Doctoral Thesis

Development and Dynamics of Material Stocks of an Urban Transport System: A Case Study from Vienna

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Dissertation

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Abstract

A significant share of material demand and material stocks within urban societies are related to the transport sector. Urbanisation, network expansions, and the transformation towards a more sustainable transport system have increased the sectors material demand and waste generation. Due to its relevance not only for the greenhouse gas emissions and but also for the overall material turnover, the sector is being addressed in various resource management strategies. In the frame of the present thesis, the transport system of the city of Vienna was investigated as a case study. The system was analysed from different levels of consideration, ranging from the material turnover and stock of the overall system to specific construction actions.

First, the currently prevailing transport system and its development since 1990 was analysed, subdivided according to various transport modes. The material turnover and material stock development associated with the transport infrastructure (new construction, maintenance, deconstruction) as well as the development of the vehicle fleet (new vehicles, end of life vehicles) was investigated. Thereto a bottom-up material flow analysis (MFA) was performed. In the investigated period from 1990 to 2015, the total material stock of the transport system in Vienna increased by 26% to a total of about 100 million tons. The results show a significant expansion of transport infrastructures within the period investigated, in particular for the transport modes public transport and active mobility (walking and cycling). The material stock per capita of the transport mode motorized individual transport remained constant (34 t/capita). In the same period, the material stock of public transport has increased by 8% to 20 t/capita and that of active mobility by around 10% to 4 t/capita. The majority of material turnover is related to maintenance and rehabilitation activities (65%), whereby this share increases accordingly with the increasing degree of development of the respective network.

Second, to estimate the future development of the urban transport system and its impact on resource demand and waste generation, the development until 2050 was modelled using different scenarios. For this purpose, the retrospective MFA model was adapted and extended accordingly. In addition to a scenario, which prolongs the status quo into the future, the following scenarios were distinguished: (i) the share of motorized individual transport in the modal split remains at current level (25%), but to meet emission reduction targets the vehicle fleet will be converted to alternative propulsion technologies; (ii) the share of public transport increases significantly from currently 38% to over 55%;

or (iii) the importance of active mobility increases significantly (from 37% to 45%). For each scenario the changes needed to provide the required transport performance per transport mode were quantified and the according development of the vehicle fleets was modelled. The results show that without any change in the choice of transport mode, the road transport network will have to be expanded further and the annual resource demand will continue to rise. In contrast, if the share of motorized individual transport decreases to below 10%, the per capita material stock of the transport sector will decrease from currently 58 t/capita by 19% to about 47 t/capita by 2050. This will be accompanied by a decreasing private vehicle fleet. The overall reduction of the private vehicle fleet will enable a significant reduction of land used as road area and will allow to use the scarce resources land within the city for other purposes (e.g., for bicycle paths or green areas).

In the third part, subsections of the urban transport system in Vienna are examined in detail. First, the material demand and waste generation associated with a refurbishment project of a section of the Vienna subway was investigated using a bottom-up MFA approach. Special attention was given to the proportion of secondary construction materials being used in practice. The investigation revealed that the use of recycled construction materials is already state of the art in civil engineering (especially in the track substruction). Thus, in the case study, around 55% recycled construction material, 40% primary material, and 5% reused components (mainly railway sleeper and rails) were built in. Finally, in another case study, a life cycle based ecological assessment of different transport modes was carried out. The object of investigation was Vienna's largest public transport provider Wiener Linien. The direct and global land use was determined using an extended ecological footprint approach, subdivided into the respective modes of transport (subway, tram, bus). The results highlight that the incorporated energy in construction materials built-in the transport infrastructure (20%) as well as the energy consumption associated with the operation (mainly electrical power and fuels) (75%) contribute the most to the overall ecological footprint of the transport provider.

The presented work illustrates the importance of the prevailing urban transport system for the total construction material turnover within urban areas. It further shows that a transformation towards carbon-free urban transport will only lead to a long-term reduction in material turnover if it is also associated with a reduction of the share of private motorized individual transport.

Kurzfassung

Ein maßgeblicher Anteil des anthropogenen Ressourcenverbrauches und des Materiallagers geht auf die Verkehrsinfrastrukturen zurück. Aktuell stehen städtische Verkehrssysteme vor einer Transformationsphase, um zukünftigen gesellschaftlichen Anforderungen gerecht zu werden. Die zunehmende Urbanisierung und damit verbundene Aus- und Umbauten der Netzwerke erhöht die Relevanz für den Ressourcenverbrauch dieses Sektors zusätzlich. Das Wissen über die Materialzusammensetzungen von Verkehrsinfrastrukturen und die Dynamiken von städtischen Verkehrssystemen sind wesentliche Vorrausetzungen, um effektive Maßnahmen im Ressourcenmanagement zu setzen. In der gegenständlichen Dissertation wurde hierzu als Fallstudie das Verkehrssystem der Stadt Wien je nach Fragestellung von unterschiedlichen Betrachtungsebenen untersucht, vom Materialumsatz des Gesamtsystems bis hin zu konkreten Baumaßnahmen.

Zunächst wurde das aktuell vorherrschende Verkehrssystems und dessen Entwicklung seit 1990 untergliedert nach Verkehrsträgern analysiert. Untersucht wurden dabei die Materialumsätze (Materialeinsatz und Abfallaufkommen) und Materiallagerveränderungen, welche mit der Infrastruktur (Neubau, Umbau, Wartung, Rückbau) sowie der Entwicklung der Fahrzeugflotte (Neufahrzeuge, Altfahrzeuge) in Verbindung stehen. Als Methode kam eine bottom-up Materialflussanalyse (MFA) zur Anwendung. Das Gesamtmateriallager des Wiener Verkehrssystems stieg im Zeitraum von 1990-2015 um 26% auf insgesamt rund 100 Millionen Tonnen an. Die Ergebnisse zeigen, dass es im Betrachtungszeitraum zum deutlichen Ausbau von Infrastrukturen des Umweltverbundes (Öffentlicher Verkehr und Aktive Mobilität) gekommen ist. Pro Kopf liegt das Materiallager des motorisierten Individualverkehrs konstant bei rund 34 t/EW, hingegen hat das pro Kopf Materiallager des Öffentlichen Verkehrs im selben Zeitraum um 8% auf 20 t/EW und jenes der Aktiven Mobilität (Gehen und Radfahren) um rund 10% auf 4 t/EW zugenommen. Der überwiegende Anteil des Materialumsatzes steht in Zusammenhang mit Wartungs- und Sanierungstätigkeiten der Infrastruktur (65%). Dieser Anteil nimmt mit zunehmenden Ausbaugrad der jeweiligen Netzwerke zu.

Um die zukünftige Entwicklung des städtischen Verkehrssystems und dessen Auswirkungen auf den Ressourcenverbrauch sowie das Abfallaufkommen abschätzen zu können, wurde anhand von unterschiedlichen Szenarien die Entwicklung bis 2050 modelliert. Dafür wurde das retrospektive MFA Modell entsprechend adaptiert und erweitert. Neben einem Vergleichsszenario welches den Status-quo fortschreibt wurden folgende Szenarien unterschieden: (i) der Anteil des motorisierten

Individualverkehres am Modal Split verbleibt am heutigen Niveau (25%) und die Fahrzeugflotte wird auf alternative Antriebssysteme umgestellt, (ii) der Anteil des Öffentlichen Verkehrs steigt deutlich auf über 55%, oder (iii) die Bedeutung der Aktiven Mobilität nimmt deutlich zu (45%). Die notwendigen Aus-, Um-, und Rückbauten der jeweiligen Netzwerke, um die entsprechende Transportleistung erbringen zu können sowie die Entwicklung der jeweiligen Fahrzeugflotten wurden hinsichtlich deren Auswirkungen auf den Materialumsatz quantifiziert. Die Auswertung zeigt, dass wenn der Anteil des motorisierten Individualverkehrs am Modal Split am heutigen Niveau verbleibt, sind zukünftig Erweiterungen des städtischen Straßenverkehrsnetzes erforderlich und der jährliche Ressourcenverbrauch steigt weiter an. Sinkt hingegen der Anteil des motorisierten Individualverkehrs auf unter 10%, so kommt es bis 2050 zu einem Rückgang des Materiallagers pro Kopf von ca. 58 t auf etwa 47 t/EW. Dies geht einher mit einer sinkenden privaten Fahrzeugflotte, wodurch ein deutlicher Rückbau von Straßenverkehrsflächen und Flächenumnutzungen (z.B.: in Radwege) möglich werden.

Im dritten Teil der Arbeit werden einzelne Subbereiche des Wiener Verkehrssystems im Detail untersucht. Zunächst wurde mithilfe einer bottom-up MFA der Materialeinsatz und das Abfallaufkommen eines konkreten Sanierungsprojektes eines Teilabschnittes der Wiener U-Bahn untersucht. Dabei stand insbesondere der Anteil von sekundären Baumaterialien in der Praxis im Fokus. Die Untersuchung ergab, dass im Tiefbau (v.a. im Unterbau) die Anwendung von recycelten Baumaterialien bereits Stand der Technik ist. So wurden in der Fallstudie rund 55% Recyclingbaumaterial, 40% Primärmaterial, und 5% wiederverwendete Bauteile (v.a. Schweller und Schienen) eingesetzt. Abschließend wurde in einer weiteren Fallstudie eine lebenszyklusbasierte ökologische Bewertung von unterschiedlichen Verkehrsträgern durchgeführt, dazu wurde der größte öffentliche Verkehrsanbieter Wiens, die Wiener Linien, als Untersuchungsobjekt herangezogen. Für das gesamte Unternehmen wurde der direkte und globale Flächenverbrauch untergliedert nach den jeweiligen Verkehrsträgern (U-Bahn, Straßenbahn, Bus) mithilfe eines erweiterten Ökologischen Fußabdruck Ansatzes bestimmt. Die Ergebnisse zeigen deutlich, dass die inkorporierte Energie in Baustoffen der Infrastruktur (20%), sowie der Energieverbrauch im Betrieb (v.a. Strom und Treibstoffe) (75%), den größten Anteil zum gesamten Ökologischen Fußabdruck des Betreibers beitragen.

Die Arbeit zeigt die Bedeutung des vorherrschenden urbanen Verkehrssystems für den gesamten Baumaterialumsatz einer Stadt auf. Deutlich wird ferner, dass eine Transformation in Richtung eines kohlenstofffreien urbanen Verkehrssystems nur bei entsprechender Reduzierung des Anteils des privaten Individualverkehres auch zu einer langfristigen Reduktion des Materialumsatzes führt.

Published Articles and Contributions

I) A. Gassner, J. Lederer and J. Fellner. Material stock development of the transport sector in the city of Vienna. Journal of Industrial Ecology, 24: 1364-1378, 2020.
DOI: https://doi.org/10.1111/jiec.13024

II) A. Gassner, J. Lederer, G. Kovacic, U. Mollay, C. Schremmer and J. Fellner. Projection of material flows and stocks in the urban transport sector until 2050 – A scenario-based analysis for the city of Vienna. Journal of Cleaner Production, 311: 127591, 2021.
DOI: https://doi.org/10.1016/j.jclepro.2021.127591

III) A. Gassner, J. Lederer and J. Fellner. Changes in Material Stocks and Flows of a Century-old Rail Network Caused by Refurbishment. 7th Transport Research Arena TRA 2018, Vienna; 16.04.2018 - 19.04.201

IV) A. Gassner, J. Lederer, G. Kanitschar, M. Ossberger, J. Fellner. Extended ecological footprint for different modes of urban public transport: The case of Vienna, Austria. Land Use Policy, 72: 85 – 99, 2018.
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Contributions of the author:

I, II) conceptualization; planning and design of the method; creation of the models; formal analysis; data collection and evaluation; literature research; paper writing.

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Contents

1. Introduction

Humankind has been experiencing a shift from a purely rural to a predominately urban living society and this trend seems to continue in the future (Grimm et al., 2008). Additionally, the material demand and waste generation have been constantly growing over the last century (Krausmann et al., 2018) whereat cities are the main drivers of this development (Kennedy et al., 2007). This material turnover is dominated by the expansion of the building and transport sectors (Johansson et al., 2013), leading to an increase in the material stocks (MS) in these sectors, even in highly industrialized societies (Lederer et al., 2020a; Miatto et al., 2019, 2017; Wiedenhofer et al., 2015). There are considerably more studies focussing on buildings than on infrastructures (Augiseau and Barles, 2017). Indeed, the transport infrastructure contributes decisively to the construction material turnover of societies (Sims et al., 2014; Tanikawa and Hashimoto, 2009; Wiedenhofer et al., 2015). Furthermore, due to the significance of the transport infrastructure with respect to the built-in of recycled construction materials mainly in road construction (Hiete et al., 2011), the construction activities related to transport infrastructure play a major role regarding construction and demolition waste (CDW) management as well as for the implementation of closed material cycles of construction materials.

The concept of an increasingly circular economy accelerated by the European Union includes all economic sectors (European Commission, 2015). Particularly important is the construction sector as this sector dominates the material turnover. For this reason, the interest in the material turnover, which can be related to the transport infrastructure, is increasing among political and administrative decision-makers at various levels. The current relevance is further strengthened by the fact, that the transportation sector is currently undergoing a major transformation period to achieve $CO_{2\text{-eq}}$ emission reduction targets. At the city level, corresponding targets for the transport sector are defined within the smart city initiatives. The initiatives of various cities include $CO_{2\text{-eq}}$ emission reduction targets (Neirotti et al., 2014) but also measures towards a more circular economy are recently pushed (Prendeville et al., 2018). Yet, data regarding the MS (intensity, composition, and its dynamics) of the transport infrastructure is often lacking. However, this information is essential for both evidence-based target setting and for the future verification of the achievement of the set targets.

Transport infrastructures are characterized by relatively homogeneous structure and material composition compared to buildings (Kleemann, 2016). Together with their specific ownership structure (i.e., state-owned, centralized management on regional or national level) this results to a high potential for optimizing material cycles. Contrary to other materials, the recycling of construction materials is to be tackled at local level. Because they have an economically and environmentally limited transport distance due to their comparatively low value and high mass (Hiete et al., 2011). To optimize the material turnover of the transport sector on the long term, a knowledge base of the prevailing system in a specific target region is required. This includes data about its past development, interdependencies between different transport modes, and estimates regarding the future development. The quantity and type of the material turnover vary considerably between different settlement densities, modes of transport, types of infrastructure, and the maintenance management (Anderson et al., 2015; Chester and Horvath, 2009; Gassner et al., 2020, 2018). For the assessment of different transport modes, both vehicles and infrastructure have to be included (Anderson et al., 2015; Chester and Horvath, 2009). Furthermore, beside local environmental impacts of urban transportation the environmental impacts on global level like material consumption, emissions or land use have to be considered (Clark and Chester, 2016).

This thesis provides data which forms the basis for the development of measures towards a more circular construction material cycle as well as input data for the environmental assessment of urban transport systems. Furthermore, by examining the transformation process of the transport sector towards a carbon free urban transport system, new information about the dynamics of this process is provided. For this purpose, the development of the transport system until 2050 within the case study city Vienna was modelled based on the objectives defined in its smart city initiative. The transformation of the transport system is defined as a goal in this initiative (City of Vienna, 2019) and, moreover, is sought a reduction of the overall raw materials consumption. Not yet available is a resource-related analysis investigating this transformation. However, decisions taken in the development of the transport system have a very long-term effect due to the long useful life of transport infrastructure (several decades). Thus, the implications with respect of the long-term resource requirements of potential alternatives must be considered at an early planning stage. Aside from authorities and policy makers, the results are of great interest to stakeholders in such disciplines such as traffic and urban planning. Hence, the thesis provides detailed information about the development of transport infrastructure and the vehicle fleets of different transport modes over time, the material intensity and composition of different transport infrastructures and, finally, their renewal rates and maintenance efforts. The addressed topic is of current relevance, as modern societies are increasingly becoming aware of multidimensional local and global impacts of their transport systems and strive to improve the resource management in this sector.

2. Objectives and thesis structure

The main objective of this thesis is to investigate historical, current, and future dynamics of the material stock (MS) and related material flows (MF) of the urban transport system in Vienna. Four main areas of investigation have been addressed:

I) To investigate a transport system and identify resource saving potentials a sound knowledge base of the past development of the prevailing system is necessary. The first part of the thesis aims to build up such knowledge base for the transport system in Vienna including both infrastructure and vehicles. Thus, a bottom-up, multi-year material flow analysis (MFA) is employed to calculate the MS and the related input and output flows of Vienna's transport system for the period 1990-2015. To set up the MFA model, firstly data about the annual development of the various transport infrastructures (construction, conversion, maintenance, and deconstruction) and the development of the vehicle fleets of different transport modes and secondly their material intensity and composition are combined.

II) The second part of the thesis aims to investigates possible future developments and transformations of the transport system in Vienna with regard to the related material demand and waste generation. Based on the above-mentioned MFA model, different scenarios considering the development until 2050 are investigated. In detail, the scenarios differ regarding to the development of the respective transport modes (e.g., network infrastructure expansions, vehicle fleet), the technological development (propulsion technology), and the modal choice of the population. Furthermore, this work includes the aim to investigate future material demand and waste generation depending on different possible transport policy decisions in the coming decades.

III) Maintenance and refurbishment of transport infrastructure dominate the construction material demand and CDW generation of the sector. The aim of the third part of this thesis is to investigate the MF and MS changes occurring within a specific refurbishment project. Thereto, the refurbishment project of a subsection of Vienna's subway network is investigated as a case study by applying a bottom-up MFA. Specific attention is given to the relation between the use of recycling material, reused components, and virgin material. Furthermore, it is investigated to which extent policy targets regarding circular economy are achieved in this refurbishment project.

IV) The transport system has an impact on both urban and global land use. The latter is directly related to the energy and resource demand of the system. In the fourth part of the thesis, the aim is to investigate these local and global impacts of different modes of transport. To this end, the main public transport provider in Vienna, Wiener Linien, is used as a case study. Using an extended ecological footprint methodology, the local and global land use of various transport modes are determined. To perform the calculation, the data base is expanded by the mobile and immobile assets, consumer goods, waste generation, and energy and fuel consumption of the provider.

Based on the above-mentioned factors, the thesis addresses the following research questions:

i. What is the mass of the in-use MS of the transport system (infrastructure and vehicles) in Vienna? How is the development of this MS over time and what is the contribution of different transport modes to this MS?

ii. What is the annual material demand and waste generation rate of the transport sector subdivided by transport mode?

iii. Which processes (e.g., new construction, maintenance) primarily cause the material turnover?

iv. How do the various scenarios affect the development of the overall MS and the annual material turnover of the transport system until 2050?

v. Are there saving potentials for raw materials within the future transport system alternatives and, if so, how can they be realized?

vi. What material flows are related in a refurbishment process of an historically grown subway infrastructure and is there a change in the overall MS?

vii. What is the relation between the use of recycled, reused, and virgin materials within a refurbishment process of a subway infrastructure in Vienna in practice?

viii. Does the ratio of recycling material use in the case study meet the policy targets regarding circular material cycles of construction materials?

ix. What is the total impact of the public transport system in Vienna in terms of its ecological footprint?

x. How do various modes of public transport differ regarding their impact on local and global land use?

This thesis builds on four papers that were authored in accordance with the main areas of investigation to answer the raised questions. The four papers are added in the Appendices. The first paper (*Material stock development of the transport sector in the city of Vienna*) tackles questions of the material stocks and flows of the prevailing transport system in Vienna (questions: i-iii). Within the second paper (*Projection of material flows and stocks in the urban transport sector until 2050 – A scenario-based analysis for the city of Vienna*) the future development of the transport system in Vienna is modelled (questions: iv-v). In the third paper (*Changes in Material Stocks and Flows of a Century-old Rail Network Caused by Refurbishment*) the focus is set on the specific material turnover of a refurbishment process and the use of recycling material (questions: vi-viii). An environmental assessment regarding the public transport provider in Vienna using the ecological footprint method is applied in the fourth paper (*Extended ecological footprint for different modes of urban public transport: The case of Vienna, Austria*) to answer question ix and x.

The further structure of this thesis is based on the four areas of investigation and is therefore built up as follows. In Chapter 3, the methods applied are briefly described and an overview of the existing literature regarding investigations of the material flows and stocks of urban transport infrastructures is given. In Chapter 4, the investigated case study city Vienna and its transport network are characterised. Chapter 5 describes the modelling approaches, system boundaries, assumptions, and input data of the material and environmental models on which the investigation is built on. Next, the results of the four papers are summarised and discussed in Chapter 6. Finally, in Chapter 7 the overall results of the thesis are discussed considering the research questions raised above and an outlook for further research is given.

3. Scientific background

3.1. Methods

3.1.1. Material flow analysis (MFA)

Material flow analysis as described by Brunner and Rechberger (2016, 2004) is a systematic assessment of the state and changes of flows and stocks of materials within a defined system. Whereby, the system boundaries are to be defined in terms of both time and space. A MFA model consists of processes (transformations, relocations, or storages of materials) and flows as connections between processes. A process that stores a material includes a so-called material stock. Within the system the law of conservation of mass is applied, to compare all inputs, stocks and outputs of a process or system. MFA can be performed on the level of goods, sub-goods, or on the level of substances. Goods are economic entities of matter (e.g., rails of tram track), while substances are chemical elements and compounds (e.g., steal in the rail). Hence, a MFA provides a systematic and comprehensive information on the sources, pathways and stocks of the material/substance under investigation (Brunner and Rechberger, 2016, 2004; van der Voet, 2002).

3.1.2. Ecological Footprint (EF)

The original concept of the ecological footprint was introduced by Rees (1992), and focussed on the idea that every individual, process, activity, and region has an impact on the Earth, through resource usage, waste generation and the use of service provided by nature. Since then, the EF has been further developed and represents now a single score indicator in life cycle assessment (LCA). The ecological footprint indicator as defined by Monfreda et al. (2004); Wackernagel et al. (2002); Wackernagel and Rees (1996) counts the biologically productive land and water a population requires to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption. In the context of life cycle accounting, the EF of a product, service or organisation, is defined as the sum of time-integrated direct land occupation (EF_{direct}) and indirect land occupation, related to nuclear energy use ($EF_{nuclear}$) and to CO_2 emissions from fossil energy use and cement burning ($EF_{Carbon\ dioxide}$) (Goedkoop et al., 2008; Huijbregts et al., 2008). As expressed in Equation 1, these three together represent the overall EF.

$$EF = EF_{direct} + EF_{Carbon\ dioxide} + EF_{nuclear} \qquad \textbf{Equation 1}$$

3.2. Literature overview

The research addressing the socio-economic metabolism has a long history. Until the early 2000s, researcher focused on characterizing annual flows, while in recent decades the interest on anthropogenic stocks gained more and more attention (Lanau et al., 2019). Buildings and infrastructures are highly relevant for the overall material turnover of societies and are therefore of special interest (Matthews et al., 2000; Tanikawa et al., 2015). The ratio between these two sectors regarding their overall MS for different areas or countries depends on local conditions like for instance the building density, the respective construction type, and the local topography. Thus, Haberl et al. (2021) found the total MS in buildings and transport infrastructure to be equal in Austria (each around 2.2 Gt), whereas in Germany the mass of infrastructures is significantly lower (around 40%) than that of buildings. However, the number of studies regarding the building sector clearly exceeds the infrastructures sector (Augiseau and Barles, 2017). Hence, the current work aims to contribute to a better understanding of the urban transport sector related MS intensities and composition as well as their long-term dynamic.

3.2.1. Retrospective and prospective material stock and flow related investigations of transport systems

The transport infrastructure has been the subject of anthropogenic stock investigations by various authors, using different approaches (top-down or bottom-up approach; retrospective or prospective; static or dynamic MFA), focussing on different materials, and were conducted for different geographical scales (i.e., regional, national, or multinational level), as shown by Lanau et al. (2019) in their review article. Furthermore, several researchers investigated one specific mode of transport within a geographical area (e.g., road-based transport, rail-based transport) either including vehicles or solely considering built-up infrastructure.

On a highly aggregated level, Wiedenhofer et al. (2015) investigated the development of material stocks and flows in buildings and transport infrastructures (road and railroad networks) for the European Union. Thereto, they applied a dynamic bottom-up approach and considered the period of 2004 to 2009 and performed a projection scenario until to 2020. They found that the stock between buildings and transport infrastructure (highly dominated by the road network) is split 50/50 and overall follows an increasing trend. Furthermore, their results highlight the significance of maintenance efforts especially for the transport infrastructure. This high relevance of maintenance efforts is in line with the results regarding the stocks and flows related to the road network of the United states (1905 – 2015) conducted by Miatto et al. (2017). The respective share of materials used for maintenance strongly depends on the degree of network expansion and the age structure of the transport network. This corresponds to the results of the study conducted by Nguyen et al. (2019), who investigated the development of the road infrastructure on national level of the developing country Vietnam for the time period 2003-2013. They found that only about 6% of total construction material use was directed to road maintenance while the main part of construction material was used for network expansion. These differences show that the maintenance effort of transport systems depends on the prevailing system, but can have a decisive influence on the overall material turnover. Thus, this aspect was given special attention in the present work.

Various studies examine one single transport mode or specific type of one transport mode, on various scales and detail dept. A recent example for rail-based systems is the study regarding the development of all subway networks on the globe (219 cities) and the associated material stocks, conducted by Mao et al. (2021). On a national level, such calculation was performed for the high-speed rail (HSR) network of China by Wang et al. (2016). Both the stock and the future development based on network expansion plans were investigated. The HSR network of California was investigated prospectively according to a planned network by Chester and Horvath (2010). Thereto, they conducted a comprehensive LCA to explore the full range of environmental effects associated with the proposed HSR. They stated that the infrastructure (construction and maintenance) contributes significantly to the overall environmental impacts of such transportation systems (Chester and Horvath, 2010, 2009).

On regional scale detailed bottom-up investigations of regional systems were performed under different focal points. For instance, Saxe et al. (2017) examined the net greenhouse gas (GHG) emissions of one specific new subway line within the subway network in the City of Toronto, Canada. Thereby, they considered not only the construction and operation (9 years) but also the GHG emissions associated and changes in residential density around the new subway line. By considering avoided emissions due to replaced ridership of other modes of transport (especially private transport), they determined the GHG payback period of the new subway line. Again, Lederer et al. (2016) considered explicitly the urban mining potential within the subway network of the city of Vienna. Thereto, they not only made a detailed bottom-up calculation of the built-in materials but also classified the materials and construction elements regarding whether those will be available as secondary materials within the next 100 years or most likely remain within the network.

Focussing on one transport mode or specific type of one transport mode has the advantage that the data structure and availability is more uniform and potentially the investigation can be performed on a high level of detail. However, the interrelationship with other transport networks within the same region are only considered to a limited extent. Hence, within the present work the interrelationship regarding current and future material turnover of different transport networks within a defined area and within an ongoing transformation phase are explicitly addressed.

Studies on urban transport systems that focus on material flows and stocks associated with the built-up infrastructure are limited and only few investigate all available transport modes within a geographic area. The urban road network of the city of Beijing was the subject of investigation in the study conducted by Guo et al. (2014). Using a bottom-up approach in combination with GIS data analysis, they determined the MS of the urban road infrastructure in high detail. Furthermore, the spatial distribution of the MS within the study area was determined. Based on the developed model, in a further study the life cycle energy consumption and GHG emissions associated with the urban road infrastructure were investigated (Guo et al., 2017). Consistent with other infrastructure LCA studies, they found that the two main stages with massive GHG emissions are production and maintenance, in which clinker production represents the largest contributing process. Another case study for the city centres of Manchester (GB) and Wakayama (JP) regarding the MS in buildings and infrastructures (roadway, railway, and sewer) was conducted by Tanikawa and Hashimoto (2009). They used a GIS-based approach and investigated the development of the MS over time (1850-2004) for the respective study areas (subareas of the two case study cities) and thus determined the spatial distribution of construction materials. Another study focusing on the development of the MS (1973-2013) in the built-up infrastructure in the cities Beijing, Tianjin and Shanghai was performed by Huang et al. (2016). They used a bottom-up approach for their investigation and found that the MS is mainly dominated by buildings in the three investigated cities and has been increasing rapidly since the early 2000s driven by affluence and population development. Very recently, Mollaei et al. (2021) applied a bottom-up material accounting approach to assess the future building and transport infrastructure stock for the two Canadian cities Kitchener and Waterloo. They calculated the future development of the road transport infrastructure until 2041 based on the projected road expansion plans of the municipalities, which is based on population development projections and policy plans. The study design and results are comparable to investigations presented in the present work, as published in the Paper II.

The results regarding above citied case studies of very fast-growing cities in Asia illustrate that the outcomes of urban MS investigations are only transferable to a limited extent from one city to another. However, so far there is no comprehensive investigation considering the long-term development of the material stocks and flows of an urban transport system (considering all modes of transport) within a European City. The present work aims to fill this gap, using the transport system of Vienna as a case study. The work distinguishes itself from previous studies due to the consideration of the impacts on the MS development driven by interrelations between various transport modes (e.g., reducing parking area to gain street space for separate biking lanes). Furthermore, the investigated transformation process towards a fossil carbon free urban transport can be considered as novel when it comes to the material turnover at the city level.

3.2.2. The anthropogenic metabolism of the city of Vienna

Numerous studies focus on topics related to the anthropogenic metabolism of the city of Vienna, making it one of the well-investigated urban areas in this respective field (Lanau et al., 2019). Using a top-down approach the urban metabolism was calculated by Obernosterer et al. (1998). In contrast, a comprehensive study regarding the building sector was conducted by Kleemann (2016), following a bottom-up approach. Based on the method developed and data generated by Kleemann (2016), several further investigations regarding Vienna's buildings sector were performed in the following years. The development of Vienna's building MS and related MF for the period from 1990 to 2015 were recently studied by Lederer et al. (2020a). The study shows that the MS in buildings in Vienna has increased by a total of about 26% within these 25 years and that the growth rates of insulation materials significantly exceed those of other building materials. Further, the impact of the increasing demand for housing and the reconstruction of the building stock on resource demand and waste generation was recently modelled by Lederer et al. (2021). Thereto, the development of Vienna's building stock was examined using different development scenarios for the period 2016 to 2050. In a recently published study, the material intensities of Viennese buildings were investigated in great detail (Lederer et al., 2021a). Therein, the authors presented the analysis of a randomized selection of buildings (256 objects) and determined their material intensities. Another study considering the overall construction sector (buildings and infrastructures) focussed on mineral construction and demolition wastes management and the identification of potentials for a more circular economy of mineral construction materials (Lederer et al., 2020b).

