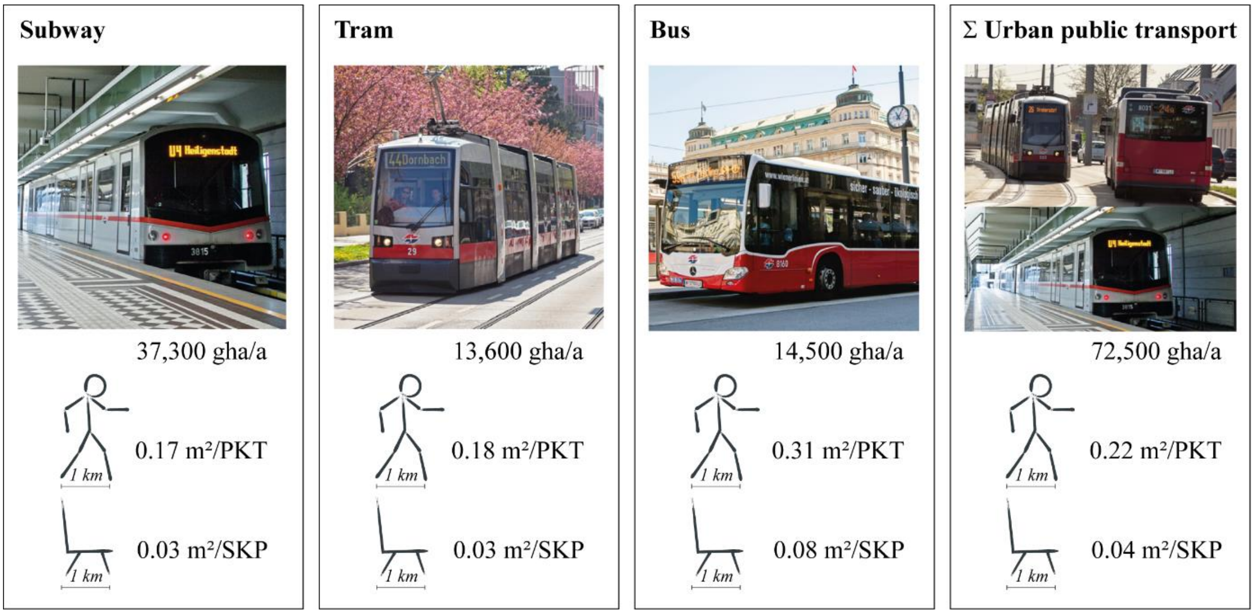

Figure 3: Overall land use divided by transport mode, land use per functional unit

4. Discussion and conclusions

A new approach for the analysis of land use of urban public transport systems is presented. The introduced classification of direct land use of transport systems distinguishes between local and global level. The differentiation between the different land uses allows the operator assessing the impact of different measures (e.g., change of electricity mix, extension of network, preference of certain transport mode) on the land use within the city of Vienna and beyond its border. The classification respects the issue that not every land use has the same relevance for each stakeholder and decision maker. Also Zeev pointed out this conclusion when distinguishes in her study between domestic and global hinterlands (Zeev et al., 2014). For instance is the challenge of scare space within a city more tangible for local politicians and authorities than the problem of CO_2 emissions. In contrast this global challenge is more important for NGOs or politicians on national and global level. For this reason, it is essential to not only distinguish between different types of land uses in the EF, as applied in the study at hand, but also to explicitly provide the results differentiated according to land use type.

The results emphasize that when the land required for the sequestration of CO_2 emissions are included in the analysis of land use, energy consumption and building materials of the urban public transport system investigated are dominating the overall land use. A significant decrease in the EF can only be reached by reducing the hinterland EF. Three potential measures to do so, which were also investigated by Lederer, are briefly discussed here (Lederer et al., 2016b). A reduction can be achieved by using a different energy mix with a higher share of renewable energies. In the short-run, however, this can only be done by purchasing more renewables from the energy provider, which means that another customer will have to buy the surplus of non-renewable energy. The transport provider is here dependent on the energy suppliers, yet remarkable changes in their energy generation towards renewables are rather an issue of decades than years. Another option to reduce the total EF is to decrease the energy consumption. This reduction lies in the hands of the transport provider as the transport provider f.i. can decide which type of vehicles or lights he acquires. However, an increase in efficiency can be reached in diverse areas within the system as presented by González-Gil for urban rail systems (González-Gil et al., 2014). Reduced energy consumption will influence the EF, but also the provider’s budget. However, budget constraints are the main reason why older and less efficient facilities are not replaced earlier. Finally, to reduce the EF per functional unit, an increase in the occupancy rate is an option which is, considering the occupancy rate of other cities, particularly in Asia, possible. For example, the occupancy rate of the subways presented by Li or Andrade and D’Agosto are about twice as high as in Vienna (Andrade and D’Agosto, 2016; Li et al., 2016). Reaching these load factors would mean an overall reduction by a factor of two. The question is whether such load factors would be accepted by the users. As Vienna is quite a prosperous city, and many of the users have alternatives – in the best case a bicycle, in the worst case (EF-wise) a car – the outcome of any attempt to increase the load factor is highly uncertain.

The result is not only relevant for Vienna, but also for other European cities of comparable size, as most of them have multi-modal transport systems similar to that in Vienna (van Egmond et al., 2003). In contrast to case studies which investigated one special transport mode such as rail transit (Li et al., 2016), high-speed rail (Chang and Kendall, 2011) or subway (Andrade and D’Agosto, 2016), the study at hand considered an integrated transport system of one provider operating three different transport modes, yielding a unique set of data. In absolute figures, the subway shows the largest contribution to the EF as well as to three out of four subcategories of the EF (except the direct land use). The total contribution of trams, busses, but also services is much lower, even though the network length of trams and busses is two and ten times larger, respectively. One reason for that is the material and energy intensive engineering work in subways, which has also been observed by Anderson (Anderson et al., 2015). Another reason is the traction energy consumed. However, when referring the results to the passengers transported, the subway has the lowest EF of all three modes of transport offered by the transport provider. In both cases, however, the question is if these results can guide decision making on whether a city of the size of Vienna should focus more on subway, tram or bus extension. This question is difficult to answer as the three transport modes are interlinked to each other in a network of main transport axes along densely populated areas (subways) and a small boned network of tram and bus lines in less densely populated areas connected to the main axes. The dense network of feeder lines guaranties nearby accessibility to the public transport network for the passengers (Ostermann et al., 2016).

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