As presented, most of the conducted studies focus on buildings, however some also address the transport infrastructure or parts thereof respectively. As mentioned early on, the MS of the subway network was previously investigated and the current work builds on this data (Lederer et al., 2016a). Another investigation related to the subway system focuses on measures to reduce the life cycle energy demand and greenhouse gas emission within the subway system, taking the new subway line U2 as case study (Lederer et al., 2016b). The overall transport system of the city of Vienna was also very recently investigated by Virág et al. (2021) using a stock-flow service nexus approach for personal mobility. They estimated the per capita MS of Vienna's transport sector to 56 t/capita which equals to the findings in the present work. Furthermore, they found that active mobility is the most resource-efficient mobility option.

Summarizing the literature, there are numerous studies regarding the anthropogenic metabolism of the city of Vienna. However, no comprehensive investigation of the development and dynamics of the MS and related MF of the urban transport system has been conducted so far. The present work closes this gab and moreover models the future development until to 2050. In combination with the work already done in the building sector, the knowledge base increases regarding the regional material turnover as well as the generation of construction and demolition waste.

4. Case study description

All infrastructure systems examined in this work refer to the transport system of the city of Vienna. Paper I and II investigate the overall transport system and its past and future development. In Paper IV the main public transport provider within the city (Wiener Linien) is assessed. A concrete refurbishment activity of a subsection of the Wiener Linien subway network is the object of investigation in Paper III. This chapter gives a brief overview of the characteristics of the case study city Vienna and its transport system. For a more detailed description of the prevailing system and its past and projected development, the reader is referred to the Appendices and the Supplementary data published together with the four papers.

4.1. City characteristics and city development plan

The City of Vienna was chosen as the study area because, regarding the historic development of the urban transport system, it is comparable to numerous cities in industrialized countries. Furthermore, the case study city is particularly interesting because of the diversity of its well-developed transport system (e.g., various transport modes, broad age distribution of the transport infrastructure) and it is characterized by good data availability. Vienna is the largest city in Austria, covering an area of 415 km^2. In the last decades there has been a significant population increase. In the period from 1990 until 2020, the population of Vienna has increased by over 25%, from 1.5 million to 1.9 million (Statistik Austria, 2020). The growth of the city has driven the expansion of the transport infrastructure in the past to provide the transport capacity needed. For Vienna, an increase in the population is also predicted for the future, but moreover there will be changes necessary to make the transport system of the city more sustainable and less CO_2 intensive.

Like many other cities, the city of Vienna started a smart city initiative to meet future challenges. The Smart City Wien Framework Strategy 2050 (SCWFS) sets guidelines for the medium- to long-term transformation of the city. For this work of particular interest are the set targets to reduce primary material consumption through closed material cycles in the construction sector (e.g., 80% of all components and materials from demolishing buildings to be reused or recycled by 2050), and the defined targets regarding the transformation of the transport system towards a more sustainable city passenger transport. In more detail, Vienna set the target to reduce Vienna’s per capita $CO_{2\text{-eq}}$ emissions in the transport sector by 50% by 2030 and by 100% by 2050. This is to be achieved by converting the vehicle fleet to low-emission propulsion technologies (e.g., battery electric vehicles

(BEV)) and a shift towards more environmentally friendly transport modes (e.g., walking, public transport) (City of Vienna, 2019).

4.2. Overview of Vienna's transport infrastructure and vehicle fleet

In Vienna, the largest share of traffic area is attributable to motorized individual transport (MIT) (e.g., roads and parking areas) like in almost all urban areas worldwide. However, Vienna also has a well-developed public transport system (PT), which has been gradually expanded in the past decades. It comprises public buses, trams, regional trains, and subway lines. Like in other cities, active mobility (walking, cycling) has regained importance in recent years, which is driven by the expansion of the infrastructure for non-motorized individual transport (NMIT). In Vienna, prevailing infrastructures and vehicles in-use are presented per transport mode (MIT, PT, and NMIT) in corresponding subcategories in Table 1. Each category is characterized by its dimensions/size or existing quantity/number (depending on the unit) in the years 1990 and 2015. Furthermore, the changes in stock size within this 25-year period are given as percentage (%). The infrastructure is further subcategorized into moving traffic infrastructure (m.t.i.) (e.g., driving lanes, train tracks) and stationary traffic infrastructure (s.t.i.) (e.g., parking areas, train depots). The values presented in Table 1 are aggregated to main categories. For annual values and a finer breakdown of categories, the reader is referred to the Supporting Information of Paper I (1990-2015) and for more information regarding of their projected development to Paper II (2016-2050).

Table 1: Vienna's transport system development across different transport modes, subcategorized according to moving traffic infrastructure (m.t.i.), stationary traffic infrastructure (s.t.i.), and vehicles (v.). From Table 1 in Paper I.

Category		Service Unit (SU)	Unit	1990	2015	Change [1] +/-
Motorized Individual Transport (MIT)	m.t.i.	Total road area	m^2	21,199,000	22,843,000	+8%
		Total road bridge area	m^2	789,000	941,000	+19%
		Traffic light-signal system	n [3]	890	1,310	+47%
		Traffic signs and sign gantry	n	55,000	60,000	+9%
		Guard railing	m	27,000	37,000	+37%
	s.t.i.	Area parking lanes and parking area on public property	m^2	3,911,000	4,261,000	+9%
		Number of parking spaces in buildings and car parks	n	117,000	213,000	+82%
		Number of parking spaces on private property	n	371,000	455,000	+22%
	v.	Total cars	n	547,000	686,000	+25%
		Total motorcycles	n	42,000	86,000	+105%
		Total lorry type N1 (<3.5 t)	n	40,000	60,000	+50%
		Total lorry type N2 (3.5t - 12t)	n	11,000	2,000	-82%
		Total lorry type N3 (12t - 40t)	n	5,000	3,000	-40%
Non-Motorized Individual Transport (NMIT)	m.t.i.	Total bicycle lane area	m^2	106,000	385,000	+263%
		Total sidewalk area	m^2	8,998,000	10,935,000	+22%
		Total pedestrian zone area	m^2	106,000	350,000	+230%
		Total pedestrian and cycling bridge area	m^2	18,000	38,000	+111%
	s.t.i.	Bicycle stands	n	130	39,000	-
		Rental bike stations (public)	n	0	120	-
	v.	Total bicycles	n	917,000	1,121,000	+22%
		Total pedelecs	n	0	49,000	-
		Total citybikes	n	0	2,000	-
Public Transport (PT)	m.t.i.	Subway network length (both directions)	m	40,000	87,000	+118%
		Regional train network length (both directions)	m	182,000	190,000	+4%
		Tram network length (both directions)	m	188,000	175,000	-7%
		Regional train stations buildings	m^3	812,000	[2] 513,000	-
		Regional train station platform roof	m^2	61,000	63,000	+3%
		Regional train station facilities (platforms, underground crossing, shelter, stairways, and elevators)	n	280	300	+7%
	s.t.i.	Tram depot buildings	m^3	1,701,000	1,701,000	±0%
		Bus garage buildings	m^3	176,000	451,000	+156%
	v.	Subway vehicles (all types)	n	250	430	+72%
		Regional train vehicles (all types)	n	150	290	+93%
		Tram vehicles (all types)	n	1350	880	-35%
		Bus vehicles (all types)	n	650	1,130	+74%

[1] If there is no comparable value in 1990 (e.g., zero), the column "change" remains empty.
[2] Main train station (Hauptbahnhof) excluded in the total volume; actual data on the built-in material is included in the model.
[3] Number (n) of infrastructure components or vehicles.

The investment in PT and NMIT transport infrastructure and the promotion of these more sustainable transport modes taken by the city of Vienna in the past decades, are reflected in a changing modal split. Since 1990 the mode choice of Vienna's population changed in favour of these two transport modes, as presented in Figure 1 (left circular chart). Correspondingly, the share of MIT on the modal split decreased from 37% in 1990 to 27% in 2015 (MA 18, 1993; Wiener Linien, 2019). However, when considering the transport performance in terms of passenger kilometers travelled (PKT), the share of each transport mode is relatively constant over the same period, as further presented in Figure 1 (right circular chart). This is because the transport distances have increased overall and especially those of the MIT sector have increased disproportionately (due to more vehicles which cover in average longer distances). In total, the PKT within Vienna has increased by 36%, from 8,151 million PKT per year in 1990 to 11,075 million PKT/a in the year 2015 (OEIR, 2019a).

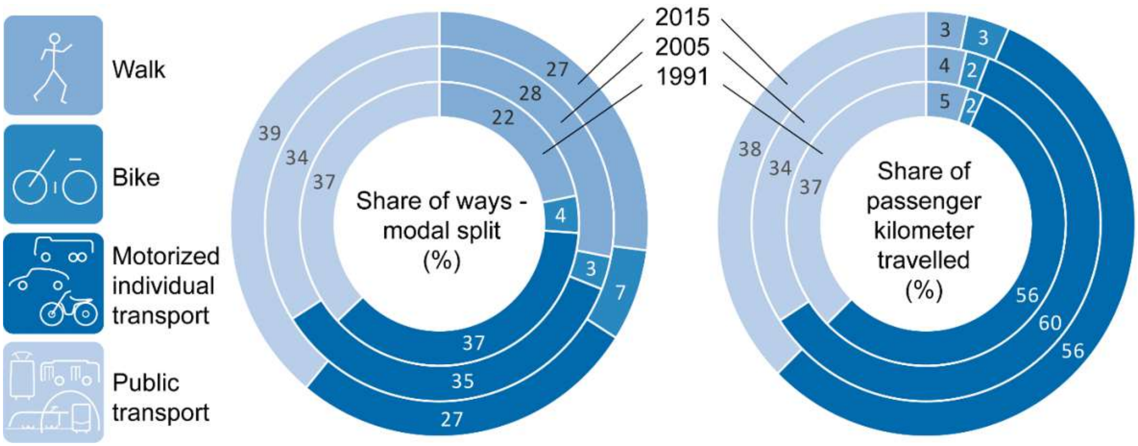

Figure 1: Development of Vienna's modal split (MA 18, 1993; Wiener Linien, 2019) and share of passenger kilometers travelled per transport mode (OEIR, 2019a). From Figure 1 in Paper I. The underlying data used to create this figure can be found in the Supporting Information S2 published together with Paper I.

4.3. Public transport provider – Wiener Linien

The largest public transport provider in Vienna is Wiener Linien. It operates the Vienna subway and tram network (for infrastructure characteristics and number of vehicles see Table 1) as well as a main part of the bus network (860 km network length in 2020). On its network, per day all vehicles together cover around 214,000 kilometers. Thus, on average, around 2.6 million passengers are transported per day by the vehicles of Wiener Linien, which sums up to around 961 million passengers per year (Wiener Linien GmbH & Co KG, 2020).

In Paper IV the Wiener Linien is the subject of the investigation. The assessment was carried out on a life cycle basis. The life cycle components included, and the system boundaries are presented in Figure 2. The inventory data from the Wiener Linien was divided wherever applicable into traffic modes. For services (i.e., administration) which were not assignable to one single transport mode the category “services” were introduced.

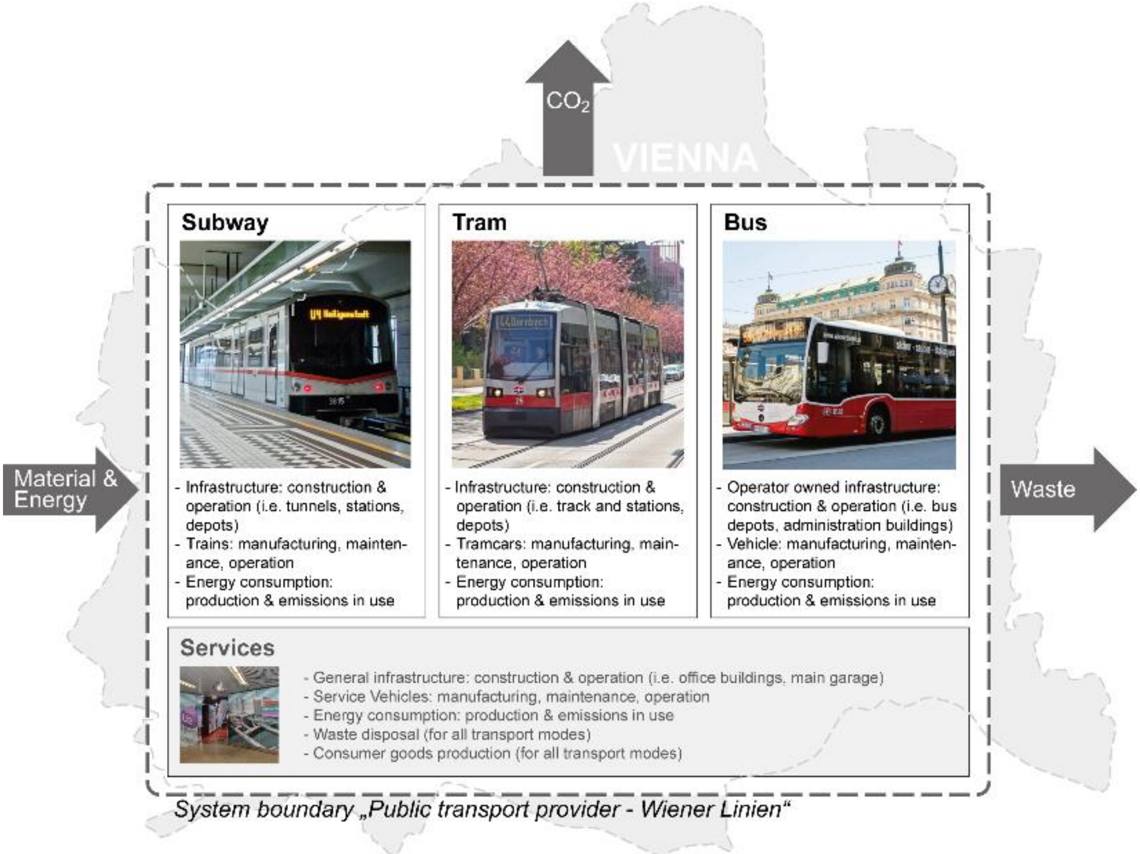

Figure 2: System boundary “Public transport provider – Wiener Linien” from Figure 1 in Paper IV

In Paper III the refurbishment process of a subsection of the Wiener Linien subway network was investigated in terms of material turnover. Thereof some elements (station buildings, viaducts) are cultural heritage monuments, because the subway infrastructure of the two lines (U4 and U6) are largely based on the former Stadtbahn (urban railway), which had already been built at the end of the 19th century. This historic infrastructure has been constantly refurbished and modified, particularly after the Second World War damage in the 1950s and when being upgraded to a subway line in the 1970s (Schlöss, 1987). This is a good example of the fact that once installed, transport infrastructure in a city usually remains in place for a very long time and is constantly expanded and rebuilt.

5. Methods and data

5.1. Modell to calculate material flows and stocks of the transport system in Vienna

The purpose of the model was to investigate the development of the in-use MS, the material input flows (MF^{IN}) and material output flows (MF^{OUT}) of the transport system of the city of Vienna. Transport modes considered are motorized individual transport, non-motorized individual transport, and public transport. The basic principles of the model can be described as bottom-up, retrospective, multi-year MFA as defined, among others, by Brunner and Rechberger (2016) and Tanikawa et al. (2015). In the multi-annual static modelling approach chosen, the calculation is based on specific service units (SU) (e.g., m² road, m subway network, number of vehicles) which are combined with specific material intensities (e.g., t/m², t/m, t/n). The model based on SU is set up using the methodology of Müller (2006), which has been previously applied, among others, by Noll et al. (2019); Wiedenhofer et al. (2015); Bergsdal et al. (2007); and Tanikawa et al. (2015).

The materials are expressed in metric tons (t) and their multiple (e.g., Million tons (Mt)). Overall, 13 material categories are considered: asphalt & bitumen; aluminium; batteries; brickwork; concrete; copper; glass; gravel, sand and natural stone; iron & steel; other metals; others (e.g., rubber); plastics; and wood. The processes defined are transport infrastructure (e.g., roads, subway network) and vehicles (e.g., cars, trains) for each transport mode. The infrastructure is further distinguished in terms of infrastructure for moving transport (e.g., roads, rail tracks) and infrastructure for stationary traffic (e.g., parking lanes, train depots). Table 1 lists the infrastructure types and vehicle categories including their initial number/size in 1990. All material input flows, and waste flows generated due to maintenance and demolition of infrastructure are considered. For the vehicles, the MF related to new vehicles and decommissioned vehicles are included, but maintenance is neglected. The spatial boundary refers to the city of Vienna, and the temporal scale covers the time interval 1990 to 2015.

A system overview is provided in Table 2. It includes an enumeration of all infrastructure and vehicle types considered as well as their allocation to moving or stationary infrastructure. Furthermore, a brief description is given about the calculation method used to calculate the MS and MF. And to each infrastructure category the equation used to calculate the maintenance is given. For the equation definition and details regarding the calculation methodology used, the reader is referred to the Chapter 3 in Paper I.

The input data (service units, material intensities, renewal rates, and useful life per infrastructure type) is expressed in SU and was taken either from official statistics, provider information, internal statistics from the municipality of Vienna, or was calculated by combining various data. Material intensities were taken from the literature combined with own calculations. For details on the input data and its sources, the reader is referred to the Main article (Paper I) and the corresponding Supporting Information S1 section 1-2, further, all numbers per year can be found in Supporting Information S2.

On the one hand, MF^{IN} are generated due to extensions (e.g., increase in m² road area in the year n) and MF^{OUT} due to decline (e.g., decrease in m tram track length in the year n) of infrastructures and vehicle fleets. On the other hand, MF^{IN} and MF^{OUT} depend on the maintenance of the transport infrastructure as well as the maintenance of underground networks (e.g., pipes and cables), which usually require work on road infrastructure. To calculate these MF, different approaches were applied. If available, reported data on the number of SU maintained per year was used for MF calculation. Otherwise, either an annual renewal rate or mean useful life was applied. MF^{IN} and MF^{OUT} related to maintenance were assumed to be equal in composition and intensity since the construction type of the infrastructure remained constant over the period investigated. Furthermore, no distinction was made between primary and secondary material. The plausibility of the results was examined for each infrastructure component investigated by comparison with the results from other cities found in the literature.

As model output, the in-use MS for different transport modes was generated for every single year from 1990 to 2015. Further, applying the model the annual resource demand was calculated caused by network expansions, infrastructure maintenance, and newly registered vehicles. The waste generated due to demolition activities, maintenance work, and end of life vehicles was quantified. To evaluate the results and compare them to other cities, the results are displayed in stock per capita (t/capita) as well as per transport performance (passenger kilometer travelled (PKT)/t).

The calculation was performed in Microsoft Excel, and the calculation file is available as Supporting Information S2 together with Paper I.

Table 2: ***System Overview - considered infrastructure and vehicles of Vienna's transport network distinguished between transport modes, and between moving traffic infrastructure (m.t.i.), stationary traffic infrastructure (s.t.i.), and vehicles (v.). From Table S1-1 published in Supporting Information S1 of Paper I.***

Transport mode	m.t.i. s.t.i. v.	Name of infrastructure categories and vehicle categories Service Unit (SU)	Functional unit	Material stock – calculation basis	Maintenance – calculation basis	Equation used for – to calculate maintenance
Motorized Individual Transport (MIT)	m.t.i.	Roads	m²	Total public traffic area per road category. It is distinguished between the road categories, superhighway, highway, major street, and drive lane.	Based on real data from the municipality (refurbished area per year), and lifetime functions for underground installations.	(2) (3) (5)
		Road bridge	m²	Nine different bridge categories are distinguished (construction type and function: road bridge or pedestrian bridge).	Calculation based on mean useful life per bridge type.	(5)
		Road equipment	n	Comprise installed light-signal systems, guard railings, sign gantries, and traffic signs. Calculation based on number of equipment installed.	A mean renewal rate for road equipment of 3 % per year is assumed.	(4)
	s.t.i.	Area parking lane	m²	Part of the public traffic area considered as own category.	Same as category roads	(2) (3)
		Parking area on public property	m²	Constant value based on 2019, (no time series data).	Calculation based on mean useful life per road construction layer.	(5)
		Parking places in private buildings and car parks	n	Based on overall building stock in Vienna and number of packing places per building category.	Calculation based on mean useful life per building category.	(5)
		Parking places on private property	n	Based on total number of registered cars and existing parking places (private and public)	Calculation based on mean useful life per road construction layer.	(5)
	v.	Cars and motorcycles	n	In Vienna registered private cars and motorcycles. Increase in average vehicle weight considered.	Not considered	-
		Lorry vehicles	n	In Vienna registered lorry vehicles. Distinguished between three different weight categories (N1, N2, N3).	Not considered	-
Non-Motorized Individual Transport (NMIT)	m.t.i.	Bicycle lane	m²	Part of the public traffic area considered as own category.	Same as category roads	(2) (3) (5)
		Sidewalk	m²			
		Pedestrian zone	m²			
		Pedestrian and cycling bridges	m²	Same as category road bridges.	Calculation based on mean useful life per bridge type.	(5)
	s.t.i.	Bicycle stands	n	Number of bicycles stands on public property.	A mean renewal rate for bicycle infrastructure of 3 % per year is assumed.	(4)
		Rental bike stations (public)	n	Number of rental bike stations on public property.	A mean renewal rate for bicycle infrastructure of 3 % per year is assumed.	(4)
	v.	Bicycles	n	Calculation based on Number of households and sale statistics.	Not considered	-
		Pedelec	n			
		Citybikes	n	Total number of vehicles in use.	Not considered	-

Transport mode	m.t.i. s.t.i. v.	Name of infrastructure categories and vehicle categories Service Unit (SU)	Functional unit	Material stock – calculation basis	Maintenance – calculation basis	Equation used for – to calculate maintenance
Public Transport (PT)	m.t.i.	Subway network	m	Network (both ways) including station buildings. Under consideration of different construction type categories.	Calculation based on mean useful life per construction element (superstructure, substructure, and buildings).	(5)
		Regional train network	m	Network including shunting yards.	Calculation based on mean useful life per construction element (superstructure, substructure, and buildings).	(5)
		Tram network	m	Network on roads and own track beds.	Calculation based on mean useful life per construction element (superstructure, substructure, and buildings).	(5)
		Regional train stations buildings	m³	Regional train station buildings are categorized by size and year of construction.	Due to the limited number of buildings, real data about construction and dismantling of regional train station buildings are included on the model.	(2) (3)
		Regional train station platform roof	m²	Total area of platform roof within Vienna. A uniform construction type is assumed.	Lifetime function	(5)
		Regional train station facilities	n	Number of train station facilities (platforms, underground crossing, shelter, stairways, and elevators) depending on the size and type of train stations.	Lifetime function	(5)
	s.t.i	Tram depot buildings	m³	Tram depot buildings are categorized by year of construction.	Lifetime function	(5)
		Bus garage buildings	m³	Bus garage buildings are categorized by year of construction.	Lifetime function	(5)
	v.	Subway vehicles	n	Registered number of vehicles.	Not considered	-
		Regional train vehicles	n	Vehicles allocated in Vienna.		
		Tram vehicles	n	Registered number of vehicles.		
		Bus vehicles	n			

5.2. Projecting material flows and stock development of the transport system considering different scenarios

Based on the MFA-model to investigate the past development of the transport sector in Vienna, presented in Chapter 5.1, a bottom-up MFA was performed to determine the future MF and MS depending on different scenarios. Thereto the classification of the transport system (e.g., transport modes, infrastructure categories) was taken from the existing MFA-model. Moreover, the assumptions made (e.g., refurbishment rates, useful lives) and the main calculation methodology remained unchanged. In order to investigate the future material stocks and flows, different scenarios were distinguished varying in their development of the SU (cf. Table 1 and Table 2). The scenarios derived from the targets set out in the Smart City Wien Framework Strategy 2050 (see Chapter 4.1). Hence, the period from 2016 to 2050 was modelled.

Three thematically focused scenarios for the transport sector of Vienna were defined. In addition, a business-as-usual scenario "A_{BAU}", which extrapolates the current state, was modelled for comparison. The current modal split of the passenger transport in Vienna is divided into 38% public transport, 25% motorized individual transport, 30% walking and 7% biking (Wiener Linien, 2020). This modal split was taken as reference and starting value for the scenarios. Table 3 presents an overview of the scenarios investigated, and their basic characteristics.

Table 3 Thematically focused scenarios for a low-carbon city transformation in Vienna. From Table 1 in Paper II.

Future scenarios	**Business as usual scenario** **2050 A_{BAU}**	**Battery electric vehicle fleet scenario** **2050 B_{+BEV}**	**Public transport scenario** **2050 C_{+PT}**	**Active Mobility scenario** **2050 D_{+AM}**
2016 - 2030	constant modal split, infrastructure development - already planned network extensions and vehicle procurements (assumed to be equal for all pathways), assuming equal vehicle numbers in all scenarios but variation in vehicle fleets regarding the changing propulsion technologies in scenarios B, C and D.			
2030 - 2050	constant modal split (MIT 25%, PT 38%, NMIT 37%); projection of the prevailing system into the future, propulsion technology of the vehicle fleet remains in the current state	constant share of MIT (25%); changed vehicle fleet: replacement of fossil fuelled cars by alternatives (electric, hydrogen); moderate increase in the share of PT (45%); decrease in active mobility - NMIT (30%)	new modal split: strong increase in the share of PT (55%); significant decrease in the share of MIT (<10%) and changed vehicle fleet; constant development of the share of active mobility - NMIT (35%)	new modal split: strong increase in distances covered through active mobility - NMIT (>45%); moderate increase in the share of PT (45%); significant decrease in the share of MIT (<10%) and a changed vehicle fleet

Accordingly, the scenarios, as defined in Table 3, affect the estimated development of the various SU to the respective modes of transport. Up to 2030, an equal development for infrastructures was assumed in all scenarios, since major infrastructure expansion projects, which will be built in in the next decade are already in construction (e.g., the subway expansion U2/U5) or are already in the planning phase (e.g., highway expansion S1). A distinction was made in the development of the vehicle fleet, since changes in the composition of vehicle fleets can develop an effect faster (e.g., increase of the share of battery electric vehicles (BEV)), if for instance basic regulations change (e.g., free parking opportunities for BEV) or the costs decrease or increase (e.g., through increase in fuel taxes, high subsidies for new BEV). In addition, the following general assumptions were applied to all scenarios. For the population development, demographic forecasts carried out by the Austrian conference for spatial planning were used for all scenarios (Hanika, 2019). In all scenarios, the same economic development – with a linear growth rate of 2% per year until 2050 – was assumed, which represents the basis for the development of the freight transport taken from Urban Innovation Vienna (2019). Concerning passenger transport, the same passenger mobility demand per capita is assumed for all scenarios.

The transport service (given in Million vehicle km/year) provided per transport mode was calculated using a multimodal macroscopic traffic model with 1,146 source districts within the Vienna metropolitan area. Among others, the following parameters were considered in the traffic model: the demographic forecast, the mobility demand per capita (trips per day), and the distribution of e.g., workplaces, leisure facilities, educational institutions, and housing within the city (OEIR, 2019b). All these general parameters were assumed to be equal for all scenarios. However, the preferred means of transport was adapted to the modal split objectives of the respective scenarios (see Table 3). The corresponding transport service projections per scenario within Vienna categorized according to transport mode are presented in Table 4. The traffic model used was developed by the Austrian Institute for Regional Studies (OEIR). Additionally, the transport performance estimates for the lorry vehicles were added, which are based on the economic trend projections and were taken from Urban Innovation Vienna (2019).

Table 4: Traffic model projections per scenario, expressed in transport service provided within Vienna per mode of transport in Million vehicle kilometers per year (motorized individual transport and public transport) and number of vehicles in operation per day for the public transport modes. The lorry vehicle kilometer estimates are taken from Urban Innovation Vienna (2019) from Table 2 in Paper II.

Transport service provided	Unit	2020	2030	2050 A_{BAU}	2050 B_{+BEV}	2050 C_{+PT}	2050 D_{+AM}
Cars	(Million vehicle km/year)	4,670	4,960	5,470	6,240	1,680	1,680
Small lorry vehicles (<3,5 t)	(Million vehicle km/year)	510	580	720			
Heavy lorry vehicles (3,6-40t)	(Million vehicle km/year)	360	390	440			
Public transport service							
Metro	(Million train km/year)	17.2	19.1	20.7	21.3	21.3	21.3
	(Number of trains in use/day)	160	150	190	170	230	230
Tram	(Million train km/year)	24.7	25.9	27.7	27.9	28.8	28.8
	(Number of trains in use/day)	470	520	530	480	750	750
Regional train	(Million train km/year)	8.4	8.4	8.9	8.2	12.9	12.9
	(Number of trains in use/day)	90	90	90	90	130	130
Public bus	(Million bus km/year)	39.5	41.9	44.9	44.9	49.4	46.9

The projected population development and modelled transport service estimates were the basis for the calculation of the respective development of the corresponding transport infrastructure and vehicle fleets. The interdependencies between different transport modes in the various scenarios were considered. If, for instance, the private vehicle fleet drops accordingly to the reduction of vehicle kilometer provided by private vehicles in one scenario (cf. Table 4), this also leads to a removal of parking infrastructure. Since within these scenarios the transport service provided by active mobility transport modes are increasing, it was assumed that these available transport areas are transformed into traffic areas used for active mobility. Corresponding assumptions were made for each transport mode and infrastructure categories and vehicle types. These assumptions are described and derived accordingly in the Main article (Paper II). Further, therein the assumed distributions of the future propulsion technologies among the vehicle fleets in Vienna based on Urban Innovation Vienna (2019) are presented.

The calculation methodology on the effects of the different scenarios on the development of SU in each modes of transport are described in detail in Chapter 2.2 of the Paper II. Hence, for a detailed definition of the scenarios and the assumptions made, the reader is referred to the Appendices and the Supplementary data published together with the Paper II.

5.3. Construction material and waste flows in subway infrastructure refurbishment

To investigate the material turnover related to a comprehensive refurbishment of the subway infrastructure, a static bottom-up MFA model was set up. For the calculation, the software STAN was used (Cencic and Rechberger, 2008). The main objective was to investigate material flows and stock changes of subway infrastructure associated with its refurbishment. Specific attention was given to the ratio between flows of recycling material, reuse material and primary raw material. Thereto the refurbishment of a subsection of Vienna's subway network was chosen as a case study. An overview of the system boundaries for the modelling of the refurbishment process of the subway subsection is provided in Figure 3.

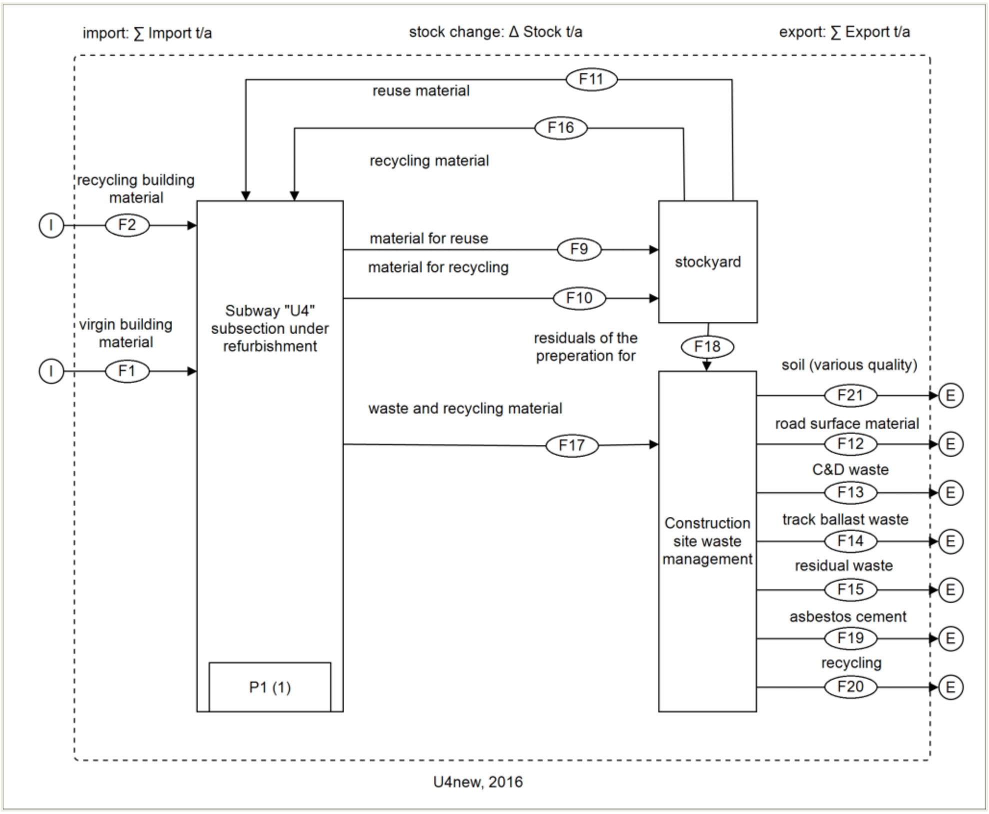

Figure 3: Model overview and system boundaries for the modelling of the refurbishment process of the subway subsection (U4) from Figure 4 in Paper III.

For the investigation real inventory data (e.g., tender documents i.a., construction plans, contract specifications, technical reports) and documents (e.g., as-built plans, waste management report of the construction site, basic soil characterisation) provided by the public transport provider Wiener Linien were used. All MF are presented in the mass unit "metric ton (t)", and the reference period selected is one year (2016). Three material categories are considered: minerals, organics, and metals. However, for the detailed investigation of MF overall 22 material and waste categories are differentiated to reflect changes in the material composition of building components (e.g., the change from a third rail (conductor rail) made of steel to one made of aluminium).

The initial state of the investigated system, a detailed description about the refurbishment process, and changed infrastructure components, as well as the input data and its sources are comprehensively described in the Main article (see Paper III in the Appendices).

5.4. Environmental assessment of a public transport provider

In this part of the work an environmental assessment was performed, using the main public transport provider of Vienna, Wiener Linien, as a case study. Therefore, the overall land consumption of the public transport provider had been determined using an extended ecological footprint (EF) analysis approach. The investigation was carried out on a life cycle basis, and the life cycle components included, and system boundaries drawn are presented in Figure 2.

In the assessment it was distinguished between i) the direct land use of the transport system within the city (direct land use), ii) the direct hinterland use necessary to provide materials, goods and energy for the infrastructure of the public transport system (direct hinterland use), iii) the consumption of land to compensate for CO_2 emissions, expressed as CO_2 emissions associated with the provision of materials and goods (embodied CO_2 hinterland use), and iv) the land needed for the sequestration of CO_2 related to the direct energy consumption of the public transport system (operational energy CO_2 hinterland use).

The direct land use was determined using spatial data (GIS data sets) evaluated by means of the open-source software QGIS (Version 2.16.2). The hinterland (ii) direct hinterland use, (iii) embodied CO_2 hinterland use, and (iv) operational energy CO_2 hinterland use was determined by establishing a material and energy inventory and applying an EF calculation using the software Simapro and the therein implemented database ecoinvent on this inventory. The total EF was determined by combining all four land use categories, thus summarizing the direct land use expressed as hectares per year (ha/a) and the direct hinterland use and CO_2 hinterland uses expressed in global hectares per year (gha/a) for the period of one year (2012). To consider the different transport capacities and performances of the modes of transport, all results were finally normalized per seat kilometer provided (SKP) and passenger kilometer travelled (PKT). Figure 4 summarizes the methodology, whereas for a comprehensive description of the method applied and materials used for the assessment the reader is referred to the Paper IV in the Appendices.

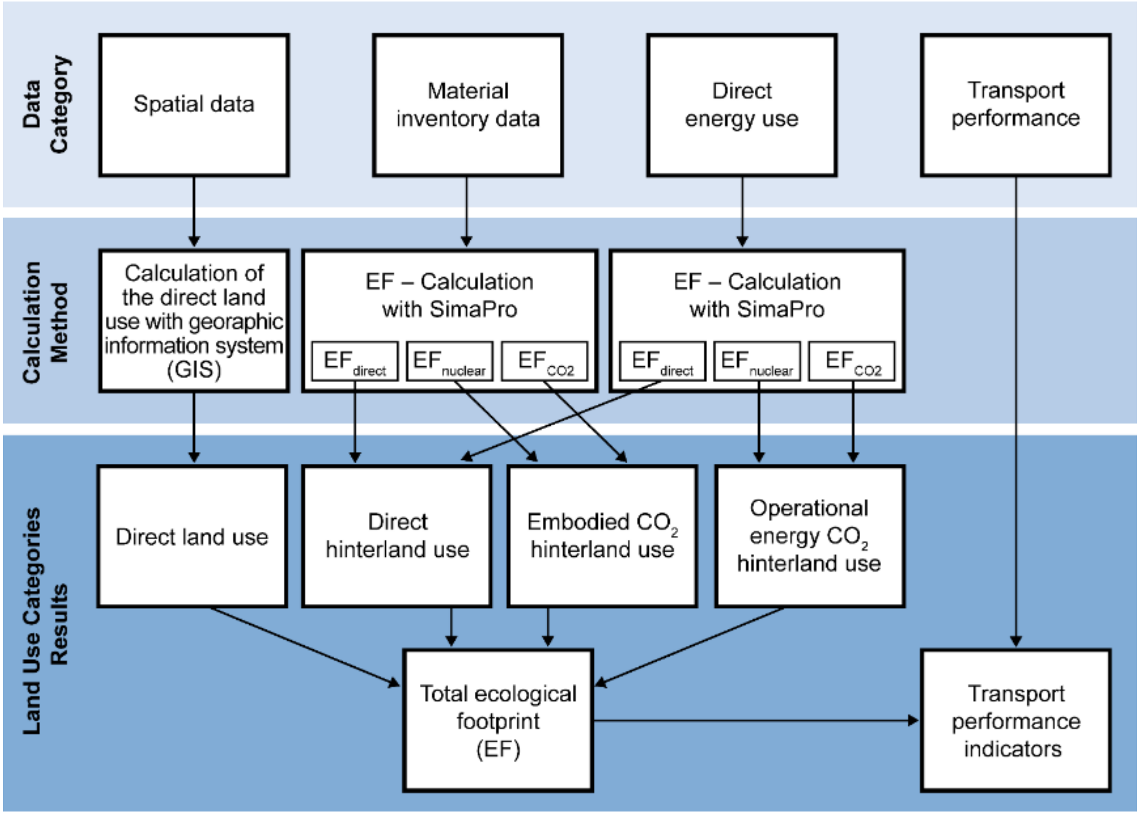

Figure 4: Data categories, calculation method and resulting land use categories from Figure 2 in Paper IV

In addition to the inventory data regarding infrastructure and vehicles (as presented in the previous chapters), data regarding the operation phase were required to perform a life cycle based environmental assessment. An overview of the inventory and its structure is presented in Figure 5, it contains the main inventory assets of each category, but it is not a complete list. The inventory data from the Wiener Linien was divided wherever applicable into transport modes. Those categories which are used across all transport modes, like assets for administration activities, were summed up into the category service.

The inventory data contained 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 energy mix had to be identified. To provide the inventory for the assets in use by the transport provider a set of formulae were used, as presented in the Main article. In general, the methodology to calculate the material inventory for the environmental assessment follows the same methodology as described in Chapter 5.1. The formulae applied have in common that some information on quantities of goods (e.g., section length, number of goods) (=service unit) was multiplied by specific material intensities of these goods (e.g., copper in wire, concrete in buildings). Similar infrastructures and appliances were clustered in joint categories, and representative elements of these categories were analysed and subsequently the data have been upscaled to account for all elements of the respective category. The material intensities and its respective sources are described in the Main article in the Appendices and in the Supporting Information published together with Paper IV.

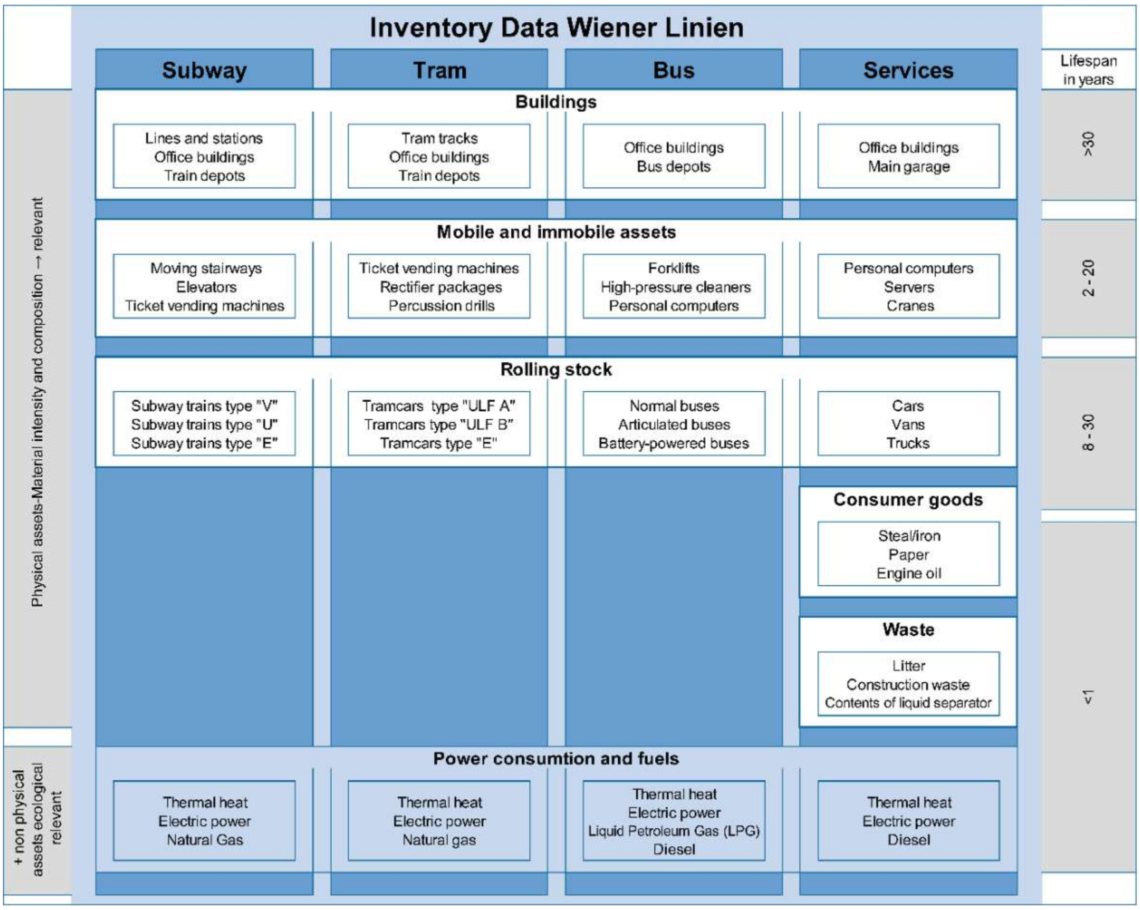

Figure 5: Inventory categories for the environmental assessment of the public transport provider Wiener Linien (incl. respective lifespans) from Figure 3 in Paper IV.

6. Results and discussion

In this chapter, the results are summarised in four sections corresponding to the four papers. For full results and profound discussion, the reader is referred to the Main Articles listed in the Appendices.

6.1. Analysis of the current and historical material flows related to the transport system of Vienna (1990-2015)

The results regarding the MS development and the annual input (MF^{IN}) and output (MF^{OUT}) flows are summarized in Figure 6. In the investigated period, the in-use MS of the transport system increased by 26%, from 83 Mt in 1990 to 103 Mt in 2015. Whereas, the per capita MS remained relatively constant (58 t/capita), due to population increase. The largest MS is attributed to motorized individual transport (MIT: 62 Mt), followed by public transport (PT: 36 Mt), and non-motorized individual transport (NMIT: 6.6 Mt). The infrastructure MS is distributed into three-quarters infrastructure for moving transport and one-quarter infrastructure for stationary traffic. The latter is only significant for MIT. Almost half of the MIT in-use MS is required for parking infrastructure.

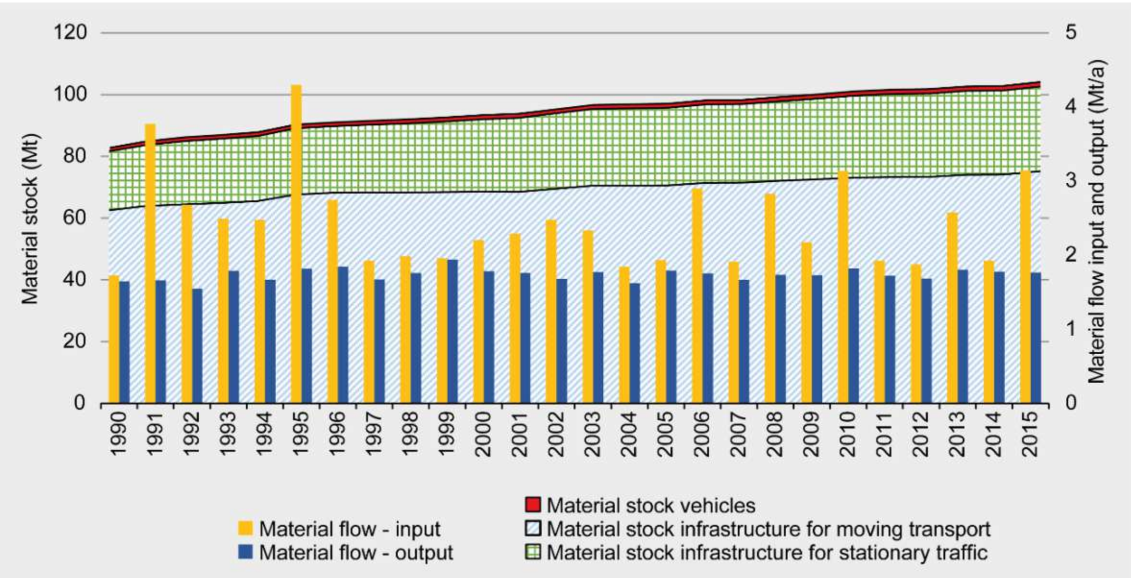

Figure 6: Overall material stock development of Vienna's transport infrastructure classified into infrastructure for moving transport (e.g., roads, train tracks), infrastructure for stationary traffic (e.g., park garages, train depots), vehicles, and annual material input and output flows from Figure 2 in Paper I. Underlying data used to create this figure can be found in the Supporting Information S2 published together with Paper I.

The amount of materials built-in exceeded the removed materials from the system, as indicated by the MS increase. Moreover, the annual MF^{IN} varied more (from 1.5 to 3.8 Mt/year; mean 2.2 Mt/year) than the waste generation (from 1.4 to 1.8 Mt/year; mean 1.6 Mt/year). This is explained by network expansions, e.g., due to subway expansions in 1991 and 1995 more materials were built into the system in comparison to other years (yellow bars in Figure 6). Network expansions are also clearly reflected in the built-in material quantities if transport modes are compared. Figure 7 shows a comparison of MF^{IN} and MF^{OUT} per transport mode infrastructure and material category. In chart (a) and (b) the MF are summed up to 5-year periods and chart (c) and (d) shows the total sum. In periods when the PT network wasexpanded (e.g., 1991-1995), the respective quantities of MF^{IN} were comparable to those of MIT, however, in periods without substantial expansions less materials were built in the PT network. For the regular maintenance of the network, larger quantities of material were needed for the MIT network than for the PT network, due to a significantly larger network. The dismantled materials were mainly caused by maintenance and were thus relatively constant in quantity and composition.

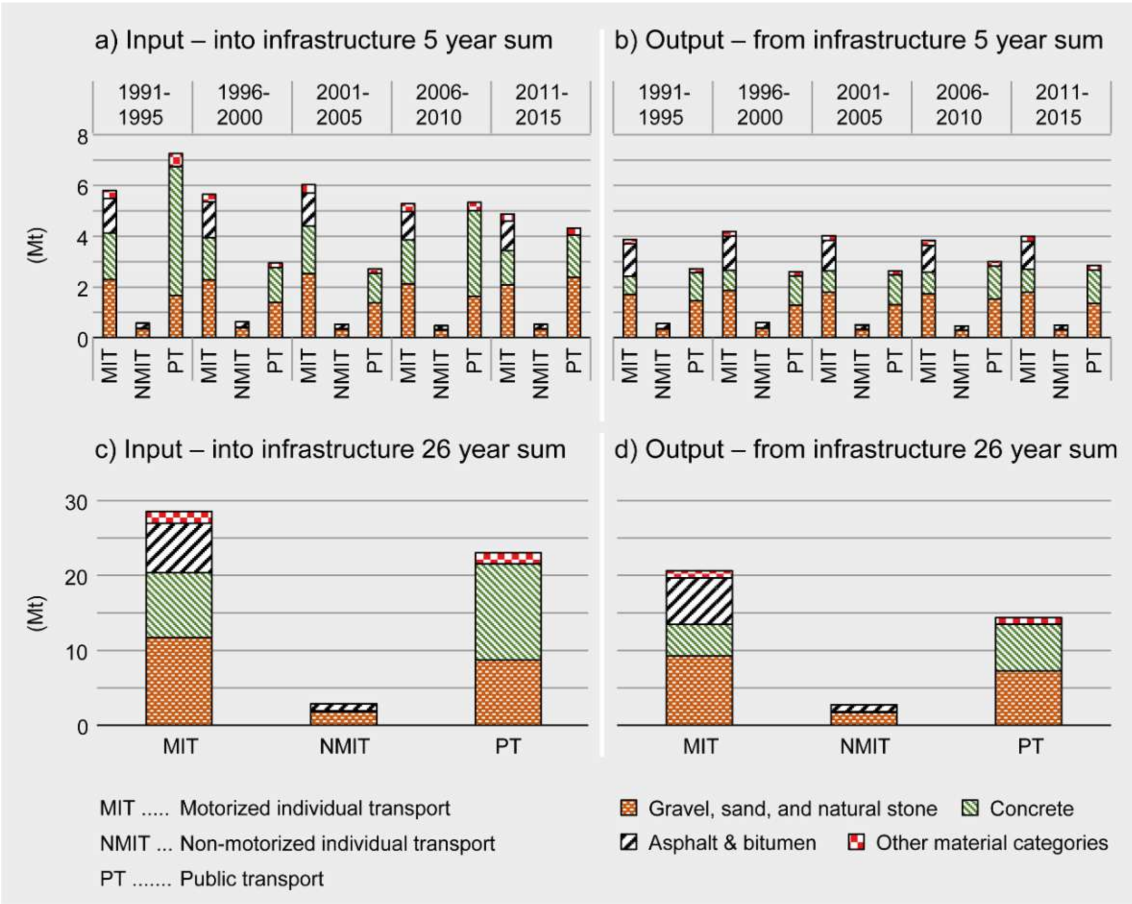

Figure 7: Material flows related to transport infrastructure in Million tons (Mt): (a) Input into infrastructure per transport mode (5-year sum); (b) Output from infrastructure per transport mode (5-year sum); (c) Total material input into infrastructure per transport mode; (d) Total material output from infrastructure per transport mode. From Figure 4 in Paper I, underlying data used to create this figure can be found in the Supporting Information S2 published together with Paper I.

Overall, in comparison to all transport modes the MIT network had the highest resource demand and waste generation in the period investigated (cf. Figure 7). In terms of material categories, asphalt &

bitumen was mainly built into the MIT infrastructure, however, concrete dominated the input into the PT network. The MF^{IN} and MF^{OUT} for MIT infrastructure were dominated by maintenance processes, or more specifically, by mineral road construction material (50%). The summed-up MF^{IN} (5-year periods) per process category showed that the maintenance of roads causes most MF^{IN}, followed by maintenance of subsurface infrastructure (pipes and cables) and new road construction (see Figure 8).

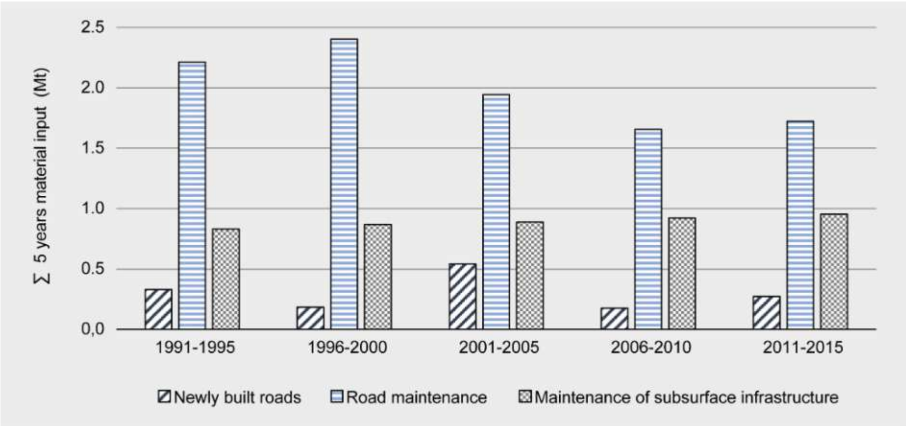

Figure 8: Five-year sum of mineral road construction material input caused by road construction and maintenance as well as maintenance of subsurface infrastructure networks (pipes and cables) in Million tons (Mt). From Figure 5 in Paper I, the underlying data used to create this figure can be found in the Supporting Information S2 published together with the Main Article.

All vehicles together (cars and motorcycles 77%, lorry vehicles 14%, regional train 3%, subway, tram, and public bus vehicles together 4%) had a share of the total MS of around 1% (1.2 Mt) compared to the infrastructure, remaining constant over the period investigated (cf. Figure 6). Thereby, the MIT vehicle (>90%) make up most of the vehicle MS. Their number increased in the period under review (cf. Table 1), also in relative terms (cars per 1,000 inhabitants from 391 to 410). Furthermore, the mean vehicle weight has increased; consequently, the total MS of vehicles increased by 32%. Until 2015, there were no significant changes in the vehicle fleet (regarding propulsion technologies) and its material composition. In 2015, the share of vehicles with alternative propulsion technologies was less than 0.2% of the overall vehicle stock, also almost all (>98%) new vehicles had a fossil fuel driven propulsion technology. If the achievement of the targets set (see Chapter 4.1) is taken seriously, the share of new vehicles registered with alternative propulsion technology must increase drastically in the following years to change the vehicle fleet significantly until 2030. Because the average stock renewal rate is 10% per year.

The investigation showed that especially for well-developed transport infrastructure systems the maintenance is especially relevant for the annual material turnover. Which is for instance clearly reflected in the results for MIT infrastructure (see Figure 8). This is in line with the results from other studies. For instance, Wiedenhofer et al. (2015) showed that for the period 2004-2009 the inputs for maintenance of the European road and rail network exceeds the inputs for expansion between 1 to 6 times. For the island of Samothraki in Greece, Noll et al. (2019) present a steadily growing resource requirement for the maintenance of buildings and infrastructure, which goes up to >80% of the overall input of construction material. Miatto et al. (2017) showed that most material inputs into the United States road network have shifted from new construction towards maintenance in the period from 1905 to 2015. Regarding road maintenance, the presented work further highlights that maintenance of subsurface networks contributes significantly to the material turnover (on average 28% of the MF^{IN} (0.2 Mt/year)). Hence, the maintenance of transport infrastructure and its management holds a high potential for resource saving and waste prevention as well as for forcing more circular material cycles.

The results of the presented MFA model are comparable to those presented in other studies. So, the total MS of the transport system contributes 22% to the anthropogenic MS (buildings and infrastructures). This corresponds to a share of about 20% for networks in heavily built-up areas referred in the literature (Augiseau and Barles, 2017). When considering the MS per capita together with those for buildings calculated by Kleemann et al. (2017), the total in-use MS in Vienna (buildings and transport infrastructure) is around 270 t/capita (in 2015), which is below the global average for industrialized countries of 335 t/capita in 2010 (Krausmann et al., 2017) as well as for the countries of Japan (310 t/capita) and the United States (375 t/capita) specifically (Fishman et al., 2014). However, it is comparable to the MS of 247 t/capita calculated with a bottom-up approach by Tanikawa and Hashimoto (2009) for the City of Wakayama. Given that Wakayama has only about one fifth of the population of Vienna and no subway network. The presented MS for the City of Manchester within the same article is with 111 t/capita significantly lower due to a different built-up density within the case study area. This illustrates the major differences between various cities depending on their built-up density and prevailing transport infrastructure.

The developed MFA model provides a detailed assessment of the transport system, but there are some limitations to be mentioned. i) The inventory data are subject to uncertainties due to simplifications and necessary assumptions (e.g., because of missing data). ii) Recycling or cascading use of materials are not explicitly calculated, hence, no recycling rates can be reported. iii) The city level as system boundary presents some difficulties since the transport system not only serves and depends on the city but also the surrounding area. iv) The data concerning transport performance is insufficient and associated with a high level of uncertainty.

6.2. Projected development of the transport system in Vienna (2015-2050)

A population of around 2.3 Million is forecasted for Vienna by the year 2050 (Hanika, 2019). This population increase (>20%) will result in an increasing need for transport. The effects on the respective vehicle fleet and the network development of the various transport modes depending on political and social decisions taken within the years to come. In this chapter, the results, based on the scenarios (cf. Table 3) and corresponding assumptions presented in Paper II, are summarized. First, the projected development of the vehicle fleet and infrastructure depending on the scenarios is described. Second, the resulting material flows and stock development are summarized. Finally, the results are briefly discussed. For more detailed results and their discussions the reader is referred to Paper II and the Supporting Information published together with the Main Article.

The projected vehicle fleet per scenario differed significantly. The differences between the scenarios were particularly large for the MIT vehicle fleet. If the motorization rate is assumed to remain on current level, the MIT vehicle fleet was projected to increase to around 1.2 million by 2050 (scenario $\mathbf{B_{+BEV}}$ +32%) from today´s figure of 900,000. If, on the contrary, a transformation towards public and active mobility transport modes takes place, the motorized vehicle fleet was calculated to be reduced to around 500,000 vehicles (scenario $\mathbf{C_{+PT}}$ -50%), which corresponds to a motorization rate of 99 cars per 1,000 inhabitants (rate in 2019: 372). For the active mobility vehicle fleet (NMIT), an increasing trend was projected in all scenarios. However, the growth varies in intensity from a stock increase of 16% in scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+BEV}}$ towards a maximum increase of >50% in scenario $\mathbf{D_{+AM}}$. The number of PT vehicles was also calculated to increase in all scenarios. Depending on the scenario, a PT fleet increase was projected in a range between 13% ($\mathbf{B_{+BEV}}$) to almost 44% ($\mathbf{C_{+PT}}$).

The road-based traffic area was projected to increase to 56 km² by 2030. Further, an increase until 2050 was only projected in the scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+BEV}}$ (+7 km²). Parking areas accounted for around 3 km² (35%) to this increase. In contrast, no additional road-based traffic area expansion was projected in scenarios $\mathbf{C_{+PT}}$ & $\mathbf{D_{+AM}}$. The use of existing areas was assumed to be changing from MIT towards NMIT. The traffic area per capita was constant, with around 27m²/capita in scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+BEV}}$. In comparison, in scenarios $\mathbf{C_{+PT}}$ & $\mathbf{D_{+AM}}$, it resulted in a decrease to around 24m²/capita. The rail-based public transport network was projected to be expanded in all scenarios compared to the status quo (network length in 2020: 450 km). The total calculated network length of scenarios $\mathbf{C_{+PT}}$ & $\mathbf{D_{+AM}}$ is with 612 km about 10% higher as compared to scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+BEV}}$ (560 km). This relatively small difference is explained by the already well-developed network. In the scenarios $\mathbf{C_{+PT}}$ & $\mathbf{D_{+AM}}$, the required additional transport capacity is mainly provided on the same network by a higher frequency of vehicles.

The resulting overall MS development calculated for the various scenarios is presented in Figure 9. Thereby, the historical trend (1990-2020) is continuing in the scenarios **A$_{BAU}$** & **B$_{+BEV}$** resulting in a total MS of more than 120 Mt (54 t/capita) in 2050. In contrast, in the scenarios **C$_{+PT}$** & **D$_{+AM}$** the MS is estimated to remain on the level of 2030 or even to decrease slightly (around 110 Mt; 47 t/capita). In all scenarios, the mineral construction material contributes about 95% to the overall MS.

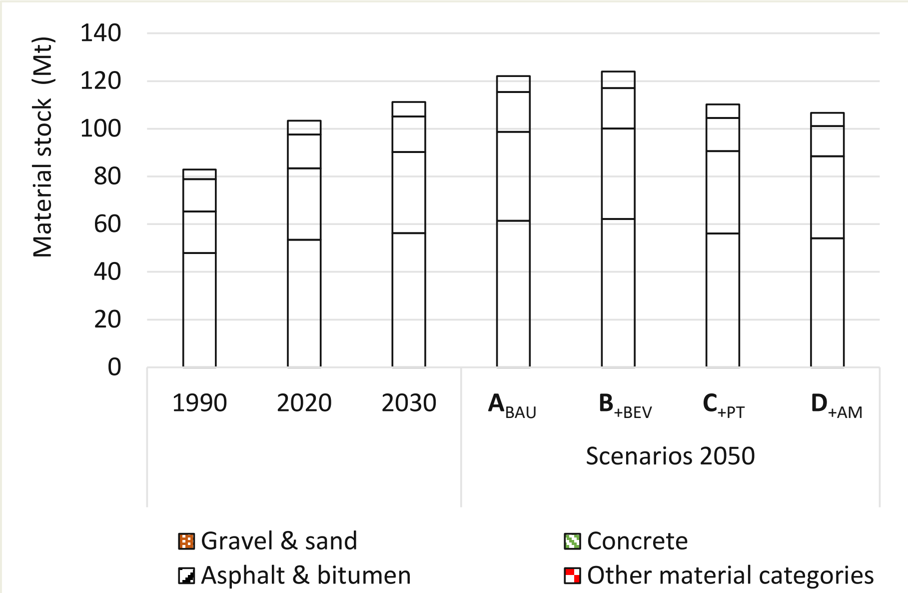

Figure 9: Material stock per scenario and material category in Million tons (Mt) from Figure 5 in Paper II.

The cumulative material in- and outputs, into/from (i) the transport infrastructure and (ii) the vehicle fleet stock, per material category in the respective scenarios for the period 2016 to 2050 are presented in Figure 10. Overall, the material input exceeds the material output in all scenarios, hence, the total MS in the year 2050 is higher in all scenarios compared to the stock of 2016. However, in scenarios **C**$_{+PT}$ & **D**$_{+AM}$ the stock decreases between 2030 and 2050. This results in a higher material output flow of mass construction materials (gravel & sand, concrete, and asphalt & bitumen) in these scenarios in comparison to scenarios **A**$_{BAU}$ & **B**$_{+BEV}$ due to the assumed dismantling of road infrastructure.

In scenario **B**$_{+BEV}$, the share of non-construction materials relative to total material turnover is higher compared to scenarios **C**$_{+PT}$ & **D**$_{+AM}$, which is mainly due to the larger private vehicle fleet stock. Overall, in scenario **B**$_{+BEV}$ the cumulative material input into the vehicle stock is around 25% higher than in scenarios **C**$_{+PT}$ & **D**$_{+AM}$. This appears low given the significant reduction of the total vehicle fleet by -70% up to 2050 assumed in these scenarios. It is because in the model the full stock reduction was reached at the end of the period. The steady stock renewal is also reflected in the output flows of end-of-life vehicles of the different scenarios. However, the input of selected materials in vehicles differ more significantly, for instance, the total input of batteries and copper is about 48% and that of aluminium about 28% higher in scenario **B**$_{+BEV}$ in comparison to scenarios **C**$_{+PT}$ & **D**$_{+AM}$.

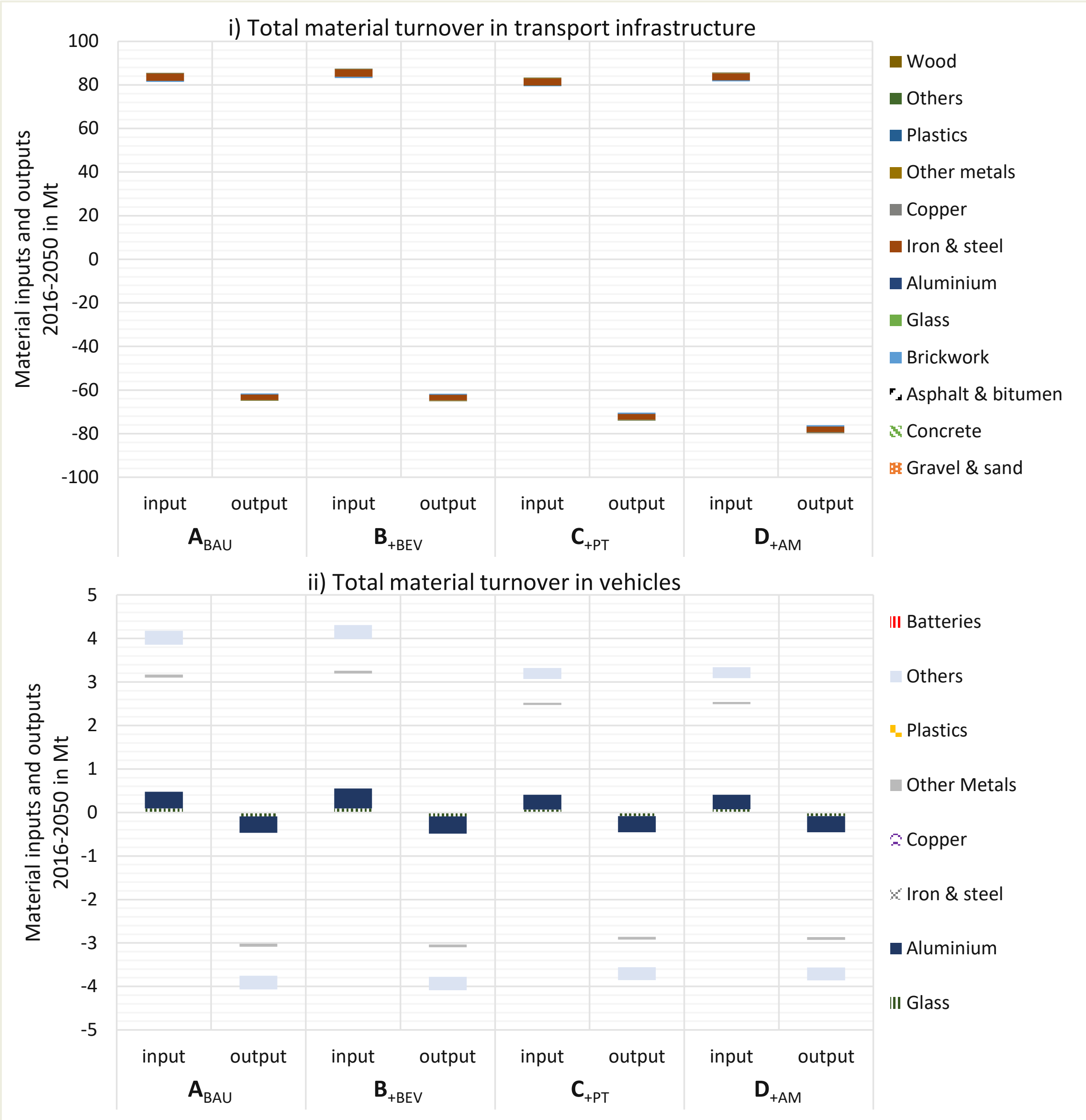

Figure 10: Cumulative material in- and outputs into/from (i) transport infrastructure, and (ii) vehicles per material categories in the scenarios 2016-2050 in Million tons (Mt) from Figure 7 in Paper II.

The projected development of the MS of Vienna´s vehicle fleet in the different scenarios ranges from 1.60 Mt (**B**$_{+BEV}$) to 0.76 Mt (**C**$_{+PT}$) in 2050. The difference was determined by the diverse development of the private vehicle fleet. For the different scenarios, it had been assumed that private car ownership correlates with private vehicle kilometer travelled within the city, which is a simplified assumption. However, on the city level numerous factors influence vehicle ownership through regulations (e.g., parking space management and fees) and even more effectively through the development of the road and parking infrastructure. The importance of the infrastructure (e.g., available parking places and road capacities) with regards to private vehicle ownership and transport mode choice has been proven in several studies (among others, by Cervero and Murakami, 2010; Christiansen et al., 2017; Knoflacher, 2006; Sun et al., 2017). Hence, the sooner traffic area transformation in favour of alternative usage takes place, as modelled in scenarios $\mathbf{C}_{+PT}$ & $\mathbf{D}_{+AM}$, the sooner the vehicle fleet will be reduced.

The overall material input into the transport infrastructure differs only slightly between the respective scenarios modelled in terms of material composition and quantity. One reason is that through the transformation there is a shift in resource demand from one mode of transport to another according to the assumed changes in the modal split. However, even more important for the overall material turnover is the fact that about 2/3 of the overall material input is caused by the maintenance of existing infrastructure. This high relevance of maintenance on material turnover for the transport infrastructure is consistent with other studies (Gassner et al., 2020; Noll et al., 2019; Wiedenhofer et al., 2015). This means, however, that a significant decrease in the material demand of the respective transport network is realized only gradually with the reduction in the network stock. In the year 2050 the annual raw material saving potential through reduced road maintenance efforts is about 20% (0.2 Mt/year) in scenario $\mathbf{D}_{+AM}$ compared to scenario $\mathbf{B}_{+BEV}$. Taking the total construction material inputs into the transport system into consideration, the effect goes down to around 6% annual saving potential since, for instance, the material input for PT increases in scenario $\mathbf{D}_{+AM}$.

Very recent investigations for the two Canadian cities Kitchener and Waterloo also used a bottom-up material accounting approach to assess the future building and transport infrastructure stock (Mollaei et al., 2021). They calculated the future development of the road transport infrastructure until 2041 based on the projected road expansion plans of the municipalities, which again is based on population development projections and policy plans. Comparing the results presented by Mollaei et al. (2021) with the results per capita of the Vienna case study shows that the MS of road infrastructure per capita for Kitchener and Waterloo (72 t/capita) is about double of the quantities calculated for Vienna (considering also the public transport, the stock figure for Vienna is still 26% lower). This can be explained by the different building densities and the fact that the transport system in Kitchener and Waterloo is mainly based on motorized individual transport (the current share of MIT is around 60% on modal split see City of Waterloo (2019)). Such differences in local conditions clearly shows the relevance of local bottom-up studies and the decisive role of specific correlations (e.g., existing infrastructure and mobility behaviour) as basis for projections.

As data availability for a complex system like the transport system of a city and its future development is limited, various simplifications and assumptions were necessary to set up the MFA model. Assumptions mainly concern the development of the service units (e.g., road network development). Despite these uncertainties, the differences assessed in the stocks and flows of the scenarios investigated, and hence the conclusions based thereon, are robust. Moreover, a comparison of the results with the findings of previous studies by numerous researchers (Miatto et al., 2017; Mollaei et al., 2021; Noll et al., 2019; Tanikawa and Hashimoto, 2009; Virág et al., 2021; Wiedenhofer et al., 2015) indicates the reliability of outcomes.

The development of the vehicle fleet per scenario had a significant influence on the results. In order to be able to depict clearly distinguishable scenarios, it was assumed that the ownership structure and propulsion technology of the vehicles in 2050 is equivalent to the current state. The impacts of a potentially increasing sharing economy or self-propelled cars on the development of the total vehicle fleet had not been considered and would require the inclusion of further scenarios. However, as there is no consensus on the impact of such developments (increase or decrease in MIT traffic), such scenarios were not considered. Furthermore, structural, political and social factors (e.g., household income, lifestyle, environmental awareness, parking regulations) that influence modes of transport chosen and affect car ownership decisions were not modelled individually as factors, but are required in order to reach the transformation described in the scenarios. The effects and interrelationships of such influences have already been investigated by other researchers (among others, by Buehler (2011); Ding et al. (2017); Vij et al. (2013)). The inclusion of all these factors as input factors in the presented case study would exceed the scope. Moreover, this would lead to a very complex model with many interdependencies, making a clear cause-effect estimate increasingly difficult.

6.3. Case study Wiener Linien I: Material flows in subway infrastructure refurbishment

The MF related to the refurbishment process of a subsection of Vienna's subway network are presented in Figure 11. Through the refurbishment process around 84,000 t of new construction materials were built-in in the section, of which two thirds were virgin material and one third recycling material (i.e., road surface material from a construction site in Vienna). Around 74,000 t were demolished and removed from the construction site and brought to landfill, waste treatment and recycling facilities. Since the amount of built-in material was considerably larger than the material removed, the overall MS increased by around 11,000 t. Hence, the specific material intensity per meter of track (both directions) increased by 3 t/m to around 110 t/m. During the refurbishment, overall (both on and off site) construction materials with a total mass of around 155,000 t were built-in the subsection. Thereof 55% were recycling material. 63,000 t of recycled track bed material were mixed with 23,000 t of recycled filling material and used as a frost protection layer. Furthermore, to some extent reuse of construction components/elements was performed (5%). The far biggest amount was due to the reuse of railway sleepers, including rails. In terms of materials this resulted in the reuse of 6,000 t (78%) of prefabricated concrete and 700 t (9%) of steel.

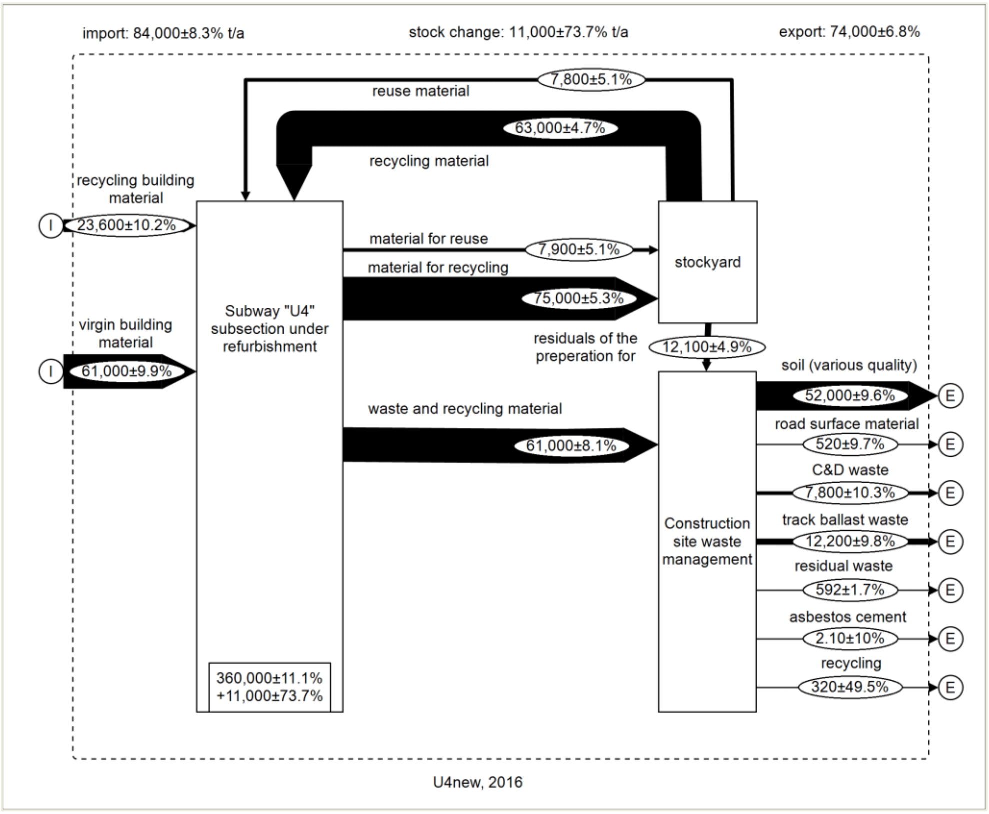

Figure 11: Results of the stock changes and aggregated flows due the refurbishment in tons from Figure 4 in Paper III.

The detailed flows of construction materials and wastes (22 different categories were considered) arising during the refurbishment process are presented in Figure 12. In terms of mass, the main materials brought into the system were gravel (57%), concrete (30%), and asphalt (11%). Around 400 t (<1%) of metals were built in the subsection, of which around 73% were iron/steel, 16% copper, and 10% aluminium. The main part of the built-in materials (new, reuse, and recycling) was used for the track substructure (69%), followed by track superstructure (24%), and buildings (7%). The main waste flows were soil excavation in different qualities (70%), track ballast (17%), construction and demolition waste (11%), road surface material (<1%), and materials for recycling (<1%).

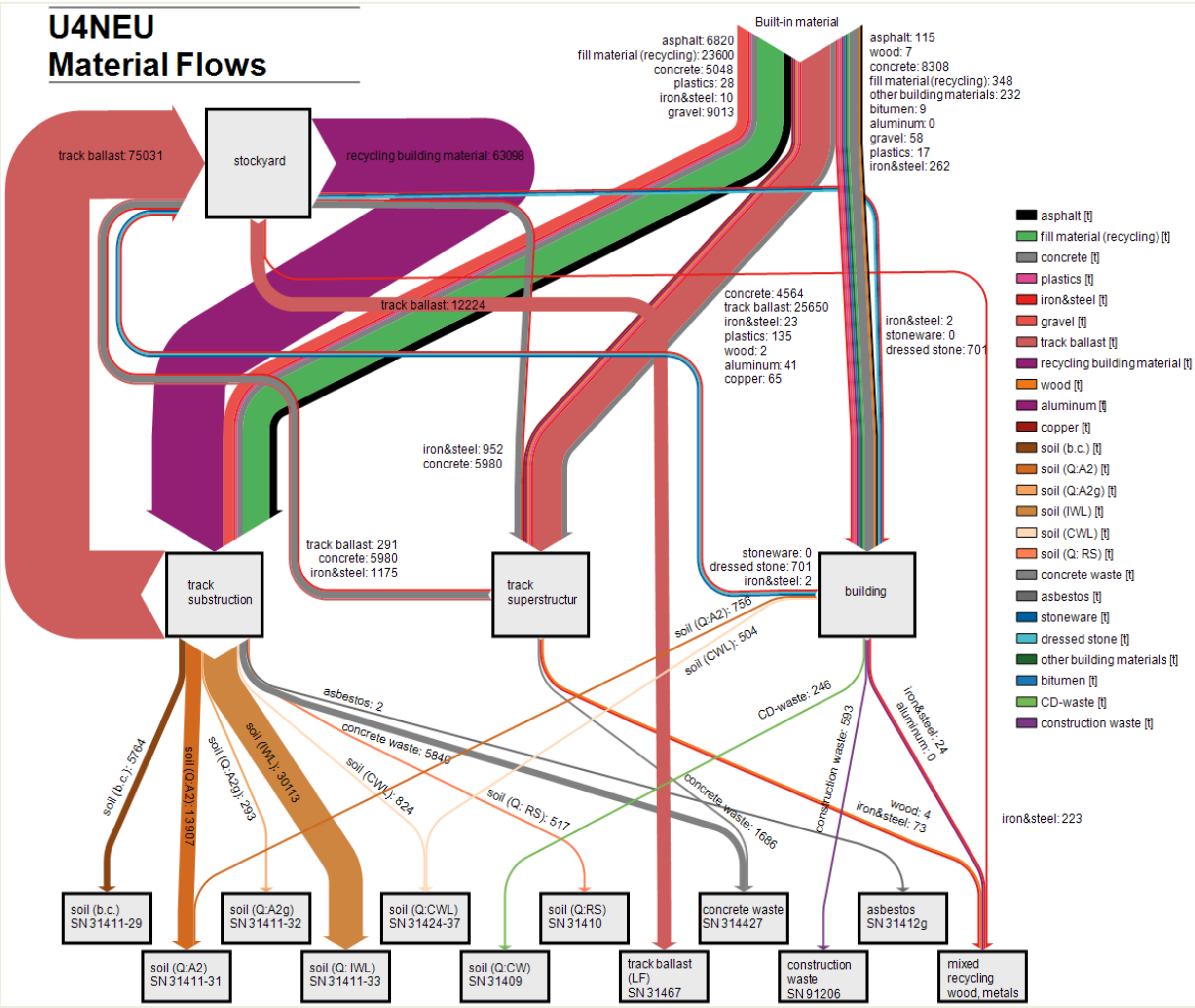

Figure 12: Construction material and waste flows in the refurbishment process of the subway subsection (U4new) in tons from Figure 5 in Paper III.

The results showed that in civil and underground engineering (e.g., railroads and roads) significant amounts of recycled construction materials are already used. This is in line with the objectives formulated at European level (i.e., (European Commission, 2020, 2015, 2014)), national resource reduction targets (i.e., (BMLFUW, 2012)), and goals defined at regional level (i.e.; Smart City framework strategy (City of Vienna, 2019)). However, predominantly the material was used for a downcycled use, as material was not used for the same purpose (e.g., concrete waste as aggregate in recycling concrete) but for a lower value use (e.g., concrete waste as technical filling material). In terms of a circular economy concept, this is only sustainable if the demand for low value material applications is higher than the amount recycling materials produced from construction and demolition waste.

6.4. Case study Wiener Linien II: Environmental assessment of a transport provider

An environmental assessment was performed to investigate the public transport provider in Vienna (Wiener Linien), using an ecological footprint (EF) approach. In the assessment, the EF of Wiener Linien was calculated to around 72,500 gha/a for the reference year 2012. The overall EF per transport mode and divided according to the defined land use categories (i) direct land use, (ii) direct hinterland use, (iii) embodied CO_2 hinterland use, and (iv) operational energy CO_2 hinterland use, is presented in Figure 13. Therein, the total EF of the provider is shown, which indicates that the transport mode subway contributes the largest share (51%), followed by bus (20%), tram (19%), and service (10%) to EF.

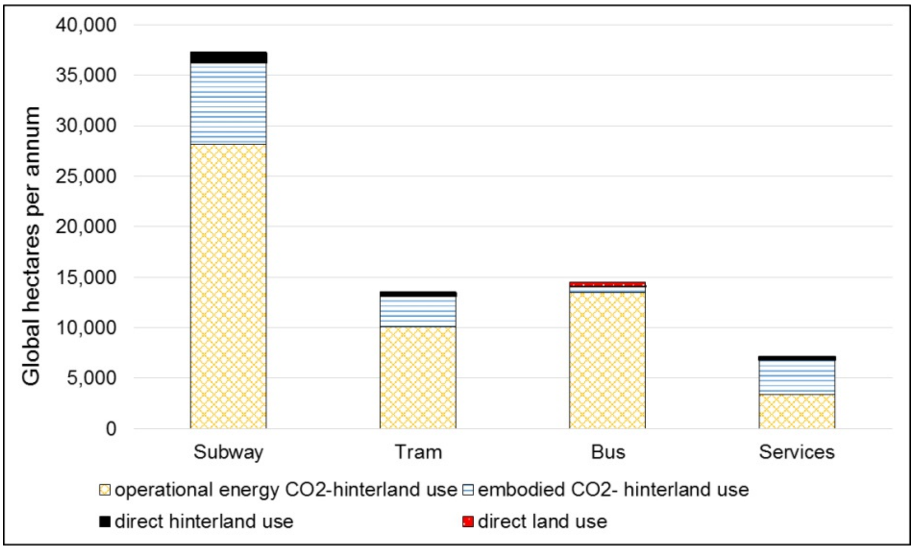

Figure 13: The overall Ecological Footprint of Wiener Linien per transport mode and divided according to the defined land use categories from Figure 9 in Paper IV.

However, if the overall EF is normalized per performance unit (passenger kilometre travelled and seat kilometre provided), this ranking of the transport modes changes, as evident in Figure 14. Whereby the category "service" was assigned according to the share of overall passengers transported per transport mode. It turned out, that the specific EF of the transport provider bus compared to the subway was around 1.7 times higher if calculated per passenger kilometer travelled (PKT). If considering the overall provided capacity per transport mode with the seat kilometer provided (SKP), this number rose to 2.5 times. Regarding the area efficiency of the public transport provider Wiener Linien, defined as PKT per ha of direct land use within the city, the results indicated an average efficiency of around 5.4 million PKT/ha. The subway showed with 23.2 million PKT/ha an almost 18 times higher area efficiency than the bus (1.3 million PKT/ha), whereas the area efficiency of the tram (5.5 million PKT/ha) corresponded to the average of the provider.

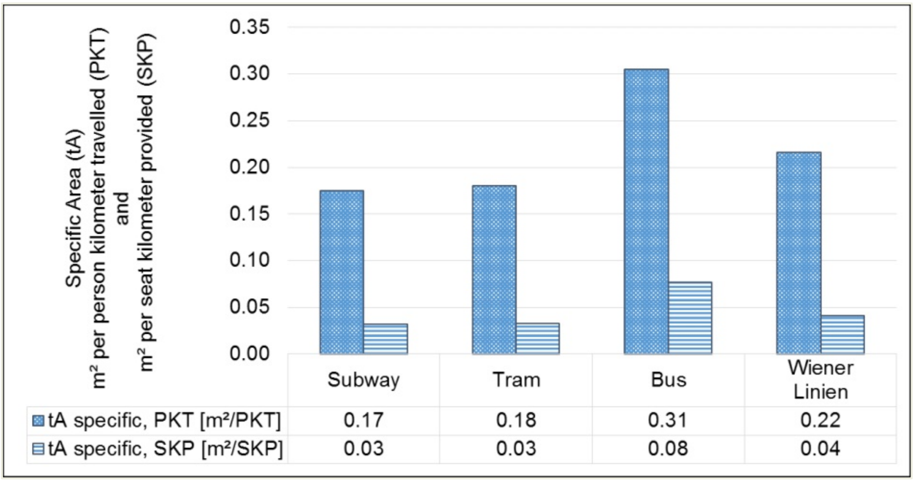

Figure 14: Specific Ecological Footprint per transport mode expressed in specific total area (tA) in square meters per Person kilometer travelled (PKT) and per seat kilometer provided (SKP) from Figure 10 in Paper IV.

In the following, the results of the distinguished land use categories (cf. Figure 4) are summarized on the level of the transport provider. The total area used in Vienna by infrastructure from the transport provider, considered as (i) direct land use (above ground), was 621 ha, mainly caused by the network (>80%). The direct hinterland (ii) to produce materials for built-up infrastructure and consumed goods as well as energy was calculated to 1,660 gha/a. Power was the inventory category (cf. Figure 5) responsible for nearly 60% of direct hinterland demand, followed by buildings (27%) and consumer goods (12%). The area needed to sequestrate embodied CO_2 emissions (e.g., caused for producing upstream products and materials), the (iii) embodied CO_2 hinterland, was determined for Wiener Linien with about 15,000 gha/a. Therein, the inventory category constructions was the most relevant (65%) due to the construction materials built in the networks, followed by consumer goods (15%).

Finally (iv), the operational energy CO_2 hinterland use was calculated with around 55,000 gha/a the largest of the land use categories. This area is theoretically needed to compensate the CO_2-emissions caused by the direct annual energy consumption of the transport provider. About 50% was caused by the energy consumption of the subway, followed by bus (24%) and tram (18%). Around 75% were caused by energy for traction power (electric power 68%, motor fuel 32%), the remaining 25% were caused by general energy consumption (e.g., lighting , heat). The very significant influence of the total energy consumption on the total EF results from the following reasons. Firstly, the operational phase mainly dominated by energy consumption usually causes the highest impacts of all life cycle stages in the environmental assessment of transport services. Secondly, the indicator of the EF is particularly sensitive to non-renewable energy sources as shown for products by Huijbregts et al. (2008). Fossil fuels still provide a significant share on the overall energy consumption of the investigated transport provider (all the motor fuel to power the buses, and around 45% of the electric power are produced with fossil fuels).

In contrast to other 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 work presented considered an integrated transport system of one provider operating three different transport modes within a city, yielding a unique data set. The joint management of networks of different transport modes and integrated planning of further development provides considerable resource saving potential by using synergies. The data collected forms the basis to investigate this effect further.

To compare the results with other studies the results per transport mode were considered. Like in other studies, although, the operation phase and especially the energy consumed therein, turned out to be the most important life cycle phase in all transport modes investigated, however, the infrastructure is not negligible. Particularly, for infrastructure-intensive transport modes such as the subway and the tram networks, a significant share of the overall impacts were related to construction materials built in the infrastructure, which has also been observed by other authors (Anderson et al., 2015; Chester et al., 2010; Chester and Horvath, 2009). Hence, the construction of the infrastructure and its maintenance are to be considered in the comparison of the environmental impacts of various transport systems.

Accordingly, the significance of the respective inventory categories (cf. Figure 5) on the results, corresponding fields of action arise to mitigate the overall EF of the transport provider. Considering infrastructure, the highest saving potential is achievable in the early stage of network planning and variant selection, as also pointed out by the guideline to the British standard on carbon management in infrastructure PAS 2080:2016 (Construction Leadership Council, 2016). For instance, aboveground routes of subway lines are preferable compared to underground routes, in terms of the overall resource demand (materials and construction activities). The second main EF mitigation field concerns the energy consumption and the respective energy mix used. By purchasing an electricity with a higher share of renewables from the energy provider, the EF could be reduced. However, at the national level, this will not lead to any reduction in emissions, only to a shift of electricity produced from fossil sources from one consumer to another if the electricity production mix remains unchanged. Hence, energy-saving measures are the preferable measure, because they can be managed and influenced by the provider itself and lead to cost savings in the long term. Increase in efficiency are achievable in diverse areas within the public transport system as presented by González-Gil et al. (2014) for urban rail systems.

7. Conclusion and outlook

Within the scope of this work, the development of the transport system in Vienna and associated MF were investigated and the future development was projected based on various scenarios up to the year 2050. Furthermore, the MF related to the rehabilitation of a subway subsection were examined in detail, and an ecological assessment of the public transport provider was carried out. This chapter summarizes the overall outcome of the investigations as presented and discussed in detail in Chapter 6. First, the responses to the research questions introduced in Chapter 2 are provided. Second, a general conclusion and an outlook are given.

7.1. Summarized responses to the research questions

i. The total in-use MS of the transport system in Vienna has increased from 83 Mt in 1990 to 103 Mt in 2015. This corresponds to around 58 t MS per capita. The largest share is attributed to motorized individual transport (62 Mt; 34 t/capita), followed by public transport (36 Mt; 20 t/capita), and non-motorized individual transport (6.6 Mt; 4 t/capita).

ii. Within the period investigated, in average the annual MF^{IN} was 2.20 Mt and the mean MF^{OUT} corresponded to 1.55 Mt per year. Due to the impact of network expansions, the MF^{IN} varied considerably more (from 1.5 to 3.8 Mt/year) than the MF^{OUT} (from 1.4 to 1.8 Mt/year). The annual material turnover of the MIT is the largest (mean MF^{IN} 1.2 Mt; mean MF^{OUT} 0.9 Mt), followed by PT (mean MF^{IN} 0.1 Mt; mean MF^{OUT} 0.1 Mt), and NMIT (mean MF^{IN} 0.9 Mt; mean MF^{OUT} 0.6 Mt).

iii. The relevance of new construction processes to the annual material turnover depends on the corresponding network expansions in the respective year and therefore fluctuates (see also mean MF^{IN}). However, for well-developed infrastructure networks the material turnover is dominated by maintenance, which is clearly reflected in the results for motorized individual transport. On average only 10% of the use of road construction material was caused by new road construction, 62% by road maintenance, and 28% were caused by construction activities related to the maintenance of subsurface infrastructure.

iv. Depending on the scenario, the overall MS calculated for 2050 varies between 107 Mt and 124 Mt. The biggest differences between the scenarios arise for the MIT network and the private vehicle fleet. If the modal split remains constant, the road-infrastructure must be further expanded to provide the transport service needed due to accommodate the increasing number of vehicles. In this case, the MS per capita for the transport system would decrease slightly to 54 t/capita. If the MIT can be reduced to a share of less than 10% of all trips (today's share amounts to 25%), the MS per capita decreases more drastically to around 47 t/capita in 2050. In the infrastructure sector, this results in an approximately 6% lower annual material input (2.4 Mt/year). The difference is more drastic for the input into the vehicle fleet, which would be around 56% lower in this case (0.07 Mt compared to otherwise 0.15 Mt per year).

v. The choice of transport modes and thus the development of the motorization rate will play an important role in terms of the development of the annual resource consumption. A reduction in the consumption of primary raw materials is achievable by shifting from private motorized vehicle-based transport towards public transport and active mobility. However, if the existing system and modal split is retained, resource consumption and the waste generated thereby will continue to rise although greenhouse emissions might be mitigated due to fewer fossil-fuel based vehicles being used. The greatest savings potential results from a reduction in the private vehicle fleet and road infrastructure as well as from the associated decline in maintenance efforts.

vi. The investigated refurbishment process of a subsection of Vienna's subway infrastructure caused an output flow (construction and demolition waste) of around 74,000 t and a material input flow (construction material) of round 84,000 t. Resulting in a MS increase by around 11,000 t. This corresponds to an increase of less than 3% (3 t/m) in relation to the specific material intensity per meter of track (both directions, 110 t/m).

vii. In the investigated case study, overall construction materials (onsite recycling material together with new construction material input) with a total mass of around 155,000 t were built-in the subsection. Thereof, 55% were recycling material, 40% virgin building material, and the remaining 5% reuse construction components/elements.

viii. With a ratio of recycling and reuse material use of around 60%, the investigated refurbishment project meet the policy targets as formulated for instance on European level (i.e., (European Commission, 2020, 2015, 2014)). However, recycling and landfilling rates of the occurring waste flows are not known in detail. Due to the waste classification of the excavated soil, it can be assumed that the main part had to be landfilled.

ix. The overall EF of Wiener Linien was calculated to around 72,500 gha/a for the reference year 2012, which equals to 0.03 gha/capita considering Vienna's population of 1.8 million inhabitants. The overall EF corresponds to a specific EF per provided capacity, expressed in seat kilometer provided (SKP), of 0.04 m^2/SKP across all transport modes. If the passenger numbers are considered, it results in a specific EF per person kilometer travelled (PKT) for the transport provider of 0.22 m^2/PKT.

x. The direct land use within the city corresponds to around 1% of the overall EF. Whereof, 80% are related to the networks of the transport modes (70% bus, 20% tram, 10% subway). Regarding hinterland land use (99% of the overall EF), a different distribution on the various transport modes has been calculated, 51% subway, 20% bus, 19% tram, the remaining 10 % are attributed to service (e.g., administration). However, the ranking changes if the transport performance is considered. Regarding the specific EF per PKT the lowest EF with 0.17 m²/PKT corresponds to the subway service, followed by the tram service with 0.18 m²/PKT, and the bus service with 0.31 m²/PKT. The considerably higher specific EF of the transport mode bus is due to the use of fossil fuels for the operation. Contrary the electric power used as traction power for rail-based transport modes was produced by 55% of renewable sources. As the indicator EF is particularly sensitive to CO_2 from fossil energy sources, this has a decisive influence on the overall result.

7.2. General conclusion and an outlook

A comprehensive assessment was conducted in this thesis, to investigate the long-term MS development of Vienna's transport system and associated material consumption and construction and demolition waste generation. The retrospective investigation showed that the MS is still growing even though the city of Vienna already has a well-developed transport system. Even though the share on modal split of public transport (38%) and non-motorized individual transport (37%) are already high compared to other European cities, most of the MS is nevertheless accounted for the motorized individual transport. However, the results highlight that the MS for the transport modes public transport and non-motorized individual transport has increased significantly over the last 25 years. This is due to a change in transport policy, which promotes public transport and active mobility. Further, the results show that within well-developed systems the material turnover (input and output) is more strongly related to maintenance and refurbishment processes. Moreover, the maintenance of other infrastructure networks has a significant influence on the material consumption, as shown for the road infrastructure with the underground networks. Hence, a central management system for road maintenance and the maintenance of underground installations has a significant potential for saving resources, waste prevention and for promoting local use of secondary raw materials (e.g., for road substructure). The case study also showed that the use of recycled construction materials is under the right circumstances already state of the art. Hence, there is a high potential to reduce the demand of primary resources within the construction sector.

Although the city of Vienna already has a well-developed transport system, it will further expand in the future. The choice of transport modes and thus the development of the motorization rate will play an important role in terms of the development of the MS and annual resource consumption. A reduction in the consumption of primary raw materials is achievable by shifting from private motorized vehicle-based transport towards public transport and active mobility. However, if the existing system and the modal split is retained, resource consumption and the waste generated thereby will continue to rise although GHG emissions might well be mitigated due to fewer fossil-fuel based vehicles being used. The greatest savings potential results from a reduction in the private vehicle fleet and road infrastructure as well as from the associated decline in maintenance efforts. Hence, obsolete (road) infrastructure should be dismantled and converted for other purposes, in order to avoid negative feedback loops (e.g., many available parking spaces on streets favour private car ownership) and to foster the transformation of the transport system (e.g., well established, and safe bike lanes infrastructure promote cycling mode share). Moreover, the resource aspect should be considered in any extension and rehabilitation project connected with road infrastructure. Thus, each project should be evaluated for its impact on the targets set in the Smart City Wien Framework Strategy to reduce GHG emissions and resource consumption.

The insights provided in the present work raise several research questions to be addressed in future. The developments in the transport system investigated should be further analysed in terms of their impact on energy consumption and GHG emissions, whereby both direct (e.g., fuel and energy consumption) and indirect consumption and emissions (e.g., goods and material production) should be considered. The future energy mix (e.g., for electricity production for the region) has to be considered, incorporating additional scenarios or at least sub-scenarios to encompass this complexity. Such analysis is crucial to examine the overall environmental impact of the city's transport system and to investigating whether a transformation causes an overall shift from direct emissions (occurring within the city) towards material incorporated emissions (occurring globally). Furthermore, it would be of great interest to analyse the environmental and social impacts of a new distribution of the scarce resource land area within the city by means of a potential reduction in road area. Finally, upcoming trends like sharing mobility concepts and autonomously driving vehicles, or a change in the movement of people (e.g., change in place of residence choice due to increase in remote working possibilities) could have a decisive influence on the cities transport system. Evaluating impacts of such trends on the material turnover will be an important upcoming research topic.

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List of Abbreviations

A$_{BAU}$	scenario A 2050: business as usual scenario
AM	active mobility
B$_{+BEV}$	scenario B 2050: battery electric vehicle fleet scenario
BEV	battery electric vehicle
C$_{+PT}$	scenario C 2050: public transport scenario
CDW	construction and demolition waste
CO_2	carbon dioxide
$CO_{2\text{-}eq}$	carbon dioxide equivalent or CO_2 equivalent
D$_{+AM}$	scenario D 2050: active mobility scenario
EF	ecological footprint
GHG	greenhouse gas
GIS	geographic information system
HSR	high-speed rail
km	kilometer
LCA	life cycle assessment
m.t.i.	moving traffic infrastructure
m^2	square meter
MF	material flow
MFA	material flow analysis
MF^{IN}	material input flow
MF^{OUT}	material output flow
MIT	motorized individual transport
MS	material stock
Mt	million tons
n	number
NFA	net floor area
NMIT	non-motorized individual transport
PKT	passenger kilometers travelled
PT	public transport
s.t.i.	stationary traffic infrastructure
SCWFS	smart city Wien framework strategy
SKP	seat kilometer provided
SU	service units

t	metric tons
v.	vehicles

Appendix

V) A. Gassner, J. Lederer and J. Fellner. Material stock development of the transport sector in the city of Vienna. Journal of Industrial Ecology, 24: 1364-1378, 2020.
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VI) A. Gassner, J. Lederer, G. Kovacic, U. Mollay, C. Schremmer and J. Fellner. Projection of material flows and stocks in the urban transport sector until 2050 – A scenario-based analysis for the city of Vienna. Journal of Cleaner Production, 311: 127591, 2021.
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Paper I

Material stock development of the transport sector in the city of Vienna

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RESEARCH AND ANALYSIS

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Material stock development of the transport sector in the city of Vienna

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Abstract

Societies aim to reduce primary raw material consumption, enhance waste recycling, and reduce waste disposal. In this regard, the circular-economy concept has gained attention and is applied in policy papers, also on the urban level. However, to assess set targets and their achievement, a sound knowledge of anthropogenic material flows and stocks is required. The material turnover of transport systems has not been sufficiently investigated yet, although they have a significant impact on overall material turnover and have a high potential for making use of recycled construction materials. To close this gap, the present study investigates the anthropogenic stocks and flows related to an urban transport system, whereby both infrastructure and vehicles are included. A bottom-up, multiyear material-flow analysis was employed to calculate the material stock and the related input and output flows of Vienna's transport system for the period 1990–2015. The results indicate the increasing importance of more environmentally friendly modes of transport. The stock of motorized individual transport has increased in absolute terms since 1990, but the stock per capita remains unchanged at 34 t/cap, whereas the per capita stock of public transport (20 t/cap; +8%) and of nonmotorized individual transport (4 t/cap; +10%) has increased. However, the primary source of material consumption (>65%) is maintenance of infrastructure. This provides a potential for more circularity because outputs and inputs are equal in terms of mass and material. The study provides a systematic analysis for developing policy and management options for sustainable resource-saving urban transport systems.

KEYWORDS
built environment, construction and demolition waste, industrial ecology, material flow analysis (MFA), transportation, urban metabolism

1 | INTRODUCTION

Material demand and waste generation have been constantly growing over the last century (Krausmann, Lauk, Haas, & Wiedenhofer, 2018) and cities are the main drivers of this development because of urbanization (Kennedy, Cuddihy, & Engel-Yan, 2007). This material turnover is dominated by the expansion of the building and transport sectors (Johansson, Krook, Eklund, & Berglund, 2013), leading to an increase in the material stocks (MS) in these sectors, even in highly industrialized societies (Lederer et al., 2020; Miatto, Schandl, Wiedenhofer, Krausmann, & Tanikawa, 2017; Miatto et al., 2019). To build up these MS, large amounts of raw materials are needed, and after their lifetime considerable quantities of construction and demolition waste (CDW) are produced. In order to reduce the material turnover and, in particular, the need for primary raw materials, the European Union aims to realize an increasingly circular economy (European Commission, 2015). Contrary to other materials, the recycling of construction materials is to be tackled at the local level because they have an economically and environmentally limited transport distance due to their comparatively low value and high mass (Hiete, Stengel, Ludwig, & Schultmann, 2011). In this regard, a number of cities define sustainable development targets in accordance with the circular economy concept (Prendeville, Cherim, & Bocken, 2018).

The city of Vienna incorporated the circular economy idea within its *Smart City Wien Framework Strategy* (2050). Therein, the target calls for 80% of all components and materials from demolishing buildings to be reused or recycled by 2050 (City of Vienna, 2019). Even though transport infrastructure is not explicitly mentioned in this context, it plays an important role in implementing a more circular material cycle of construction materials since transport infrastructure is of major significance with respect to the potential for making use of recycled construction materials (e.g., road construction) (Hiete et al., 2011). Furthermore, construction activities related to transport infrastructure are the second largest source of demolition waste after buildings (Lederer et al., 2020).

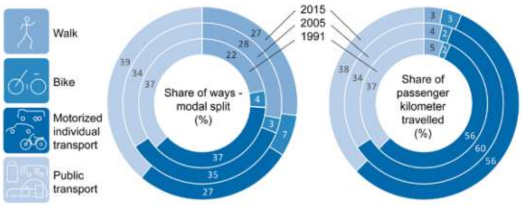
As the transport sector also represents an important source of greenhouse gas emissions and is thus targeted by current CO_2-eq emission reduction goals (e.g., the city of Vienna aims to reduce its per capita CO_2-eq emissions in the transport sector to 50% by 2030), the transport infrastructure is currently experiencing a transformation phase. This transformation to a more sustainable passenger transport system should be achieved by a shift in modal choice towards public transport, fewer private vehicles, and a zero emissions vehicle fleet (City of Vienna, 2019). To achieve such a significant transformation, the transport infrastructure must be designed and constructed accordingly (e.g., with extensions to the public transport, pedestrian, and bicycle network) (Environment Agency Austria [UBA], 2019). Such systematic changes require corresponding time for planning and implementation as well as time and efforts to persuade the population (e.g., when a reduction in public parking infrastructure meets social resistance) and must be carried out stepwise. So, to reach the 2030 targets, the required structural changes to the transport infrastructure should have already been initiated in recent decades and even be partially implemented today. If the required structural changes are taking place, this reflects an increase and variation in the dynamic of the MS of various transport modes. The dynamics of MS determine the speed at which technological changes can be implemented (Pauliuk & Müller, 2014). This dynamic is particularly relevant for the vehicle fleet, which has high stock renewal rates, but infrastructure should not be neglected either. In this context, a comprehensive understanding of recent developments of the MS in urban transport systems is crucial for the improvement of the future transport system of a city: first, to assess set targets and their achievement, and second, to identify potential fields to reduce primary raw material consumption in order to enhance waste recycling and to reduce waste disposal.

In terms of MS development in general, there are significantly more studies on buildings than on transport infrastructure (e.g., roadways, railway tracks, or subway networks). However, the latter significantly contributes to the total MS of construction materials. The share between MS in buildings and MS in infrastructure depends heavily on the prevailing transport system and its respective density, that is, depending on the area investigated, the share of infrastructure is between 20% and 60% (Augiseau & Barles, 2017). At a country level, the material composition and development of the MS in road networks has been investigated for the European Union (Wiedenhofer, Steinberger, Eisenmenger, & Haas, 2015), the United States (Miatto et al.,2017) and Japan (Hashimoto, Tanikawa, & Moriguchi, 2009). The mass and material composition of the MS in Beijing's road system was analyzed by Guo, Hu, Zhang, Huang, and Xiao (2014), as were the life cycle greenhouse gas emissions (Guo, Hu, Zhang, Zhang, & Zhang, 2017). Tanikawa and Hashimoto (2009) investigated the MS of urban road and railway networks in the city centers of Manchester (GB) and Wakayama (JP).

All in all, existing material studies on transport infrastructure either focused on only one transport mode (e.g., roads), or were solely dedicated to material stocks and stock dynamics of the infrastructure, thereby neglecting the generation of CDW, which is crucial from a circular economy perspective (Augiseau & Barles, 2017; Lanau et al., 2019). Although numerous studies describing the anthropogenic metabolism of Vienna are available, making it one of the most well-investigated urban areas in this respective field, they either focus on buildings (Kleemann, Lederer, Rechberger, & Fellner, 2017; Lederer et al., 2020), following a top-down approach (Obernosterer et al., 1998), or investigate a subsystem of the transport modes, such as the subway infrastructure (Lederer, Kleemann, Ossberger, Rechberger, & Fellner, 2016). There is not a single study known to the authors which provides a detailed analysis of Vienna's (or any other city's) transport system distinguishing between all prevailing transport modes, their infrastructures, and vehicles.

The present study aims to provide the lacking quantitative analysis regarding the MS development of the total transport infrastructure and the vehicle fleet on a city level, as well as the related material flows (MF). As for the transport infrastructure, the focus is set on the underlying processes (e.g., network extensions, maintenance) causing the material turnover of construction materials. However, regarding the vehicle stock, of special interest is the stock renewal rate because it provides information about the speed at which technological changes can be implemented. In order to compare different transport modes, both vehicles and infrastructure have to be considered for the environmental assessment (Anderson, Wulfhorst, & Lang, 2015; Chester & Horvath, 2009). The present study thus provides data which is necessary for the development of measures towards a more circular construction material cycle as well as input data for the environmental assessment of various transport modes. Furthermore, by examining the transformation process of the transport sector, new information about the dynamics of this process is provided. Aside from authorities and policy makers, the results are of great interest to experts in such disciplines such as traffic and urban planning since the study provides detailed information about the development of transport infrastructure and the vehicle fleets of different transport modes over time, the material intensity of different transport infrastructures and, finally, their renewal rates. Specifically, the study aims to answer the following questions:

FIGURE 1 Development of Vienna's modal split (MA 18, 1993; Wiener Linien, 2019) and share of passenger kilometers traveled per transport mode (OEIR, 2019). Underlying data used to create this figure can be found in the Supporting Information S2



1. What is the mass of the in-use material stock of the transport system (infrastructure and vehicles) in a well-established, highly developed European city and what is the contribution of different transport modes to this stock?
2. Which changes, in terms of the mass and material composition of the material stock, can be observed for the different transport modes within the recent past?
3. What is the annual material demand and waste generation rate of the transport sector broken down by transport mode?
4. Which processes (e.g., new construction, maintenance) primarily cause the material turnover?

To address these questions, Vienna's transport system development between 1990 and 2015 were investigated.

2 | STUDY AREA

The City of Vienna was chosen as the study area because, as regards the historic development of the prevailing urban transport system, it is comparable to numerous cities in industrialized countries. Furthermore, the case study city is particularly interesting because of the diversity of its well-developed transport system (e.g., various transport modes, broad age distribution of the transport infrastructure) and it is characterized by good data availability. In Vienna, the largest share of traffic area is attributable to motorized individual transport (e.g., roads and parking areas) like almost all large cities worldwide. However, Vienna also has a well-developed public transport system, which has been gradually expanded. It comprises public buses, trams, regional trains and metro lines. The size and the development of the infrastructures investigated from 1990–2015 is presented in chapter 4.1 of the results section. Like in other cities, active mobility (walking, cycling) has regained importance in recent years, which is also reflected in the modal split wherein walking increased from 22% to 27% and biking from 4% to 7%, as presented in Figure 1. Vienna is the largest city in Austria, covering an area of 415 km^2. Over the period studied, the population of Vienna has increased by over 20%, from 1.5 million to 1.8 million (Statistik Austria, 2019).

3 | METHODS

The "Overview, Design, Details" protocol is used to describe the modeling approach and data used. The protocol was adapted for material flow analysis models by Müller, Hilty, Widmer, Schluep, and Faulstich (2014) and was applied by Noll, Wiedenhofer, Miatto, and Singh (2019). The protocol has the advantage that it provides a structure to systematically describe the model and data, from a generalized overview to an increasing degree of detail, thereby making the complexity of the model manageable for the reader (Müller et al., 2014). Keywords of the protocol are set in italics within the sections 3.1 to 3.3. The calculation was performed in Microsoft Excel and is published in the Supporting Information S2. Additional information regarding input data can be found in the Supporting Information S1.

3.1 | Overview

The *purpose* of the study is to investigate the development of the in-use material stocks (MS), the material input flows (MF^{IN}) and material output flows (MF^{OUT}) of the transport system of the city of Vienna. Transport modes considered are motorized individual transport, nonmotorized individual transport and public transport.

The *materials* are expressed in metric tons (t) and their multiple (e.g., Million tons (Mt)). Overall, 13 material categories are considered: asphalt & bitumen; aluminum; batteries; brickwork; concrete; copper; glass; gravel, sand and natural stone; iron & steel; other metals; others (e.g., rubber); plastics; and wood.

The *processes* defined are transport infrastructure (e.g., roads, metro network) and vehicles (e.g., cars, trains) for each transport mode. The infrastructure is further distinguished in terms of infrastructure for moving transport (e.g., roads, rail tracks) and infrastructure for stationary traffic (e.g., parking lanes, train depots). All material input flows, and waste flows generated due to maintenance and demolition are considered regarding infrastructure. For the vehicles, the MF related to new vehicles and decommissioned vehicles are included, but maintenance is neglected.

The *spatial* boundary refers to the city of Vienna, and the *temporal scale* covers the time interval 1990 to 2015. A *system overview* is presented in the Supporting Information S1 in Table S1-1. It includes an enumeration of all infrastructure and vehicle types considered as well as their allocation to moving or stationary infrastructure.

3.2 | Design concept

The *basic principles* of the model can be described as bottom-up, retrospective, multiyear material flow analysis as defined, among others, by Brunner and Rechberger (2016) and Tanikawa, Fishman, Okuoka, and Sugimoto (2015). In the multiannual static *modeling approach* chosen, the calculation is based on specific service units (SU) (e.g., m^2 road, m metro network, number (n) of vehicles) which are combined with specific material intensities (e.g., t/m^2, t/m, t/n). The model based on SU is set up using the methodology of Müller (2006), which has been previously applied, among others, by Bergsdal, Bohne, and Brattebø (2007); Noll et al. (2019); Wiedenhofer et al. (2015); and Tanikawa et al. (2015).

The input data is expressed in SU and is taken either from official statistics, provider information, internal statistics from the municipality of Vienna, or is calculated by combining various data. Material intensities are taken from the literature combined with own calculations. On the one hand, MF^{IN} are generated due to extensions (e.g., increase in m^2 road area in the year n) and MF^{OUT} due to decline (e.g., decrease in m tram track length in the year n) of infrastructures and vehicle fleets. On the other hand, MF^{IN} and MF^{OUT} depend on the maintenance of the transport infrastructure as well as the maintenance of underground networks (e.g., pipes and cables), which usually require work on road infrastructure. To calculate these MF, different approaches are applied. If available, reported data on the number of SU maintained per year are used for MF calculation. Otherwise, either an annual renewal rate or mean useful life is used. MF^{IN} and MF^{OUT} related to maintenance are assumed to be equal in composition and intensity since the construction type of the infrastructure remained constant over the period investigated. Furthermore, no distinction is made between primary and secondary material. In other words, internal recycling flows appear as separate MF^{OUT} and MF^{IN}.

Within the analysis no *dissipative* flows are modeled since these are negligible for the quantitative examination of construction materials. The results are not presented with their *spatial distribution* within the city. No *uncertainty* assessment is integrated into the model since data in this regard was not available. The plausibility of the results is examined for each infrastructure component investigated by comparison with the results from other cities found in the literature.

3.3 | Model calculations

In the following, a *detailed model description*, including the calculation procedure, is presented. The *initial state* and the annual in-use MS are dependent on the total number of service units. In particular, the total MS is calculated by applying Eq. 1, adopted from (Noll et al., 2019; Tanikawa et al., 2015).

$$MS_{m,i,t} = \sum_{i}^{n} SU_{i,t} \times MI_{m,i} \tag{1}$$

$MS_{m,i,t}$ is the total stock in materials *m* in all SU *i* in the year *t* [t]; $SU_{i,t}$ is the inventory (total service units) of each type *i* in the year *t* [m^2 or number], and $MI_{m,i}$ is the material intensity of a certain material *m* in one unit of SU *i* [t/m^2].

To calculate the annual MF^{IN} for the new installation of new SU, Equation (2) adapted from Noll et al. (2019) is implemented within the model.

$$MF^{IN\_NEW}_{m,i,t} = \sum_{i}^{n} SU^{NEW}_{t} \times MI_{m,i} \tag{2}$$

$MF^{IN\_NEW}_{m,i,t}$ is the annual material input flow for newly installed SU^{NEW}_{t} of materials *m* of various SU types *i* in the year *t*; $\sum_i^n SU^{NEW}_t$ encompasses all newly built (infrastructure) or newly registered (vehicles) service units of type *i* in the year *t*. The material intensity $MI_{m,i}$ is expressed in mass per material *m* and SU type *i*.

The annual MF^{OUT} for demolished infrastructures and end-of-life vehicles is calculated according to the same principle, see Equation (3).

$$MF^{OUT\_DEM}_{m,i,t} = \sum_{i}^{n} SU^{DEM}_{t} \times MI_{m,i} \tag{3}$$

$MF^{OUT\_DEM}_{m,i,t}$ is the annual material output flow for removed SU^{DEM}_{t} of materials *m* of various SU types *i* in the year *t*; $\sum_i^n SU^{DEM}_t$ encompasses all demolished (infrastructure) or deregistered (vehicles) service units of type *i* in the year *t*. The material intensity $MI_{m,i}$ is expressed per material *m* and SU type *i*.

If real data on the number of SU maintained per year are available, Equations (2) and (3) are used to calculate the MF^{IN} and MF^{OUT}. However, for all other infrastructure types, the MF^{IN} and MF^{OUT} is calculated by applying Equation (4) (renewal rate (RR)) or Equation (5) (lifetime based (LT)). The corresponding equation is assigned to each infrastructure type in Table S1-1 in the Supporting Information S1.

$$MF^{RR}_{m,i,t} = MS_{m,i,t} \times RR_{m,i} \tag{4}$$

$MF^{RR}_{m,i,t}$ is the annual MF^{IN} and MF^{OUT} of material m that is needed for the maintenance of infrastructure type i in the year t; $MS_{m,i,t}$ is the total stock in materials m of the infrastructural type i in the year t, and $RR_{m,i}$ is the renewal rate for the material m and for the infrastructure type i.

$$MF^{LT}_{m,i,t} = MS_{m,i,t}/LT_i \tag{5}$$

$MF^{LT}_{m,i,t}$ is annual MF^{IN} and MF^{OUT} of material m that is needed for the maintenance of infrastructure type i in the year t; $MS_{m,i,t}$ is the total stock in materials m of the infrastructural type i in the year t, and LT_i is the mean useful life in years for the infrastructure type i [years].

3.4 | Model input

The *model input data* (service units, material intensities, renewal rates, and useful life per infrastructure type) are derived from various sources, for instance statistics, company information or the literature (for details, see the Supporting Information S1 Section 1–2 and all numbers per year can be found in Supporting Information S2). In the following, an overview of the input data is presented, which is subdivided into, first, road-based infrastructure, second, rail-based infrastructure and, third, vehicles.

In order to calculate the MS of the surface of traffic areas (e.g., roads, bicycles and pedestrian areas), the total area (= SU) per category published in statistics (City of Vienna, 2016) is used. The corresponding material intensities are based on calculations. The mean allocation of road surface types (City of Vienna Municipal Department 28 [MA 28], 2019) for each specific traffic area are combined with the standard cross-sections that are used in Vienna (Austrian Research Association for Roads, Railways and Transport [FSV], 2017). The annual difference in traffic area (e.g., newly built roads) is based on statistics from the municipality (City of Vienna, 2016; City of Vienna Municipal Department 28 [MA 28], 2018). Furthermore, road construction materials and waste generation related to the maintenance of subsurface infrastructure (pipes and cables) are considered by applying Equation (5) to the subsurface infrastructure, thereby calculating the road area affected. The total length of the subsurface infrastructure is provided by the City of Vienna (2016). The mean trenches width and useful life is provided by Wiener Netze (2018).

Input data for bridges (SU: bridge area per bridge type) is calculated using data from AustriaWiki (2018); the respective material intensities are based on Lünser (1999) and Helminger (1978a, 1978b, 1978c), and maintenance MF are calculated using Equation (5).

Road equipment (SU: number of, e.g., light signal systems) is taken from statistics—partially for light signal systems (City of Vienna, 2016; MA 33, 2019a, 2019b)—or it is calculated based on road length and the literature data (Mottschall & Bergmann, 2013, p. 32). The assessment of new road equipment is based on the change in the total number from consecutive years. Material intensities are taken from Mottschall and Bergmann (2013), and the maintenance MF are calculated by applying Equation (4).

The parking area on public property is regarded as constant due to lack of data, and is taken from the City of Vienna Municipal Department 41 (MA 41) (2019a). The respective maintenance MF are calculated by applying Equation (4). For parking spaces on private properties and within private buildings (SU: number of parking spaces), no statistical data is available. Hence, to calculate the number of parking spaces within existing buildings, a sample ($n = 255$) of randomly selected buildings (from all buildings in Vienna) was analyzed. Thus, key figures about the number of parking spaces for each building category are generated. These were applied to the total stock of buildings (City of Vienna Municipal Department 41 [MA 41], 2019b) under consideration of legally specified parking space obligation, which requires for newly built buildings: 1 parking space per 100 m^2 usable area (WGarG, 2008). The material intensities per parking space within buildings are taken from the Leibniz Institute of Ecological Urban and Regional Development (IOER) (2017a, 2017b) and related maintenance MF are calculated with Equation (5). The parking spaces (outdoor) on private property are estimated based on total available parking spaces and the total number of registered vehicles (for details see Table S1-2). Material intensities and maintenance related to MF are calculated in the same manner as parking areas on public property.

For rail-based infrastructure, three different networks, namely metro, tram, and regional train, are distinguished. The metro network was investigated by Lederer et al. (2016). The data published therein is used as input data in the model. The tram network length (= SU) is taken from Wiener Linien (2019), and the material intensities are calculated based on standard cross sections used for the network in Vienna and on the literature data (Schmied, Mottschall, & Löchter, 2013; Wiener Linien, 2012). The track length of the regional train network is provided by the City of Vienna (2016) and Austrian State Railways (OEBB) (2016). Missing years are interpolated. Different construction types of the network are based on investigations of the Orthophoto of 2015 (City of Vienna Municipal Department [MA 41], 2015). The material intensities for track components are derived from calculations based on the values of several sources (Lederer et al., 2016; Mottschall & Bergmann, 2013; Ostermann, Rollinger, & Kehrer, 2016; Schmied et al., 2013). The MF related to the maintenance of the rail-based networks are based on mean useful life per construction element (superstructure, substructure, and buildings), applying Equation (5).

The unit for buildings (e.g., train stations, train depots) is cubic meter gross volume (m^3 GV), and input data is derived from the 3D building model for Vienna (City of Vienna Municipal Department [MA 41], 2019b). The material intensities are taken from Kleemann et al. (2017). However, for Vienna's main train station, actual data (built-in material) are implemented in the model taken from Austrian State Railways (OEBB) (2015).

Finally, the number and type (= SU) of vehicles are taken, for private vehicles, from Statistik Austria (2019), for metro and tram vehicles, from Wiener Linien (2019) and Beyer and Svetelsky (2018), for public bus vehicles, from Stadtverkehr Austria (2019) and Wiener Linien (2019), and for regional train vehicles, from Anon (2019), Austrian State Railways (OEBB) (2019) and Obermayr (2019). Bicycles and pedelecs are calculated based on trade statistics (Chamber of Commerce, 2013; Association of Sport Goods Manufacturer and Supplier of Austria [VSSOE], 2013, 2014, 2015, 2016) and the number of households. The material intensities and mean vehicle weights per vehicle category are derived from several sources (Beyer & Svetelsky, 2018; Federal Ministry Transport, Innovation and Technology [BMVIT], 2013; Cherry, Weinert, & Xinmiao, 2009; Kraftfahrt-Bundesamt [KBA], 2019; Öko-Institut e.V., 2009; Struckl, 2007 2004).

3.5 | Model output and evaluation

As *model output*, the in-use MS for different transport modes is generated for every single year from 1990 to 2015. Further, the model calculates the annual resource demand caused by network extensions, infrastructure maintenance, and newly registered vehicles. The waste generated due to demolition activities, maintenance work, and end of life vehicles is quantified. The results of the analysis are given separately for each transport mode, infrastructure category and vehicles. 13 different material categories are distinguished. To *evaluate* the results and compare them to other cities, the results are displayed in stock per capita (t/capita) as well as per transport performance (passenger kilometer traveled (PKT)/t). For this, the MS are divided by the inhabitants (Statistik Austria (2019)). However, passenger kilometers traveled (Austrian Institute for Regional Studies [OEIR], 2019) are divided by the mass of MS in the corresponding year. To describe the development of the transport behavior of the population, the modal split is used provided by Wiener Linien (2019). Modal split and passenger kilometers traveled only consider transport performance for passenger transport; cargo transport is not included. The modal split represents the percentage distribution of traffic routes differentiated according to the means of transport (Ostermann et al., 2016).

4 | RESULTS

4.1 | Development of service units

Rising population and the objective of promoting specific transport modes lead to changes and expansion in the transport system. An overview of these changes from 1990 to 2015 is presented in Table 1. The developments are presented for each transport mode and the therein contained categories for the years 1990 and 2015 (annual values are presented in the Supporting Information S2).

The transport behavior of Vienna's population changed regarding the choice of transport mode. The share of motorized individual transport on the modal split decreased from 37% to 27% in the year 2015 (Figure 1, left). However, when considering the transport performance in terms of passenger kilometers traveled (PKT), the share of each transport mode is relatively constant over the same period (Figure 1, right). In total, the PKT within Vienna has increased by 36%, from 8,151 million PKT per year (mio PKT/a) in 1990 to 11,075 mio PKT/a in the year 2015.

4.2 | Material stock

The in-use MS of the transport system has increased by 26%, from 83 Mt in 1990 to 103 Mt in 2015 (Figure 2). The MS per capita (60 t/capita) increased slightly due to expansion activities in the middle of the period under consideration and has returned to 1990 levels due to stronger population growth in recent years (Figure 3b). In comparison, the overall MS in buildings in Vienna was calculated to be 210 t/capita according to Kleemann et al. (2017).

The infrastructure is distributed into three-quarters infrastructure for moving transport and one-quarter infrastructure for stationary traffic. The latter is only significant for motorized individual transport. Almost half of the motorized individual transport in-use MS is required for parking infrastructure. The proportion has even increased during the period considered (from 37% to 44%). This is mainly because the number of underground garages has increased significantly (by +38%) and parking space in an underground garage needs significantly more materials than a parking space at an outdoor parking lot. All vehicles together (cars and motorcycles 77%, lorry vehicles 14%, regional train 3%, metro, tram, and public bus vehicles together 4%) have a share of the total MS of around 1% (1.2 Mt) compared to the total infrastructure, as represented in Figure 2.

The three transport modes investigated show differences in their MS development, as presented in Figure 3a. The largest MS is attributed to motorized individual transport (62 Mt), followed by public transport (36 Mt), and nonmotorized individual transport (6.6 Mt).

TABLE 1 Vienna's transport system development across different transport modes, subcategorized according to moving traffic infrastructure (m.t.i.), stationary traffic infrastructure (s.t.i.), and vehicles (v.)

Category		Service Unit (SU)	Unit	1990	2015	Change +/– [a]
Motorized individual transport (MIT)	m.t.i.	Total road area	m^2	21,199,000	22,843,000	+8%
		Total road bridge area	m^2	789,000	941,000	+19%
		Traffic light-signal system	n (number)	890	1,310	+47%
		Traffic signs and sign gantry	n	55,000	60,000	+9%
		Guard railing	m	27,000	37,000	+37%
	s.t.i.	Area parking lanes and parking area on public property	m^2	3,911,000	4,261,000	+9%
		Number of parking spaces in buildings and car parks	n	117,000	213,000	+82%
		Number of parking spaces on private property	n	371,000	455,000	+22%
	v.	Total cars	n	547,000	686,000	+25%
		Total motorcycles	n	42,000	86,000	+105%
		Total lorry type N1 (< 3.5 t)	n	40,000	60,000	+50%
		Total lorry type N2 (3.5–12 t)	n	11,000	2,000	–82%
		Total lorry type N3 (12–40 t)	n	5,000	3,000	–40%
Nonmotorized individual transport (NMIT)	m.t.i.	Total bicycle lane area	m^2	106,000	385,000	+263%
		Total sidewalk area	m^2	8,998,000	10,935,000	+22%
		Total pedestrian zone area	m^2	106,000	350,000	+230%
		Total pedestrian and cycling bridge area	m^2	18,000	38,000	+111%
	s.t.i.	Bicycle stands	n	130	39,000	–
		Rental bike stations (public)	n	0	120	–
	v.	Total bicycles	n	917,000	1,121,000	+22%
		Total pedelecs	n	0	49,000	–
		Total citybikes	n	0	2,000	–
Public transport (PT)	m.t.i.	Metro network length (both directions)	m	40,000	87,000	+118%
		Regional train network length (both directions)	m	182,000	190,000	+4%
		Tram network length (both directions)	m	188,000	175,000	–7%
		Regional train stations buildings	m^3	812,000	[b] 513,000	–
		Regional train station platform roof	m^2	61,000	63,000	+3%
		Regional train station facilities (platforms, underground crossing, shelter, stairways, and elevators)	n	280	300	+7%
	s.t.i.	Tram depot buildings	m^3	1,701,000	1,701,000	±0%
		Bus garage buildings	m^3	176,000	451,000	+156%
	v.	Metro vehicles (all types)	n	250	430	+72%
		Regional train vehicles (all types)	n	150	290	+93%
		Tram vehicles (all types)	n	1350	880	–35%
		Bus vehicles (all types)	n	650	1,130	+74%

[a] If there is no comparable value in 1990 (e.g., zero), the column "change" remains empty.
[b] Main train station (Hauptbahnhof) excluded in the total volume; actual data on the built-in material is included in the model. If there is no comparable value in 1990 (e.g., zero), the column "change" remains empty.

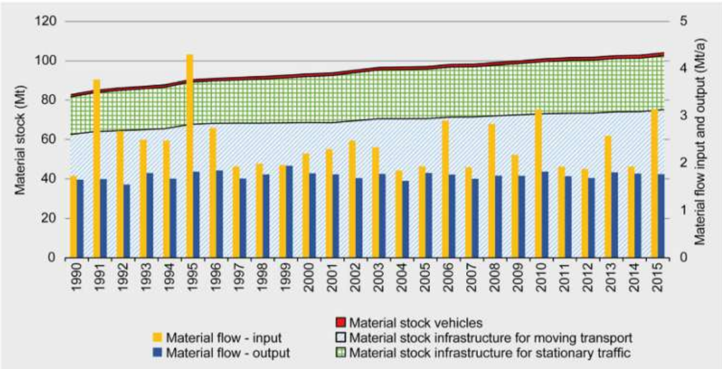


FIGURE 2 Overall material stock development of Vienna's transport infrastructure classified into infrastructure for moving transport (e.g., roads, train tracks), infrastructure for stationary traffic (e.g., park garages, train depots), vehicles, and annual material input and output flows. Underlying data used to create this figure can be found in the Supporting Information S2

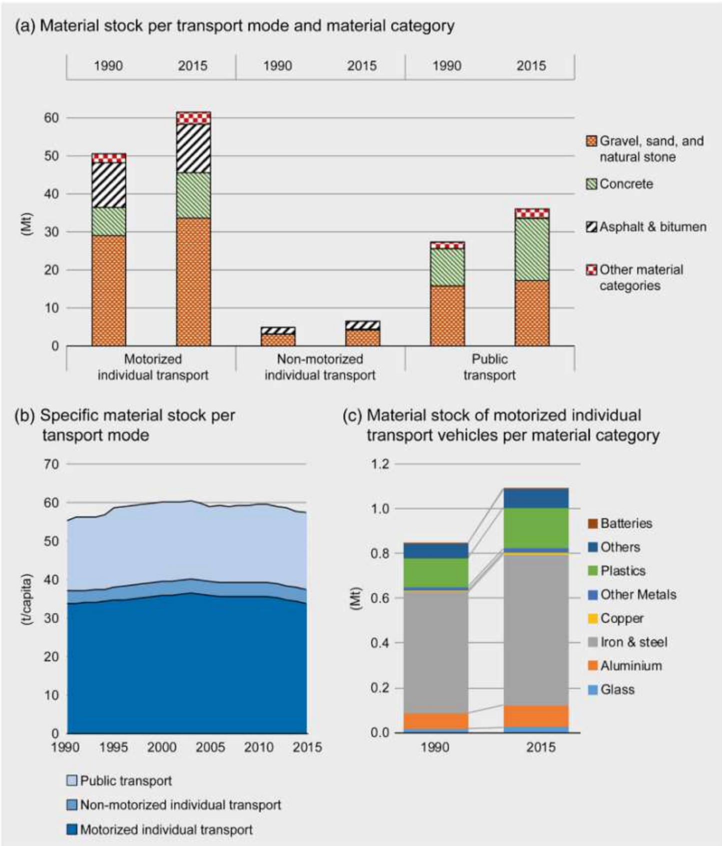


FIGURE 3 Material stock (MS) development from 1990 to 2015: (a) Material stock in infrastructure and vehicles per transport mode and material category; (b) Specific material stock in infrastructure and vehicles per capita divided into transport mode; (c) Material stock of the motorized individual transport vehicle fleet divided into material category. Underlying data used to create this figure can be found in the Supporting Information S2

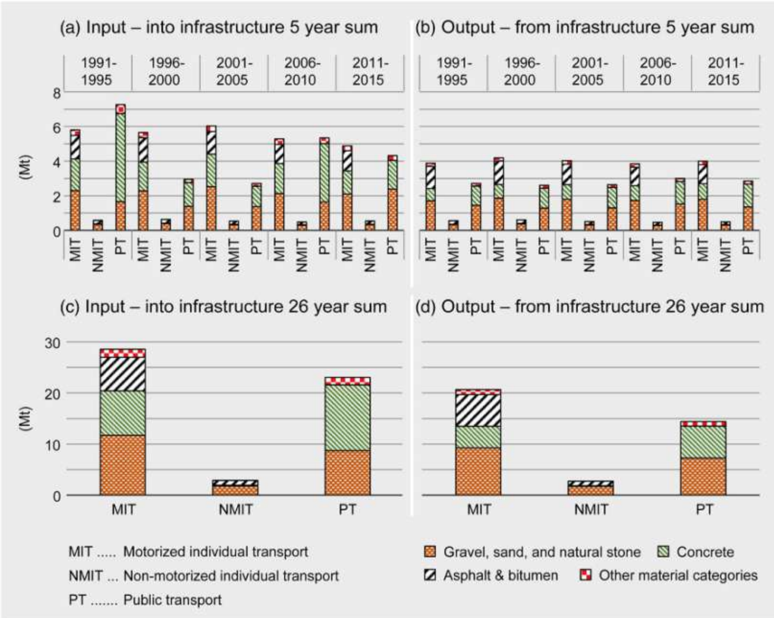


FIGURE 4 Material flows related to transport infrastructure: (a) Input into infrastructure per transport mode (5-year sum); (b) Output from infrastructure per transport mode (5-year sum); (c) Total material input into infrastructure per transport mode; (d) Total material output from infrastructure per transport mode. Underlying data used to create this figure can be found in the Supporting Information S2

Nonmotorized individual transport shows the highest relative growth rate, with an increase of 34% (+1.7 Mt). Growth is mainly due to the expansion of bicycle and pedestrian networks (+1.6 Mt), but also due to new services such as a public rental bike system (+ >0,1 Mt). The relative increase in MS of public transport (+32%; +8.7 Mt) was higher in comparison to motorized individual transport (+22%; +11 Mt).

Regarding the relative material composition of the in-use MS, there has been no significant shift in the ranking, but the percentage distribution has changed. The two categories "gravel, sand, and natural stone" (58% → 53%) and "asphalt & bitumen" (16% → 14%) have decreased in relative terms. However, the share has increased for the material categories "concrete" (21% → 27%) and "iron & steel" (3% → 4%). All other material categories have a share of 1% or less of the overall in-use MS. The distribution and development of the various materials differs for the three transport modes, as shown in Figure 3a.

The vehicle number has increased (see Table 1), also in relative terms. For instance, the number of cars per 1,000 inhabitants increased in Vienna from 391 to 410, those of motorcycles from 28 to 47. Furthermore, the mean vehicle weight has increased; consequently, the total MS of vehicles increased by 32%. The motorized individual transport vehicle MS development is presented in Figure 3c. It also shows that the material composition has not changed significantly. Motorized individual transport vehicles have a share of over 90% of the total MS of all vehicles considered. This subcategory is dominated by cars (in 2015 > 75%). However, the proportion of lorry vehicles has significantly declined, from 26% in 1990 to 15% in 2015 due to a drastic decrease (−70%) in the number of heavy lorry vehicles registered in Vienna (see Table 1).

Considering how intense infrastructure is used in terms of passenger kilometers traveled per ton of MS, the values for the transport modes investigated are in the same order of magnitude, with a range of 94 to 115 million passenger kilometers traveled per ton of MS.

4.3 | Material input (MF^{IN}) and Material output (MF^{OUT})

The annual amount of materials built-in exceeds the removed materials from the system, as indicated by the growth of the overall MS. Moreover, the annual material demand (input flow) varies much more (from 1.5 to 3.8 Mt/year; mean 2.2 Mt/year) than the waste generation (output flow; 1.4 to 1.8 Mt/year; mean 1.6 Mt/year). This is explained by single construction activities. For instance, due to significant extensions of the metro network in the years 1991 and 1995, the MF^{IN} into the system in these years are higher (yellow bars in Figure 2). In contrast, the calculated MF^{OUT} is constant and amounts to about 1.6 Mt per year (blue bars in Figure 2).

Network expansions are also clearly reflected in the built-in material quantities when transport modes are compared. Figure 4 shows a comparison of MF^{IN} and MF^{OUT} into and from infrastructures per transport mode and material category. In chart (a) and (b) the MF are summed up to

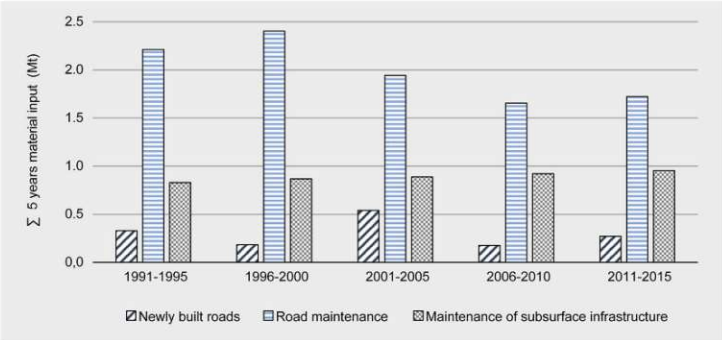


FIGURE 5 Five-year sum of mineral road construction material input caused by road construction and maintenance as well as maintenance of subsurface infrastructure networks (pipes and cables). Underlying data used to create this figure can be found in the Supporting Information S2

5-year periods. In these periods in which public transport networks are being expanded, the respective quantities of MF^{IN} are comparable to those of motorized individual transport. In other periods, the amount of material that is built in the public transport network is significantly less than that built in the motorized individual transport network. Hence, for the maintenance of the network, larger quantities of material are needed for the larger motorized individual transport network than for the public transport network, which is also reflected in the higher MF^{OUT} of the motorized individual transport network. The dismantled materials are mainly caused by maintenance and are thus relatively constant in quantity and composition. If networks are extended, MF^{IN} and MF^{OUT} are different in terms of material composition. For instance, in the 5-year period (1991 – 1995) the MF^{IN} in public transport is dominated by concrete, while at the same time much smaller amounts of concrete are dismantled. This is due to the extensions of the metro network in these years. However, in the following two periods (1996–2002 and 2001–2005) the material composition of the MF^{IN} and MF^{OUT} are comparable.

In chart (c) and (d) in Figure 4 the MF^{IN} and MF^{OUT} related to infrastructure are summed up for the period investigated. The motorized individual transport network has the highest resource demand and waste generation compared to all transport modes. It shows that the material category "asphalt & bitumen" was mainly built into the individual transport network. However, the largest share of concrete was built into the public transport network. The mass of built-in material in the motorized and nonmotorized individual transport network within the 26 years amounts to roughly 50% of the initial in-use stock (1990). For the public transport network, the figure amounts to 85%.

The total MF^{OUT} is also dominated by the motorized individual transport network (see Figure 4d). The MF^{IN} and MF^{OUT} for motorized individual transport infrastructure are dominated by maintenance processes, or more specifically, by mineral road construction material (50%). The summed-up MF^{IN} (5-year periods) per process category shows that the maintenance of roads causes most MF^{IN}, followed by maintenance of subsurface infrastructure (pipes and cables) and new road construction (see Figure 5).

5 | DISCUSSION

5.1 | The relevance of maintenance

The total in-use MS of the transport infrastructure in Vienna, including vehicles, is on average ~46 times the annual MF^{IN}. In other words, every 50 years the same amount of built-in material is built into the system as the amount of initial MS provided that the maintenance intensity remains unchanged. However, for expanding networks such as public transport, this rate is higher due to new construction (~30 years).

Well-developed systems with low growth rates are characterized by lower fluctuations of the MF^{IN}. Further, the MF^{IN} is then dominated by maintenance, which is clearly reflected in the results for motorized individual transport. In the last 5 years, 10% of the use of road construction material was caused by new road construction and 55% by road maintenance. The findings on the importance of maintenance for MF^{IN} and MF^{OUT} in well-established, highly developed cities and regions is in line with other studies. For instance, Wiedenhofer et al. (2015) showed that for the time period 2004–2009 the inputs for maintenance of the European road and rail network exceeds the inputs for expansion between 1 and 6 times. For the island of Samothraki in Greece, Noll et al. (2019) present a steadily growing resource requirement for the maintenance of buildings and infrastructure, which goes up to >80% of the overall input of construction material. Miatto et al. (2017) showed that most material inputs into the United States road network have shifted from new construction towards maintenance in the period investigated, from 1905 to 2015. Regarding road maintenance, the present paper illustrates that maintenance of subsurface networks contributes significantly to the MF^{IN} and MF^{OUT}. In Vienna, on average 28% (0.2 Mt/year) of annual MF^{IN} for road construction is caused by maintenance of subsurface networks.

5.2 | Modified vehicle fleet

In its *Smart City Wien Framework Strategy*, the city of Vienna has defined a target according to which by 2050 all cars within the city limits must use alternative propulsion technologies (City of Vienna, 2019). In 2015, the proportion of vehicles with alternative propulsion technologies was less than 0.2% of all registered vehicles. Accordingly, the material composition of the MS (see Figure 3c) remains relatively constant. If the achievement of the targets is taken seriously, there will be significant changes in the composition of MF^{IN} and MF^{OUT} in the future. For instance, a higher share of batteries within vehicles can be expected. However, it will take many years before the entire fleet is converted to new propulsion technologies. Although the stock renewal rate is 10% per year, so far most new vehicles have a fossil fuel driven propulsion technology (>98% in 2015). The propulsion technologies have not changed regarding lorry vehicles either. However, the number of registered heavy-duty vehicles have declined significantly. This is not due to a reduction in goods transport. In Austria, goods transport capacity (ton-kilometers) has increased by 170% since 1980 (Federal Ministry Transport, Innovation and Technology [BMVIT], 2012, 24). There is no data available for Vienna specifically, but it can be assumed that Vienna, with its strong economic performance, has the same or an even higher increase relative to Austria as a whole. In the year 2015, 75% of the goods transport volume (t) on roads in Austria was provided by lorry vehicles registered in Austria, but only 46% of the transport capacity (ton-kilometers) was provided by national carriers (Statistik Austria, 2017, 28). Heavy goods such as building materials are thus more likely to be supplied by national carriers, whereas international carriers supply consumer goods. The registered vehicles within a region, therefore, do not necessarily reflect the vehicle fleet traveling in this area.

5.3 | Model output in comparison to waste statistics

The available data concerning CDW arising in Vienna has been collected in an article by Lederer (2020) and is based on several sources (Lechner et al., 1995; City of Vienna Municipal Department 48 [MA 48], 2007, 2012; Environment Agency Austria [UBA], 1998). A comparison of waste statistics and the calculated model MF^{OUT} is only reasonable for selected waste fractions since only certain fractions within the available data sources can be clearly assigned to waste generated by civil engineering surfaces (e.g., CDW from buildings) and to waste generated by civil engineering underground (e.g., CDW from road and railway construction). Based on waste code numbers, two waste fractions are clearly attributable to the transport network, namely road construction waste (from surface layer) and track ballast waste. The calculated mean MF^{OUT} for "asphalt and bitumen" is around 0.27 Mt/year. This value is almost identical to the mean amount of road construction waste of 0.28 Mt reported in the statistics (values for 12 years). However, the calculated mean MF^{OUT} for "track ballast" of 0.12 Mt/year is five times higher than the mean reported track ballast waste (0.02 Mt/year). Only values for 6 years are reported in the statistics, thus the mean value gives rise to great uncertainties. Furthermore, some CDW fractions (e.g., track ballast, concrete waste) is processed at construction sites and reinstalled in the system, as described for the rehabilitation of rail infrastructure in Vienna by Gassner, Lederer, and Fellner (2018). In the model presented, however, such flows are accounted for as MF^{IN} and MF^{OUT}. Hence, it also enables material and waste flows currently not regarded in waste statistics to be captured. For the circularity of materials in the construction sector, this means that official data tend to underestimate the real recycling rates, as on-site recycling activities are often not accounted for.

5.4 | Material stock compared to those of other case studies

The MS of the transport system contributes 22% to the total in-use MS in buildings and infrastructures. This corresponds to a share of about 20% for networks in heavily built-up areas referred to in the literature (Augiseau & Barles, 2017). When considering the MS per capita together with those for buildings calculated by Kleemann et al. (2017), the total in-use MS in Vienna (buildings and transport infrastructure) is around 270 t/capita (in 2015), which is below the global average for industrialized countries of 335 t/capita in 2010 (Krausmann et al., 2017) as well as for the countries of Japan (310 t/capita) and the United States (375 t/capita) specifically (Fishman, Schandl, Tanikawa, Walker, & Krausmann, 2014). However, it is comparable to the MS of 247 t/capita calculated with a bottom-up approach by Tanikawa and Hashimoto (2009) for the City of Wakayama. Wakayama has only about one fifth of the population of Vienna and has no metro network. In the same article, the authors also presented values for the City of Manchester; but with a MS of 111 t/capita, the values are much lower. With 248,000 t/km^2, the MS for buildings and transport infrastructure per area are the lowest for Vienna, compared to 1,121,000 t/km^2 (Wakayama) and 418,000 t/km^2 in Manchester. In contrast to the study at hand, only segments of the cities that were fully covered with buildings and streets are considered, which explains the lower material density with respect to area in Vienna.

All in all, the comparison with other studies shows, first, that only limited information about the material stock in the transport infrastructure of other cities is available. The building stock is more often the focus of investigations. This observation is interesting insofar as this transport infrastructure MS is managed by a few stakeholders only, making it thus much easier to implement new management concepts, such as the circular economy. Second, existing key figures for the per capita MS of the transport infrastructure might vary significantly between different regions, which most probably result from the settlement structure, but potentially may also derive from different methodologies, system boundaries and accounting systems applied in the studies. Only a larger number of MS studies, determined with comparable methods, will allow significant comparison between cities. This circumstance also illustrates the importance of bottom-up studies when it comes to the setting or the assessment of set targets aiming to reduce the material consumption and increase recycling management within a specific region (e.g., *Smart City Wien Framework Strategy)*, since figures from other regions provide only limited information about MS and especially MF for a specific region or rather are associated with large uncertainties.

5.5 | Limitations

The study at hand provides a detailed assessment of the transport system. However, as a transport system is complex, there are limitations and uncertainties to be dealt with in future research. Firstly, although the material inventory presented has a high level of detail, service units and material intensities were clustered in joint categories. As a result of the clustering, uncertainties and simplifications naturally occur. Secondly, no explicit recycling loops or cascading uses are included, but solely the magnitudes of MF (input, output) are discussed. Hence, no recycling rates are discussed in the paper at hand. Thirdly, the city level as system boundary presents some difficulties in terms of assessing transport systems. Cities are open systems and depend on the outside world (e.g., import and export of goods and labor) (Bai, 2007). Hence, cities are traffic hubs, and transport infrastructures are larger than what city dwellers alone might require for their exclusive needs. Fourthly, the data concerning transport performance is insufficient since there is no data source which publishes passenger kilometers traveled for Vienna on an annual or regular basis. In general, the availability of data can be described as inadequate with respect to traffic performance data (Ostermann et al., 2016). Consequently, to present a consistent time series, only values from one source (Austrian Institute for Regional Studies [OEIR], 2014) are considered in the study at hand.

6 | CONCLUSION AND OUTLOOK

To evaluate the in-use MS and related MF of Vienna's transport infrastructure, a comprehensive model was set up. The retrospective investigation shows that the MS is still growing even though the city of Vienna already has a well-developed transport system. The distinction between different transport modes enables a direct comparison of the prevailing networks and their developments. It turns out that the dynamics of the transport modes investigated are different. Furthermore, they differ significantly in the material composition, thus impacting the recyclability of wastes generated thereof and the potential utilization of recycling materials. Within the period considered, the MS is dominated by motorized individual transport, followed by public transport, and nonmotorized individual transport. However, the results highlight that the MS for the transport modes "public transport" and "nonmotorized individual transport" have increased significantly over the last 25 years. This requires large quantities of MF^{IN} for new construction of infrastructure, whereas the transport mode "motorized individual transport" shows a much lower growth rate. This is due to a change in transport policy, which promotes public transport and active mobility. Further, the results show that within well-developed systems the MF^{IN} and MF^{OUT} are more strongly related to maintenance and refurbishment processes. Moreover, the maintenance of other infrastructure networks can have a significant influence on the material consumption, as shown for the road infrastructure with the underground networks. Hence, a central management system for road maintenance and the maintenance of underground installations has great potential for saving resources, waste prevention and for promoting local use of secondary raw materials (e.g., for road substructure).

For future research, a common model of transport infrastructure and buildings should be considered to model all construction and demolition waste. In this way, the cascading use of construction material can be investigated. Furthermore, forecasts are of great interest with a focus on the targets set by the city of Vienna.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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Paper II

Projection of material flows and stocks in the urban transport sector until 2050 – A scenario-based analysis for the city of Vienna

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Projection of material flows and stocks in the urban transport sector until 2050 – A scenario-based analysis for the city of Vienna

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ABSTRACT

The transport sector plays a decisive role in climate change mitigation, especially in cities, as it significantly contributes to global resource and energy consumption. Hence, decarbonising this sector is increasingly recognized as an important means of mitigating climate change, which is reflected in numerous smart city initiatives. However, existing studies thereon have focused almost exclusively on energy and CO_2, thereby neglecting the consumption of material resources required to transform urban transport systems so as to be compatible with a low carbon future. In this study, we hence investigate the effects of transforming urban transport systems on future material stock and material flows using the city of Vienna as a case study. For this purpose, a material flow analysis for the infrastructure and vehicles required until 2050 has been conducted taking different scenarios into consideration, which are mainly characterized by different modal splits. The results show that different paths of development among the various transport modes significantly affect the overall material stocks and flows. If the modal split remains constant, the road-infrastructure has to be further expended to provide the transport service needed due to the expected increase in population in Vienna. The material stock per capita for the transport system remains constant at around 54 t/capita for this scenario. If the motorized individual transport can be reduced to a share of less than 10% of all trips (today's share amounts to 25%), the material stock per capita decreases to around 47 t/capita in 2050. As this case allows for infrastructure (e.g. parking infrastructure, road lanes) to be dismantled, the annual material demand for maintenance efforts is also reduced by a fifth (to 460 kg/cap/yr). Despite the reduction in material stocks and flows achievable by changing the current modal split, a significant change in the waste composition in terms of the end-of-life vehicles generated is to be expected in the coming decades. Annual quantities of old batteries, for instance, might rise from today's 1.5 kg/capita up to 70 kg/capita. These changes will definitely challenge the waste management sector, but also represent an opportunity for the recovery of valuable resources. Based on the results, it can be concluded that the transformation of an urban transport system towards lower greenhouse gas emissions also has the potential to reduce future material demand and waste generation. However, this requires a change in the modal split, whereas solely moving to a fossil-free vehicle fleet has the contrary effect.

1. Introduction

The transport sector contributes significantly to global resource and energy consumption (Sims et al., 2014). Hence, the objective of decarbonising the transport sector can be found in strategic papers at all levels of decision-making. On city level, transport policy has always been an important issue, with a particular focus on traffic management. In recent years, however, issues concerning decarbonisation and a shift towards sustainable transportation have gained in importance. For this reason, targets in this regard are addressed in smart city initiatives (Neirotti et al., 2014). One advocate of such a scheme, which also includes within in its smart city initiative a transformation of the transport system, is the city of Vienna in Austria. In its Smart City Wien Framework Strategy (SCWFS), different targets for urban and social development have been defined. Among them is the target to reduce Vienna's per capita $CO_{2\text{-eq}}$

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Abbreviations

Smart City Wien Framework Strategy (SCWFS).
Material Flow Analysis (MFA).
Service Units (SU).
Motorized Individual Transport (MIT).
Non-Motorized Individual Transport (NMIT).
Public Transport (PT).
Battery Electric Vehicle (BEV).
Active Mobility (AM).
Scenario A: Business as usual scenario ($\mathbf{A}_{BAU}$).
Scenario B: Battery electric vehicle fleet scenario ($\mathbf{B}_{+BEV}$).
Scenario C: Public transport scenario ($\mathbf{C}_{+PT}$).
Scenario D: Active mobility scenario ($\mathbf{D}_{+AM}$).
Net floor area (NFA).

emissions in the transport sector by 50% by 2030 and by 100% by 2050. This is to be achieved by converting the vehicle fleet to low-emission propulsion technologies (e.g. battery electric vehicles) and a shift towards more environmentally friendly transport modes (e.g. walking, public transport) (City of Vienna, 2019a). In the social and political discourse, a shift in transport mode choice versus technological development often represent counter-poles. Particularly at the European policy level, technological progress in the field of motorized individual transport is proposed as a key to reducing the emissions of this sector (Emberger, 2017). According to Urban Innovation Vienna (2019), the above-mentioned targets of the SCWFS can be achieved by means of technological developments in the transport fleet without changing traffic behaviour in terms of the modal split. However, this calculation only considered the direct $CO_{2\text{-eq}}$ emissions of the vehicle fleet while neglecting entirely greenhouse emissions caused by the construction and maintenance of transport infrastructure.

The latter, however, contributes decisively to the overall material turnover of societies, especially for bulk building materials and metals (Augiseau and Barles, 2017; Tanikawa and Hashimoto, 2009; Wiedenhofer et al., 2015). Thus, transport infrastructure contains a significant resource saving potential within a city (Lederer et al., 2020b). The quantity and type of materials used vary considerably between different modes of transport (Anderson et al., 2015; Chester and Horvath, 2009; Gassner et al., 2020; 2018). Hence, the modal split distribution and the transport infrastructure associated with it together influence the resource demand and waste generation of cities. It is therefore important to evaluate and assess possible future pathways, not only according to energy-related but also resource-related criteria. Although the transformation of the transport system is defined as a target in SCWFS and, furthermore, a reduction in overall raw materials consumption is a goal within the strategy (City of Vienna, 2019a), a resource-related analysis investigating this transformation is not yet available. Decisions taken regarding the development of the transport system have a very long-term effect due to the long useful life of transport infrastructure (several decades). Thus, the implications in respect of the long-term resource requirements of potential alternatives have to be considered at an early stage before actions are taken. In order to provide this information to the city administration and decision makers, the following research questions are investigated using the city of Vienna as a case study.

1) How will the transport infrastructure and the vehicle fleet develop up to the year 2050 on the basis of different future scenarios?
2) How do different developments in the transport system affect material stocks and material flows?
3) Are there saving potentials for raw materials within the future transport system alternatives and, if so, how can they be realized?

To answer these questions, a material flow analysis (MFA) considering different future scenarios until 2050 is performed. The method applied and the definition of the various scenarios are described in chapter 2. The subsequent results chapter describes the development of the transport system in the respective scenarios and their respective impacts on the material stocks and flows. These results are discussed in chapter 4 and, finally, a short conclusion is drawn. All calculations were done in MS Excel and the respective file is provided as supporting information.

2. Material and methods

2.1. Methodical approach

In the present study a bottom-up material flow analysis (MFA) is used to determine the future material flows and stocks. The method has already been widely used also for investigating transport and other infrastructures (Gassner et al., 2020; Guo et al, 2014, 2017, 2014; Lederer et al., 2016; Miatto et al., 2017; Noll et al., 2019; Tanikawa et al., 2015; Wallsten et al., 2013; Wiedenhofer et al., 2015). In the study at hand, an existing MFA-model for the transport system of Vienna published by Gassner et al. (2020) is used. Gassner et al. (2020) developed a bottom-up, multi-year MFA model for the Vienna transport system and investigated the period 1990–2015 retrospectively. In their model, the calculation is based on specific service units (SU) (such as: road area per road type (m^2), length of metro network (m), number of vehicles), which are combined with specific material intensities for the respective SU. Similar to that which has already been applied in various studies, among others by Müller (2006) as well as Wiedenhofer et al. (2015), in the present study the future development of the SU is calculated on the basis of different scenarios up to the year 2050. The assumptions made therein and the calculation methods applied to determine the future SU are described in section 2.2. The calculated SU are used as input data for the MFA-model, based on Gassner et al. (2020).

2.2. System boundaries

The City of Vienna was chosen as the study area because the transport system of Vienna is well developed and diverse in terms of transport modes, but above all because it is facing a transformation process. This is true for many cities in industrialized countries, so the results of this case study are applicable to other cities. Furthermore, the historical development of the transport system has already been investigated by Gassner et al. (2020) and the current study can build upon this work. The system under investigation is the transport system within the administrative border of Vienna. In particular, the transport infrastructure and vehicles are considered. A distinction is made between different modes of transport, namely motorized individual transport (MIT), non-motorized individual transport (NMIT) and public transport (PT). The time span of investigation covers the period from 2016 to 2050 and the calculations are made in successive annual periods.

2.3. Materials considered

The materials are expressed in metric tons (t) and their multiples (e.g. Million tons (Mt)). The material groups considered are: asphalt & bitumen; aluminium; batteries; brickwork; concrete; copper; glass; gravel & sand; iron & steel; other metals; others (e.g. rubber); plastics; and wood (Gassner et al., 2020).

2.4. Material stock, flows and intensities

In addition to the material flows related to the construction and demolition of transport infrastructure, the flows caused by the maintenance of transport infrastructure are also considered. The annual input and output flows are calculated according to the respective changes in stock (increase/decrease). The material flows necessary for maintenance are based on the renewal rates and useful lives of the infrastructures and infrastructural components, as described by Gassner et al. (2020). For vehicles, however, the material flows associated with maintenance and operation are not part of the investigation. The specific material intensities defined for the respective SU are taken according Gassner et al. (2020). The material intensities are assumed to be constant over the period investigated. All material intensities and respective references used can be found in the calculation MS excel file provided as supporting information.

2.5. Scenarios

Three thematically focussed scenarios for the transport sector of Vienna are investigated. In addition, a business-as-usual scenario "**A_{BAU}**", which extrapolates the current state, is modelled for comparison. In the prevailing transport system of Vienna the modal split is divided into 38% public transport, 25% motorized individual transport, 30% walking and 7% biking (Wiener Linien, 2020a). This modal split is referenced in the scenarios. Table 1 presents an overview of the scenarios investigated. All basic assumptions applied to all scenarios as well as how future transport demand is calculated is described in the following section 2.5.1. Further, the calculation approach to estimate the future vehicle fleet per scenario is explained in section 2.5.2. Assumptions made and calculation methods applied to determine the development of the transport infrastructure per transport mode and scenario are summarized in section 2.5.3.

2.5.1. General assumptions and calculation procedures

In order to calculate the future development, some general assumptions applied to all scenarios are made. For the population development, demographic forecasts carried out by the Austrian conference for spatial planning are used for all scenarios (Hanika, 2019). For all scenarios, the same economic development – with a linear growth rate of 2% per year until 2050 – is assumed, which represents the basis for the development of the freight transport taken from Urban Innovation Vienna (2019). Concerning passenger transport, the same passenger mobility demand per capita is assumed for all scenarios.

Table 1
Overview and description of the transport scenarios examined.

Future scenarios	Scenario A_{BAU}: Business as usual scenario 2050	Scenario B_{+BEV}: Battery electric vehicle fleet scenario 2050	Scenario C_{+PT}: Public transport scenario 2050	Scenario D_{+AM}: Active mobility scenario 2050
2016–2030	constant modal split, infrastructure development - already planned network extensions and vehicle procurements (assumed to be equal for all scenarios), assuming equal vehicle numbers in all scenarios but variation in vehicle fleets with regard to the changing propulsion technologies in scenarios B_{+BEV}, C_{+PT} and D_{+AM}.			
2030–2050	constant modal split (MIT 25%, PT 38%, NMIT 37%); projection of the prevailing system into the future, propulsion technology of the vehicle fleet remains at the current state	constant share of MIT (25%); changed vehicle fleet: replacement of fossil fuelled cars by alternatives (electric, hydrogen); moderate increase in the share of PT (45%); decrease in active mobility - NMIT (30%)	new modal split: strong increase in the share of PT (55%); significant decrease in the share of MIT (<10%) and changed vehicle fleet; constant development of the share of active mobility - NMIT (35%)	new modal split: strong increase in distances covered through active mobility - NMIT (>45%); moderate increase in the share of PT (45%); significant decrease in the share of MIT (<10%) and a changed vehicle fleet

2.5.1.1. Transport service estimates.

The transport service (given in Million vehicle km/year) provided per transport mode is calculated using a multimodal macroscopic traffic model with 1146 source districts within the Vienna metropolitan area. Among others, the following parameters are considered in the model: the demographic forecast, the mobility demand per capita (trips per day), and the distribution of e.g. workplaces, leisure facilities, educational institutions, and housing within the city (OEIR, 2019). All these general parameters are the same for all scenarios. However, the preferred means of transport was adapted to the modal split objectives of the respective scenarios (see Table 1). The corresponding transport service projections per scenario within Vienna categorized according to transport mode are presented in Table 2. The traffic model used was developed by the Austrian Institute for Regional Studies (OEIR). Additionally, the transport performance estimates for the lorry vehicles are included (see Table 2). They are based on the economic trend and are taken from Urban Innovation Vienna (2019).

2.5.2. Vehicle fleet estimates

The future vehicle fleet of all scenarios is assessed using the same calculation method, which is described in detailed in the following section. The future number of MIT vehicles per vehicle type $V_i(t_n)$ is calculated based on the total transport service provided per vehicles type (*i*: cars and lorry vehicles) (see Table 2) according to Eq. (1):

$$V_i(t_n) = \frac{total\ Vkm_i(t_n)}{specific\ Vkm_i} \tag{1}$$

where *total* $Vkm_i(t_n)$ is the total transport service provided by the vehicle category (*i*) in the year (t_n), and *specific* Vkm_i is the average mileage covered by one single vehicle per year within Vienna. The *specific* Vkm_i are assumed to be constant over time and the same for all scenarios. The *specific* Vkm_i are assumed to be 7400 km/year per car (based on the long-term average (1990–2015)), 8100 km/year per small lorry vehicle, and 72,000 km/year per heavy lorry vehicle.

The future number of two-wheeled vehicles $V_i(t_n)$ (*i*: private bikes, public bikes and motorcycles) is calculated based on the level of motorization per 1000 capita according to Eq. (2):

$$V_i(t_n) = MR_{i_{per\_1000\ capita}} * \frac{Pop}{1000} \tag{2}$$

where $MR_{i_{per\_1000\ capita}}$ is the number of vehicles per vehicle category *i* per 1000 capita, and *Pop* is the population in the year n. The current and future motorization rates per vehicle category used are summed up in Table 3.

The rolling stock of Vienna's rail-based public transport is calculated based on the number of trains in use per day to provide the transport service demanded (Table 2). Thereby, a vehicle reserve is considered. In Vienna, this reserve amounts to 25% for metro vehicles, 13% for tram vehicles and 22% for urban railway vehicles. For the metro and tram services, the vehicle fleet can be forecasted quite well until 2030 because the provider has already ordered 34 metro trains and 156 tramcars (City of Vienna, 2019b; Siemens Mobility GmbH, 2018). The public bus vehicle fleet is calculated based on the total bus vehicle kilometres (see Table 2) according to Eq. (1), whereby the *specific* Vkm_{bus} corresponds to 47,000 km/year and bus (based on the long-term (1990–2015) average).

2.5.2.1. Vehicle propulsion technology estimates.

For the future private vehicle fleet, the distribution between the propulsion technologies used is assumed to be the same for the scenarios **B_{+BEV}**, **C_{+PT}** and **D_{+AM}**. This distribution is changing over time towards fossil-fuel free technologies

Table 2
Traffic model projections per scenario, expressed in transport service provided within Vienna per mode of transport in Million vehicle kilometres per year (motorized individual transport and public transport) and number of vehicles in operation per day for the public transport modes. The lorry vehicle kilometre estimates are taken from Urban Innovation Vienna (2019).

Transport service provided	Unit	2020	2030	2050 A_{BAU}	2050 $B_{+\ BEV}$	2050 $C_{+\ PT}$	2050 $D_{+\ AM}$
Cars	(Million vehicle km/year)	4,670	4,960	5,470	6,240	1,680	1,680
Small lorry vehicles (<3,5 t)	(Million vehicle km/year)	510	580	720			
Heavy lorry vehicles (3,6-40t)	(Million vehicle km/year)	360	390	440			
		Public transport service					
Metro	(Million train km/year)	17.2	19.1	20.7	21.3	21.3	21.3
	(Number of trains in use/day)	160	150	190	170	230	230
Tram	(Million train km/year)	24.7	25.9	27.7	27.9	28.8	28.8
	(Number of trains in use/day)	470	520	530	480	750	750
Regional train	(Million train km/year)	8.4	8.4	8.9	8.2	12.9	12.9
	(Number of trains in use/day)	90	90	90	90	130	130
Public bus	(Million bus km/year)	39.5	41.9	44.9	44.9	49.4	46.9

Table 3
Current motorization rate for bikes and motorcycles in Vienna and expected changes (given in %) by 2050 per scenario.

Motorization rate (MRi)	Unit	2020	2030	2050 A_{BAU}	2050 $B_{+\ BEV}$	2050 $C_{+\ PT}$	2050 $D_{+\ AM}$
Private bikes	Number per 1000 capita	640	Constant			+10%	+30%
Public bikes		2	Constant		+100%	+300%	+500%
Motorcycles		50	+10%		+100%	+20%	+60%

by 2050, except for the $\mathbf{A_{BAU}}$ scenario, where the current distribution is kept constant over time. The distributions of the propulsion technologies among the private vehicle fleet in Vienna today (taken from Statistik Austria (2019b)) and in 2030 and 2050 (Urban Innovation Vienna, 2019) are presented in Table 4.

2.5.3. *Transport infrastructure estimates 2050 and forecast until 2030*

In this section the general calculation procedures for infrastructure development are presented. Until 2030 no distinction is made between the scenarios, and already planned expansion projects are considered. Beyond that, the calculations are adapted to the scenarios defined. For all modes of transport, the infrastructure required for both moving and stationary traffic is considered. However, other indirectly associated infrastructure associated with the transport sector, such as car workshops, petrol stations or charging infrastructure for electric vehicles, are not taken into account.

2.5.3.1. Road-based transport infrastructure estimates. The high-level road network will be expanded by 2030. A new highway bypass south of Vienna together with feeder roads will add about 6.4 km of highway, 9.5 km of road tunnel, and 400 m of road bridges to the existing network (ASFINAG, 2019a, 2019b; City of Vienna MA18, 2018). In the period after (2030–2050), for scenarios $\mathbf{C_{+\ PT}}$ & $\mathbf{D_{+\ AM}}$ it is assumed that the high-level road network will not be further expanded. In scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+\ BEV}}$, it is assumed that the road area per capita will remain constant over time. Therefore, the total traffic area $TA_i(t_{2050})$ per road category (i: superhighway, highway) in the year 2050, Eq. (3), is calculated as follows:

$$TA_i(t_{2050}) = TA_{i,\ per_{capita}(t2030)} * Pop_{(t2050)} \tag{3}$$

where $TA_{i,\ per\_capita}$ is the capita specific traffic area per road category based on the level of 2030 ($t2030$), and $Pop_{(t2050)}$ is the population in the year 2050.

In terms of the low-ranking road network, only extensions in urban development areas are assumed until 2030. Urban development areas cover a space of about 8.52 km^2 by 2030 and in the period 2030–2050 around 1.7 km^2. In addition, it is planned to increase the building density in the built-up areas in order to create corresponding living space (City of Vienna, 2014a). Around 29% of this space will be used as traffic areas, based on the current allocation of area to different uses (City of Vienna, 2016). It is assumed that this traffic area will be divided into 45% road area, 30% sidewalks and pedestrian zones, 15% bicycle lanes, and 10% parking area.

For scenarios $\mathbf{C_{+\ PT}}$ & $\mathbf{D_{+\ AM}}$, there will be no further expansions of the low-ranking road network, except those in urban development areas, after 2030. On the contrary, it is assumed that driving lanes of the low-

Table 4
Shares of the propulsion technology in use (Statistik Austria, 2019) *and assumed shares for 2030 and 2050 based on* Urban Innovation Vienna (2019).

Propulsion technology	2020				2030				2050			
	Car	Motorcycle	Lorry <3.5t	Lorry >3.5t	Car	Motorcycle	Lorry <3.5t	Lorry >3.5t	Car	Motorcycle	Lorry <3.5t	Lorry >3.5t
Petrol	45%	97%	5%		30%	85%			3%	5%		
Diesel	52%	1%	93%	100%	43%		77%	85%	3%			
Battery electric vehicle	<1%	2%	1%		15%	15%	17%	8%	82%	95%	95%	50%
Compressed Natural Gas (CNG)	<1%		1%		1%		2%	2%	1%			
Hybrid Petrol/Electro (hybrid)	<2%				5%		2%	2%	1%			
Diesel/Electric (hybrid)	<1%				5%		2%	2%	1%			
Hydrogen					1%		1%	1%	10%		5%	50%

ranking road network will be deconstructed by 10% in scenario $\mathbf{C}_{+\ PT}$, and by 30% in scenario $\mathbf{D}_{+\ AM}$ (based on the stock of 2030). This reduction is assumed to be due to the considerable reduction in MIT volume in both scenarios (−60% in vehicle km/year (see Table 2)). The road length will remain the same, but lanes of multi-lane roads will be reduced significantly. Hence, the road network will continue to provide equal accessibility and therefore security of supply (e.g. delivery traffic) throughout the city.

Due to increasing individual traffic in scenarios $\mathbf{A}_{BAU}$ & $\mathbf{B}_{+\ BEV}$, it is assumed that the low-ranked road area per capita will remain at the level of 2030. In these two scenarios, hence, Eq. (3) is applied to calculate the total low-ranked road area in 2050.

Applicable to all scenarios is the intention to convert all potentially deconstructed MIT traffic areas (e.g. parking lanes, drive lanes) into other traffic areas according to the following distribution: 10% biking lanes, 15% pedestrian zones, 40% sidewalks and 35% non-traffic areas (e.g. green area, playgrounds).

For bridges of the low-ranking road, pedestrian and cycling network, an equal stock increase rate as for the respective traffic areas is assumed. However, if there is a decrease in traffic areas, the number and size of bridges are assumed to remain constant. In scenarios $\mathbf{A}_{BAU}$ & $\mathbf{B}_{+\ BEV}$, an additional Danube bridge is assumed to be constructed for the high-level road network; whereas in scenarios $\mathbf{C}_{+\ PT}$ & $\mathbf{D}_{+\ AM}$ no further expansion of this bridge category is expected.

Based on the assumption that the public parking area, which is available per registered vehicle, remains constant at the current level, the total parking area $PA_i(t_n)$ per category i is determined with Eq. (4):

$$PA_i(t_n) = specific\_PA_{1_{per\ vehicle}} * \sum V(t_n)_{vehicles} \tag{4}$$

where $specific\_PA_{i_{per\ vehicle}}$ is the specific area per vehicle and corresponds to 5.45 m^2 (reference year 2015), and $\sum V(t_n)_{vehicles}$ is the total number of vehicles (cars and small lorry vehicles) registered in the corresponding year.

The number of parking places in public car parks is calculated using Eq. (4), where the places per vehicle remains constant with 0.12 places per vehicle registered (=current value). A constant expansion of parking spaces in park and ride car parks is assumed in all scenarios until 2050, based on the development observed between 2009 and 2019 (+30% every 10 years).

Newly erected parking places on private property (outdoor and within buildings) are calculated based on the projection of the construction of new buildings, taken from Lederer et al. (2020). The total number of parking places on private property $PP_{privat}(t_n)$ are calculated according to Eq. (5):

$$PP_{privat}(t_n) = \frac{newNFA(t_n)}{requiredPP_{per\ NFA}} \tag{5}$$

where $newNFA(t_n)$is the total new useable floor area in m^2, and $requiredPP_{per\ NFA}$ represents the parking place rate per useable floor area. The legally specified parking space obligation demands 1 parking space per 100 m^2 useable area (WGarG, 2008). For scenarios $\mathbf{A}_{BAU}$ & $\mathbf{B}_{+\ BEV}$, this rate remains the same until 2050, whereas in scenarios $\mathbf{C}_{+\ PT}$ & $\mathbf{D}_{+\ AM}$ an increase to 500 m^2 of useable floor area per parking space is assumed from 2030 onwards. In all scenarios, 18 m^2 per parking place and a distribution of 60% for underground parking, 35% for parking lots, and 5% for parking deck are assumed. Based on the projected demolition of buildings by Lederer et al. (2020), the demolished parking places are determined with Eq. (5), according to the *removed* NFA.

For all scenarios, it is assumed that the traffic area reserved for pedestrians (e.g. sidewalks and pedestrian zones) will at least remain at the level of 2020, therefore Eq. (3) is applied. The currently planned basic network of bicycle lanes (+80 km) will be erected by 2030 (City of Vienna, 2014b; City of Vienna MA18, 2019a). From 2030 to 2050 the basic network will be further expanded (+160 km). This already planned minimum of additional bicycle lanes is assumed for all scenarios. In addition, further traffic area for active mobility areas will arise in urban development areas and will also depend on the scenarios through deconstructed MIV traffic areas, as described above.

2.5.3.2. Public transport infrastructure estimates. The development of the public transport network can be well estimated for the next 10 years and is assumed to be the same for all scenarios. The metro network will be extended by round 15 km by 2030, whereby the new lines will mainly run underground (Wiener Linien, 2020b). Already planned projects concerning the expansion of the tram network add up to around 23 km of new lines (=46 km track length) by 2030 (City of Vienna MA18, 2019b). The projects planned for the expansion und capacity increase measures of the regional train network within Vienna amount to about 12 km of newly built train tracks and 6 newly constructed train stations (OEBB, 2018).

For the period 2030–2050, the development is adjusted according to the respective scenarios. Overall, it is assumed that the public transport network will be expanded in all scenarios; the specific increase rates are summarized in Table 5. The assumptions are based on a network analysis taking the urban development areas and the transport demand per scenario (see Table 2), into account. In addition, expansions already announced for the period after 2030 are considered in the scenarios. The share of the specific construction types (e.g. underground or above-ground metro) per network is assumed according to the current stock and the course of the route (built-up or unbuilt area).

3. Results

3.1. Development of the transport system in Vienna

A population of around 2.3 Million is forecasted for Vienna by the year 2050 (Hanika, 2019). This population increase (>10%) will result in an increasing need for transport, as presented in Table 2. Considering the assumptions made in the respective scenarios, the transport system of Vienna will change until the year 2050. The change affects both the vehicle fleet and the transport infrastructure.

3.1.1. Vehicle fleet development

The vehicle fleet is determined by the population development, people's choice of transport mode and the resulting transport service available per transport mode. In the respective scenarios, the vehicle fleets of the different transport modes, hence, develop differently, as shown in Fig. 1. For the active mobility vehicle fleet, an increasing trend can be observed in all scenarios (see Fig. 1(i)). The increase is significantly higher in scenario $\mathbf{D}_{+\ AM}$ (+>50%) than in scenarios $\mathbf{A}_{BAU}$ & $\mathbf{B}_{+\ BEV}$ (+16%). In scenarios $\mathbf{B}_{+\ BEV}$, $\mathbf{C}_{+\ PT}$ and $\mathbf{D}_{+\ AM}$, the vehicle fleet composition will change, from bicycles towards an increasing share of pedelecs and other electrified vehicle types such as e-scooters. The number of public transport vehicles is also increasing in all scenarios. Major expansions of the fleet will have already taken place by (+13%). In order to fulfil transport service needs as required (see Table 2), the

Table 5
Summary of the status quo of public transport infrastructure and its development for the different scenarios.

Public transport infrastructure development	Status quo	Stock change compared to 2020				
	2020	2030	2050 A_{BAU}	2050 $B_{+\ BEV}$	2050 $C_{+\ PT}$	2050 $D_{+\ AM}$
Total metro network (km)	93	+16%	+22%		+42%	
Total tram network (km)	208	+9%	+14%		+23%	
Regional train network (km)	190	+6%	+10%		+18%	

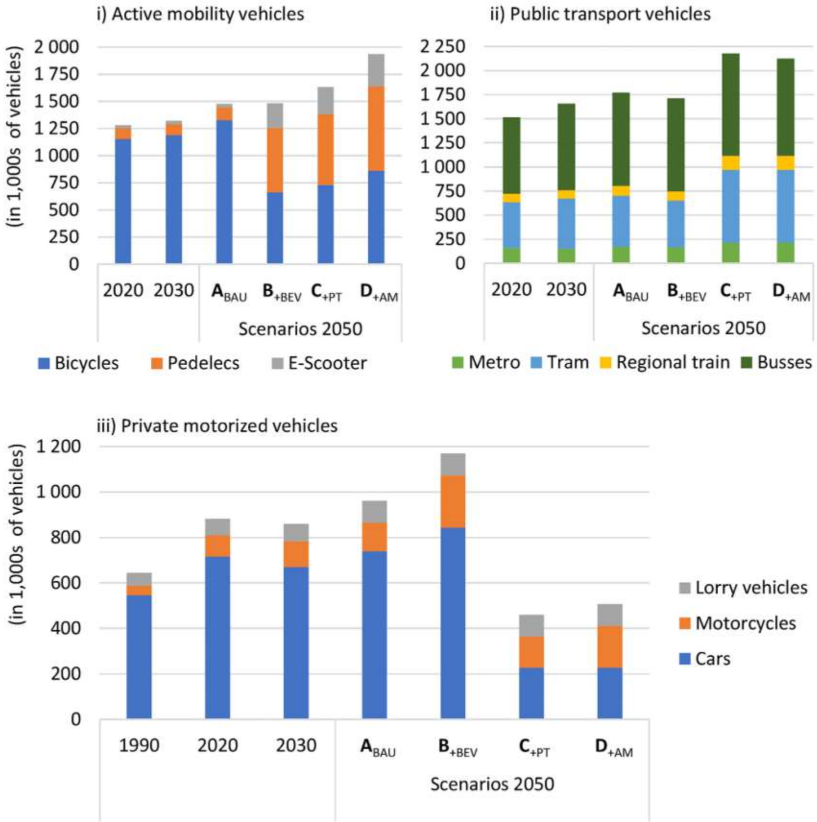

Fig. 1. Vehicle fleet development per scenario and vehicle type for (i) active mobility vehicles (in 1,000s of vehicles), (ii) public transport vehicles (number of trains and busses), and (iii) private motorized vehicles (in 1,000s of vehicles).

public transport vehicle fleet will increase significantly in scenarios **C**$_{+\ \mathrm{PT}}$ & **D**$_{+\ \mathrm{AM}}$, as presented in Fig. 1(ii)).

The most significant differences between the scenarios arise for the fleet of the motorized individual transport (see Fig. 1(iii)). If the preferred choice of transport mode will remain at the current level, the number of private motorized vehicles increases to around 1.2 million by 2050 (scenario **B**$_{+\ \mathrm{BEV}}$ +32%) from today's figure of 900,000. If, on the contrary, a transformation towards public and active mobility transport modes takes place, the motorized vehicle fleet is reduced to around 500,000 vehicles (scenario **C**$_{+\ \mathrm{PT}}$ -50%), which corresponds to a motorization rate of 99 cars per 1000 inhabitants (rate in 2019: 372). Fig. 2 compares the development of the car fleet in both scenarios **B**$_{+\ \mathrm{BEV}}$ and **C**$_{+\ \mathrm{PT}}$, taking the propulsion technology into consideration. The vehicle fleet is about 70% smaller in scenario **C**$_{+\ \mathrm{PT}}$ than in scenario **B**$_{+\ \mathrm{BEV}}$ in 2050. This implies that, depending on the future scenario, the total number of battery electric vehicles (BEV) in Vienna will be either 700,000 or 200,000 in the year 2050.

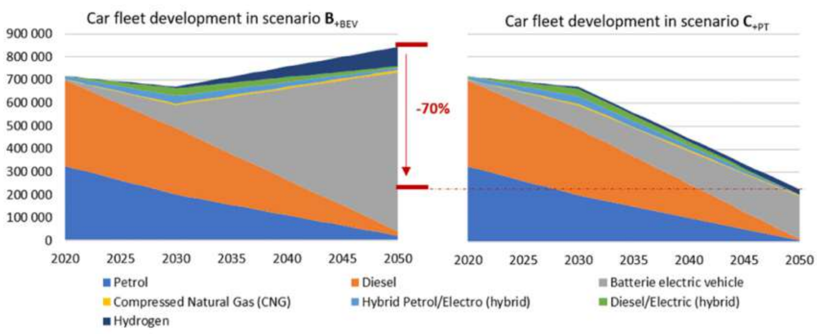

Fig. 2. Development of private car vehicle fleet for scenarios **B** $_{+\ \mathrm{BEV}}$ and **C** $_{+\ \mathrm{PT}}$.

3.1.2. Transport infrastructure development

The development of traffic areas per scenario distinguished between road area, parking area, and area for active mobility, which is presented in Fig. 3. The road-based traffic area will increase to 56 km^2 by 2030. Further increases of about 7 km^2 will occur by 2050 in scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+\,BEV}}$. The required parking places contribute 3 km^2 (35%) to these increases. The traffic area per capita remains constant, with around 27m^2/capita in scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+\,BEV}}$. In comparison, in scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$, it decreases to around 24m^2/capita.

The rail-based public transport network is expanded in all scenarios compared to the status quo (network length in 2020: 450 km), as shown in Fig. 4. The total network length of scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$ is, with 612 km, about 10% higher as compared to scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+\,BEV}}$. This relatively small difference is explained by the already well-developed network. The required additional transport capacity for these scenarios (see Table 2) is therefore mainly provided on the existing network by additional rolling stock.

3.2. Material stocks and flows in the transport system of Vienna

3.2.1. Material stock development of the transport system

As shown in Fig. 5, the overall material stock of the transport system in Vienna increases in scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+\,BEV}}$ to more than 120 Mt, thereby basically continuing the historical trend (1990–2020). In comparison to 2030, a net stock addition of >12 Mt is predicted for these two scenarios. In contrast, the material stock remains at the same level or slightly decreases in scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$ compared to 2030. In all scenarios, the mass construction material categories of infrastructure buildings (gravel & sand, concrete, asphalt & bitumen) remain the most important material categories. They contribute about 95% to the overall material stock.

The material stock per capita remains constant at around 54 t/capita for scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+\,BEV}}$. However, in scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$ the material stock per capita decreases to about 47 t/capita. This is mainly due to a significant decline in the per capita material stock of the motorized individual transport, as shown in Fig. 6. In contrast, the per capita material stock of public transport and non-motorized individual transport increases in both of these scenarios, from today 22 t/capita to maximum 25 t/capita.

3.2.2. Material inputs and outputs in the transport system

The development in material stocks goes along with different material in- and outputs. Fig. 7 presents the cumulative material in- and outputs, into/from (i) the transport infrastructure and (ii) the vehicle fleet, per material category for the respective scenarios for the period 2016 to 2050. Overall, the material input exceeds the material output in all scenarios because the total material stock in the year 2050 is higher

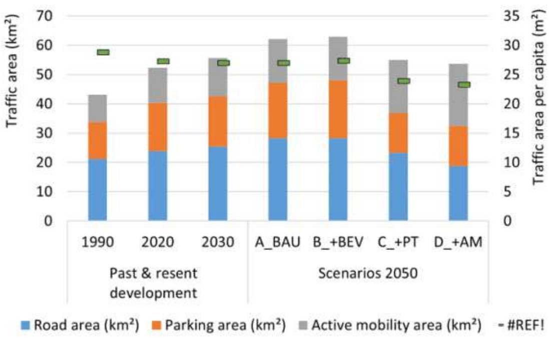

Fig. 3. Road-based infrastructure development per scenario and traffic area type in square kilometres (km^2) and the specific traffic area per capita in m^2 (secondary x-axis green bars).

in all scenarios compared to the stock of 2016. However, in scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$ the stock decreases between 2030 and 2050. It turns out that the overall material inputs of the scenarios differ less than the material output flows. This is due to the high proportion of the material turnover for maintenance of the existing infrastructure (on average, two thirds), which is based on the total network stock of the respective infrastructures. For scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$, the material output of mass construction materials (gravel & sand, concrete, and asphalt & bitumen) is higher in comparison to scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+\,BEV}}$ due to the dismantling of road infrastructure.

In scenario $\mathbf{B_{+\,BEV}}$, the share of non-construction materials relative to total material turnover is higher compared to scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$, which is mainly due to the larger private vehicle stock, see Fig. 7 (ii). Overall, in scenario $\mathbf{B_{+\,BEV}}$ the cumulative material input into the vehicle stock is around 25% higher than in scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$. This appears low given the significant reduction in the total vehicle fleet by −70% up to 2050, but is due to the fact that the vehicle stock of 2030 will only gradually be reduced and because end-of-life vehicles will only be partly replaced during this period. This is also reflected in the respective output flows of end-of-life vehicles of the different scenarios. However, the input of selected materials in vehicles differs more significantly, so the total input of batteries and copper is about 48% and that of aluminium about 28% higher in scenario $\mathbf{B_{+\,BEV}}$ in comparison to scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$.

The material turnover per scenario is shown in Fig. 8 for 2050, the final year modelled. The total material turnover (sum of inputs and outputs) is higher in all scenarios compared to the current state in 2020 as the networks will expand until 2050. On a per capita basis, however, the material turnover remains more or less constant, with 1–1.1 t/cap/yr. The material input into the transport infrastructure (Fig. 8 (i)) exceeds the output by up to 24% in scenarios $\mathbf{A_{BAU}}$ & $\mathbf{B_{+\,BEV}}$, which results in an increase in the material stock. Moreover, for these two scenarios, primary raw materials are required even if theoretically all waste could be recycled. For scenarios $\mathbf{C_{+\,PT}}$ & $\mathbf{D_{+\,AM}}$ the input and output are almost equal or, rather, the output flows exceed the input flows by up to 8%.

Almost 75% of the material turnover is caused by maintenance works of the network. Changes in the latter as simulated in the different scenarios affect these works and thus the material flows. In scenario $\mathbf{D_{+\,AM}}$, for instance, the material demand for maintenance of road-based infrastructure is reduced by more than 20% to 460 kg/cap/yr in comparison to scenario $\mathbf{B_{+\,BEV}}$. At the same time, maintenance works for the rail-based infrastructure increase in scenario $\mathbf{D_{+\,AM}}$ by 10% compared to $\mathbf{B_{+\,BEV}}$, resulting in an annual per capita material input of 310 kg. Thus, the overall material input caused by maintenance is reduced by around 8% (to 770 kg/cap/yr) in scenario $\mathbf{D_{+\,AM}}$. The respective scenarios differ even more significantly regarding the material turnover for the vehicle fleet, as presented in Fig. 8 (ii). The range extends from a significant increase in the annual material input (+30%; $\mathbf{B_{+\,BEV}}$) to almost halving it (−45%; $\mathbf{C_{+\,PT}}$) compared to the current state.

4. Discussion

4.1. Implications of the development of the transport system in the respective scenarios and raw material saving potentials

4.1.1. Vehicle fleet

The projected development of the material stock of Vienna's vehicle fleet in the different scenarios ranges from 1.60 Mt ($\mathbf{B_{+\,BEV}}$) to 0.76 Mt ($\mathbf{C_{+\,PT}}$) in 2050. The difference is determined by the diverse development of the private vehicle fleet. For the different scenarios, it has been assumed that private car ownership correlates with the modal split. This is a simplified assumption as the private vehicle stock is the sum of various individual preferences and decisions made by the respective vehicle owners. They are all influenced by social developments and regulations (e.g. taxation) on national and European levels. However, the city also has a decisive influence on vehicle ownership through local

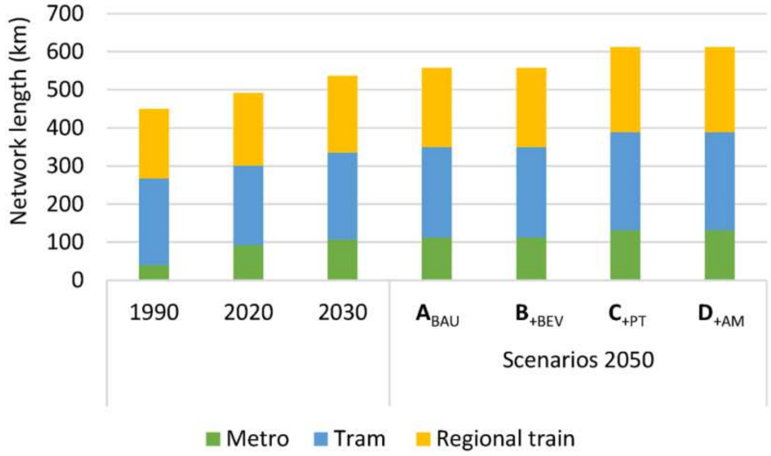

Fig. 4. Rail-based infrastructure development per scenario and transport mode type in kilometres (km) of network length (both ways).

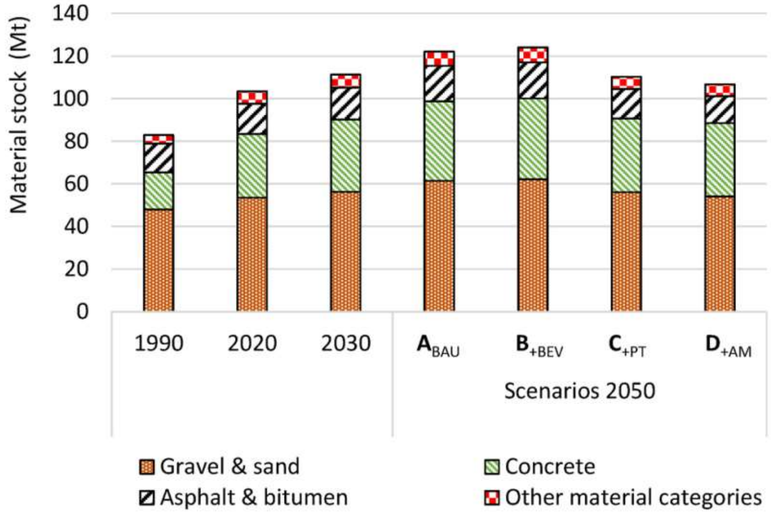

Fig. 5. Material stock per scenario and material category in Million tons (Mt).

regulations (e.g. parking space management and fees) and the development of the road and parking infrastructure. The importance of the infrastructure (e.g. available parking places and road capacities) with regards to private vehicle ownership and transport mode choice has been proven in several studies (among others, by Cervero and Murakami, 2010; Christiansen et al., 2017; Knoflacher, 2006; Sun et al., 2017). Hence, the sooner traffic area transformation in favour of alternative usage takes place, as modelled in scenarios $\mathbf{C}_{+\ \mathrm{PT}}$ & $\mathbf{D}_{+\ \mathrm{AM}}$, the sooner the vehicle fleet will be reduced.

A reduced vehicle fleet is of interest to the city beyond traffic planning objectives as its reduction contributes to meeting a further target addressed by the Smart City Wien Framework Strategy, namely, the reduction of the consumption-based footprint (City of Vienna, 2019a). The relevance is illustrated by the difference of about 60,000 newly registered cars every year between scenario $\mathbf{B}_{+\ \mathrm{BEV}}$ versus scenarios $\mathbf{C}_{+\ \mathrm{PT}}$ & $\mathbf{D}_{+\ \mathrm{AM}}$, which is associated with a reduction in the annual demand for steel by 44,000 t, aluminium by 11,000 t, copper by 3,500 t and batteries by 9,000 t. In the present study, the energy consumption as well as consumer durables in operation (e.g. tires, maintenance) have not been considered. However, it can be assumed that savings in these areas will reinforce the positive effects of scenarios $\mathbf{C}_{+\ \mathrm{PT}}$ & $\mathbf{D}_{+\ \mathrm{AM}}$.

The share of the vehicle material stock relative to the overall material stock of the transport system is, unsurprisingly, with 1.1%–2.0% (depending on the scenario) quite small and comparable to the current share of 1.8%. The renewal rate of the vehicle fleet is about 10 years (Gassner et al., 2020), therefore its influence on the total input (4–5%) and output flows (5–6%) of the transport systems is significantly higher since the built infrastructure has a much longer lifetime. Although the annual material turnover for the vehicles is more than one order of magnitude smaller in comparison to the one for the built infrastructure, the materials used in vehicles are much more valuable and their production or disposal is associated with significantly higher environmental impacts, implying that their reduction is most probably more important for the overall environmental performance of the transport system.

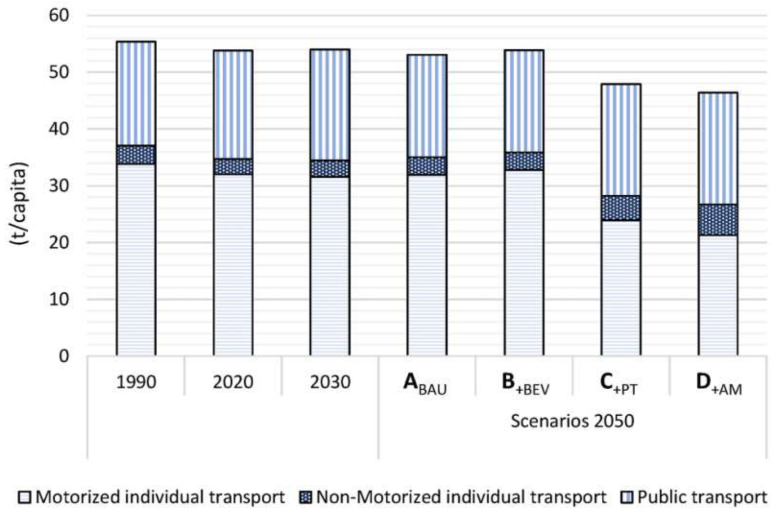

Fig. 6. Material stock per capita and transport mode and for the different scenarios investigated, given in tons per capita (t/capita).

Assumed changes in the material composition of vehicles due to a projected shift in the propulsion technology will challenge the waste management sector (e.g. new types of waste or different waste composition). As presented in the results, considerable quantities of batteries are expected to become waste assuming that the battery-operated propulsion technology becomes established as the leading technology in the coming decades. Hence, proper recycling technologies capable of handling a variety of different batteries must be established as currently each car manufacturer has developed its own battery type. Efficient recycling technologies for batteries constitute a prerequisite to reducing the environmental burdens associated with their production and to securing a future supply of required raw materials such a lithium, as shown by Ziemann et al. (2018).

Although changes in the composition of the material stocks and related flows are observable for the overall transport system, they might be even more pronounced for individual transport modes. For instance, due to the increasing use of electrical support in active mobility vehicles, the battery stock in these vehicles increases by around 800% to 3 kt by 2050, which corresponds to only 1–4% of the total battery stock. In this subsystem, however, this type of vehicle causes significantly higher environmental impacts on production and disposal compared to conventional bikes. Hence, their useful lifetime has a major impact on emissions per service unit, as shown by Moreau et al. (2020) for dock-less e-scooters. They further show that the means of transport that such vehicles replace is particularly decisive for the environmental impacts on the transport system. The city administration should therefore monitor new systems like dock-less e-scooters and positively influence them by targeted management (e.g. quality standards for publicly offered vehicles, combination with public transport). Furthermore, a collection system for end-of-life vehicles of this type should be set up as they contain a potential of up to 240 t of batteries per year. This corresponds to about twice the amount of batteries wasted from cell phones (100 t/year) in Vienna, assuming that on average the cell phone or its battery (50g) is replaced once a year per capita.

4.1.2. *Transport infrastructure*

By 2030 the total material stock of Vienna's transport infrastructure will increase by 8% to 111 Mt. However, the material stock per capita remains constant due to a similar increase in population. For the subsequent period 2030 to 2050, the material stock develops differently in the respective scenarios. A significant shift in the modal split towards PT or NMIT holds the potential to reduce the per capita material stock of the transport system by about 13%. However, if the share of motorized individual transport remains at the current level, as assumed in scenarios $\mathbf{A}_{\mathrm{BAU}}$ & $\mathbf{B}_{+\ \mathrm{BEV}}$, the material stock per capita remains constant and the overall material stock of the system further increases by 12% by 2050 compared to 2030. In other words, the development of the total material stock of the transport system depends significantly on the development of the modal split and thus the private vehicle stock.

The overall material input into the transport infrastructure differs only slightly between the respective scenarios modelled in terms of material composition and quantity. One reason is that through the transformation there is a shift in resource demand from one mode of transport to another according to the assumed changes in the modal split. So, in those scenarios, where it is assumed that the road-infrastructure is reduced (scenarios $\mathbf{C}_{+\ \mathrm{PT}}$ & $\mathbf{D}_{+\ \mathrm{AM}}$), the infrastructure for PT and NMIT is being expanded more compared to the scenarios $\mathbf{A}_{\mathrm{BAU}}$ & $\mathbf{B}_{+\ \mathrm{BEV}}$. However, even more important for the overall material turnover is the fact that about 2/3 of the overall material input is caused by the maintenance of existing infrastructure. This high relevance of maintenance on material turnover for the transport infrastructure is consistent with other studies (Gassner et al., 2020; Noll et al., 2019; Wiedenhofer et al., 2015). This means, however, that a significant decrease in the material demand of the respective transport network is realized only gradually with the reduction in the network stock. So, in the year 2050 the annual raw material saving potential through reduced road maintenance efforts is about 20% (0.2 Mt/year) in scenario $\mathbf{D}_{+\ \mathrm{AM}}$ compared to scenario $\mathbf{B}_{+\ \mathrm{BEV}}$. Taking the total construction material inputs into the transport system into consideration, the effect goes down to around a 6% annual saving potential as, for instance, the material input for PT increases in scenario $\mathbf{D}_{+\ \mathrm{AM}}$.

Due to the centralized management of transport infrastructure (road, railways) and the more or less similar composition of input and output, material cycles in this sector are easier to close than in other sectors. Lederer et al. (2020b) investigated the raw material saving potential through enhancing material cycles in the construction sector of Vienna. With regard to infrastructure, they identified two measures with a high saving potential, which are the substitution of gravel in unbound form with secondary material and enhanced asphalt recycling. Hence, a significant share of the future material demand for the transport infrastructure might be covered through waste-derived materials. The theoretical possibility of a closed-loop material cycle during the

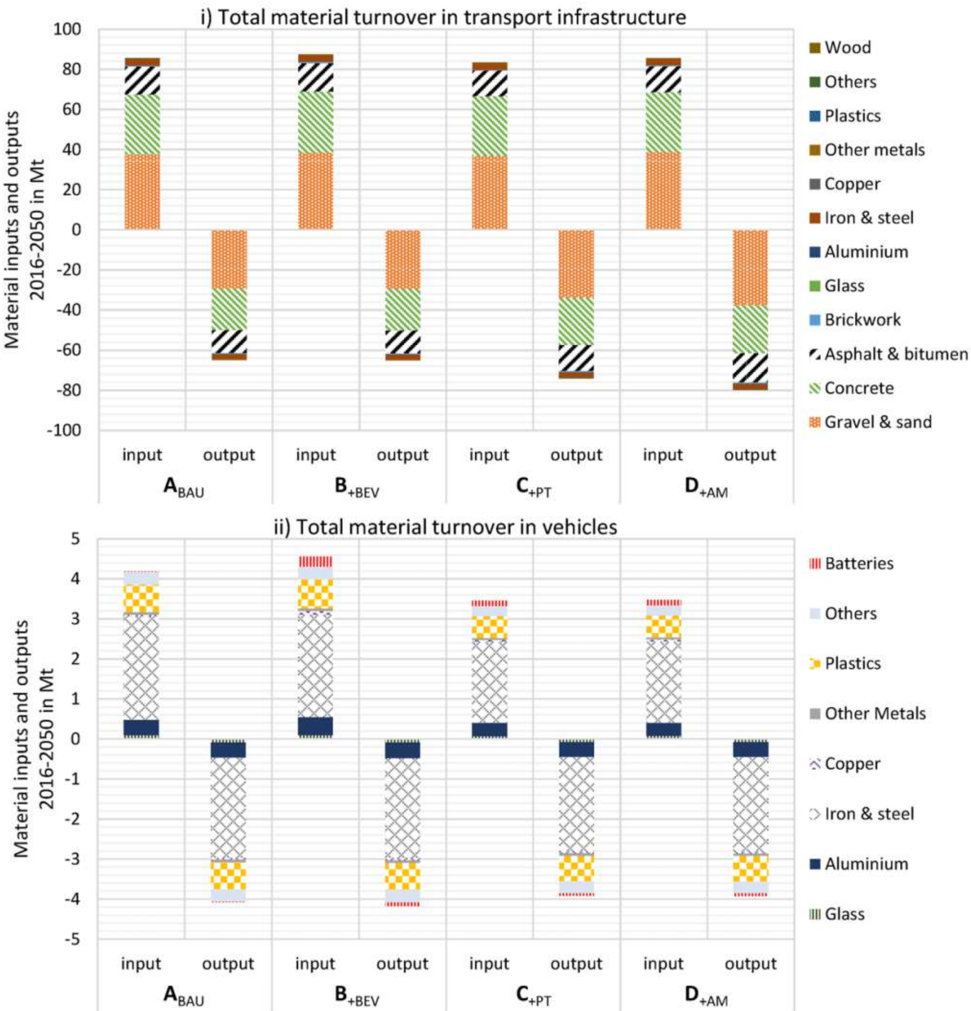

Fig. 7. Cumulative material in- and outputs into/from (i) transport infrastructure, and (ii) vehicles per material categories in the scenarios 2016–2050 in Mt.

transformation of the transport infrastructure only arises on the premise that the network or material stock of the network remains constant or decreases. This applies to scenarios $\mathbf{C}_{+\ PT}$ & $\mathbf{D}_{+\ AM}$, whereas for scenarios $\mathbf{A}_{BAU}$ & $\mathbf{B}_{+\ BEV}$, the inputs exceed the outputs. For the latter, thus, even with a 100% recycling rate for construction materials, additional raw material input would be necessary in any case.

4.2. Comparison of the chosen model approach and findings to other studies

In the present study, the future development of the transport infrastructure was model considering different scenarios. Thereto, development in the recent decades and correlations observed between different indicators (e.g. correlation of road area and population development) as published by Gassner et al. (2020) have been used. Other studies conducted in the field largely applied the same approach to investigate material stocks and flows, as stated by Lanau et al. (2019) in their review of 249 publications on built environmental stock studies (buildings and infrastructure). The developed scenarios, which are in line with the objectives regarding the mobility behaviour and urban development set in the SCWFS, were used to model possible future trends of material stocks and flows. A similar study for the development of the urban building sector in Vienna up to 2050 was recently conducted by Lederer et al. (2021). They also used a time span of 30 years for future predictions, which corresponds to times chosen in other studies as well, see for instance (Mollaei et al., 2021; Schiller, 2007; Tanikawa et al., 2002). Very recent investigations for two Canadian cities Kitchener and Waterloo also used a bottom-up material accounting approach to assess the future building and transport infrastructure stock (Mollaei et al., 2021). They calculated the future development of the road transport infrastructure until 2041 based on the projected road expansion plans of the municipalities, which again is based on population development projections and policy plans. A similar approach was used in the present study too, the near development (up to 2030) is based on existing infrastructure development plans. For the far future (2030–2050) the development was modelled based on the projected population development and different policies assumed (depending on the scenario). Comparing the results presented by Mollaei et al. (2021) with the results

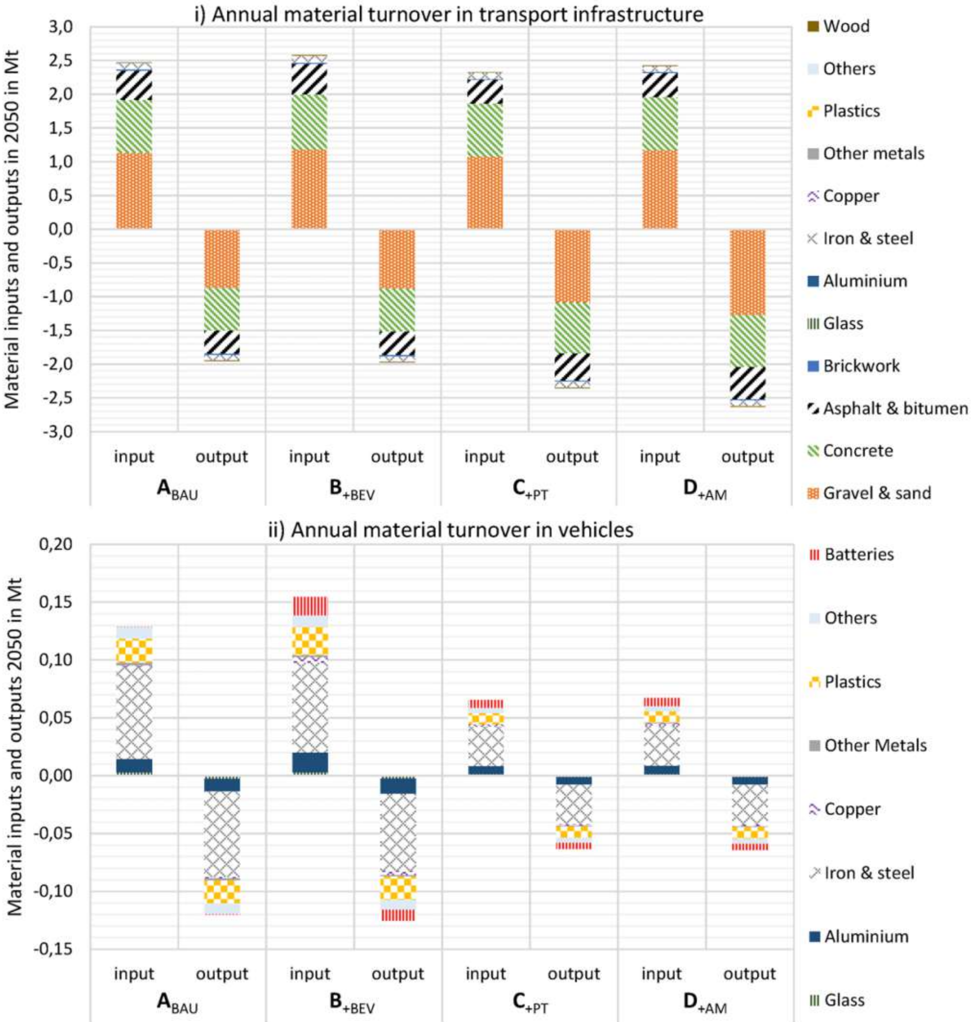

Fig. 8. Material in- and outputs into/from (i) transport infrastructure, and (ii) vehicles per material categories in the scenarios in the year 2050 in Mt.

per capita of the present study shows that the material stock of road infrastructure per capita for Kitchener and Waterloo (72 t/capita) is about double of the quantities calculated for Vienna (considering also the public transport, the stock figure for Vienna is still 26% lower). This can be explained by the different building densities and the fact that the transport system in Kitchener and Waterloo is mainly based on motorized individual transport (the current share of MIT is around 60% on modal split see City of Waterloo (2019)). Such differences in local conditions clearly shows the relevance of local bottom-up studies and the decisive role of specific correlations (e.g. existing infrastructure and mobility behaviour) as basis for projections. The transport system of the city of Vienna was also very recently investigated by Virág et al. (2021) using a stock-flow service nexus approach for of personal mobility. Virág and colleagues calculated the per capita material stock of Vienna's transport sector with 56 t/capita which equals to the findings in the present study. Furthermore, they found that active mobility is the most resource-efficient mobility option. This corresponds with the findings in the present study on city level. Since, if the share active mobility will be increased drastically, as defined in scenario $\mathbf{D}_{+\ AM}$, this will lead to a reduced overall material demand.

4.3. Limitations

As data availability for a complex system like the transport system of a whole city is limited, the MFA model makes use of various simplifications and assumptions. They mainly concern the development of the service units (e.g. road network development) as well as their material composition and intensities. Despite these uncertainties, the differences assessed in the stocks and flows of the scenarios investigated, and hence the conclusions based thereon, are robust. Moreover, a comparison of the results with the findings of previous studies by numerous researchers (Gassner et al., 2020; Miatto et al., 2017; Noll et al., 2019; Tanikawa and Hashimoto, 2009; Wiedenhofer et al., 2015) indicates the reliability of outcomes. The development of the vehicle fleet per scenario has a significant influence on the results. In order to be able to depict clearly distinguishable scenarios, it was assumed that the ownership structure of the vehicle fleet in 2050 is equivalent to the current state. The impacts of a potentially increasing sharing economy or self-propelled cars on the development of the total vehicle fleet have not been considered and would require the inclusion of further scenarios. However, as there is no consensus on the impact of such developments (increase or decrease in MIT traffic), such scenarios were not considered. Furthermore, structural, political and social factors (e.g., household income, lifestyle, environmental awareness, parking regulations) that influence modes of transport chosen and affect car ownership decisions were not modelled individually as factors, but are required in order to reach the transformation described in the scenarios. The effects and interrelationships of such influences have already been investigated by other researchers (among others, by Buehler, 2011; Ding et al., 2017; Vij et al., 2013). The inclusion of all these factors as input factors in the presented model would exceed the scope of this study. Further, potential long-term effects on the transport demand and mode choice that may result from current pandemic containment measures (e.g. permanent increase in remote working and digitalisation) have not been considered. Since such long-term effects are not yet assessable.

4.4. Future research

The insights provided in the study at hand raise several research questions to be addressed in future work. The developments in the transport system investigated should be further analysed in terms of their impact on energy consumption and greenhouse emissions, whereby both direct (e.g. fuel and energy consumption) and indirect consumption and emissions (e.g. goods and material production) should be considered. The future energy mix with regard to electricity production for the region considered must be also be taken into account, incorporating differentiated additional scenarios or at least sub-scenarios to encompass this complexity. Such analysis is definitely crucial to examining the overall environmental impact of the city's transport system and to investigating whether a transformation causes an overall shift from direct emissions (occurring within the city) towards material incorporated emissions (occurring globally). Furthermore, it would be of great interest to analyse the environmental and social impacts of a new distribution of the scarce resource land area within the city by means of a potential reduction in road area. The long-term effects of current pandemic containment measures on the movement of people (e.g. change in place of residence choice due to increase in remote working possibilities) are currently difficult to assess. Nonetheless, sustainable changes in the mobility of people are to be expected, which should be investigated as soon as valid data are available. Furthermore, upcoming trends like sharing mobility concepts and autonomous vehicles could have a decisive influence on the cities transport system. To evaluate the impacts on the material turnover will be an important upcoming research topic.

5. Conclusion

Although the city of Vienna already has a well-developed transport system, it will further expand in the future. The choice of transport modes and thus the development of the motorization rate will play an important role in terms of the development of the material stock and annual resource consumption. A reduction in the consumption of primary raw materials is achievable by shifting from private motorized vehicle-based transport towards public transport and active mobility. However, if the existing system and modal split is retained, resource consumption and the waste generated thereby will continue to rise although greenhouse emissions might well be mitigated due to fewer fossil-fuel based vehicles being used. The greatest savings potential results from a reduction in the private vehicle fleet and road infrastructure as well as from the associated decline in maintenance efforts. To foster the transformation of the transport system towards less carbon and resource intensity and to avoid negative feedback loops, obsolete (road) infrastructure should be dismantled and converted for other purposes. What's more, the resource aspect should be considered in any extension and rehabilitation project connected with road infrastructure. Hence, each project should be evaluated for its impact on the targets set in the Smart City Wien Framework Strategy in order to reduce greenhouse gas emissions and resource consumption.

CRediT authorship contribution statement

Andreas Gassner: Conceptualization, Methodology, Data curation, Calculation, Visualization, Writing – original draft. **Jakob Lederer:** Funding acquisition, Writing – review & editing, Conceptualization. **Gerald Kovacic:** Data curation, performed the calculation of the future transport service estimates with the multimodal macroscopic traffic model and assisted with future infrastructure development estimates, Writing – review & editing. **Ursula Mollay:** Validation, assisted in the design of the scenarios, Writing – review & editing. **Christof Schremmer:** Validation, assists in the design of the scenarios, Writing – review & editing. **Johann Fellner:** Funding acquisition, Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127591.

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Paper III

Changes in Material Stocks and Flows of a Century-old Rail Network Caused by Refurbishment

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Changes in Material Stocks and Flows of a Century-old Rail Network Caused by Refurbishment

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Abstract

The main objective of the paper at hand is to investigate material flows and stock changes of subway infrastructure associated with its refurbishment. Specific attention is given to the relation between recycling, reuse and virgin material flows. Furthermore, the extent to which policy targets are achieved in a specific refurbishment process is investigated. Thereto the refurbishment of a subsection of Vienna's subway network was chosen as a case study. To fulfil the objective, a bottom up material flow analysis (MFA) of the refurbishment process on the subsection was performed. Results show that the overall material stock is 360,000 t, of which three-fourths remained unchanged within the refurbishment. Within the refurbishment process, in total material with a mass of around 155,000 t was built into the system. The share of recycling material was significantly higher than the use of virgin material. In detail 39% virgin construction material, 15% recycling construction material, 41% on site-recycling construction material and 5% reuse construction components were built into the section.

Keywords: Vienna, public transport, Material Flow Analysis (MFA), refurbishment, subway network, reuse and recycling construction material

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1. Introduction

Infrastructural networks such as subways are generally thought of in terms of their passenger transport function within urban areas. Since the emergence of the concept of urban metabolism (Baccini and Brunner, 1991), however, researchers have shown increasing interest in other main features and side effects of infrastructure networks such as environmental emissions and resource use for their operation as well as materials required and resource constraints associated with their construction. Subsequently, a number of studies have investigated these aspects of subway networks such as, for instance, Andrade and D'Agosto, (2016); Chester and Horvath, (2009); Lederer et al., (2016); or Li et al., (2016). While all of these studies have to some extent collected primary data on material flows and resource use during the construction phase of subway lines, material flows and resource use during the maintenance phase usually refer to data from databases. A review by Augiseau and Barles (2017) on construction material flows, however, suggests that the demolition and renovation of networks are often not subject to monitoring by the public authorities and therefore not recorded with the same accuracy in these databases. If studies deal with refurbishment processes of subway networks, they tend to be primarily focused on technical challenges (e.g. Petr and Jaroslav, 2006; Posgay, 1996) and consequently exhibit little interest in detailed material flows and changes in material stock. The study at hand aims to make a contribution towards filling this gap. Due to legislative and policy changes at the urban, national and supra-national level (BMLFUW, 2016; City of Vienna, 2014; EUROPEAN PARLIAMENT AND OF THE COUNCIL, 2008) aimed at decreasing resource consumption by means of a circular economy, the study focuses on the reuse of construction elements and the utilization of recycling construction materials. In terms of mass, construction and demolition activities are among the biggest sources of waste in Europe (construction and demolition waste (CDW). They account for approximately 25% - 30% of all waste generated in the EU and consist of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, and excavated soil, many of which can be recycled. In order to tackle this challenge, the recycling of construction and demolition waste is encouraged by an EU-wide mandatory target of 70% (European Commission, 2015). Policy objectives are important. Yet in order to meet these objectives, the use of recycling building material, at best produced by demolition material of the construction site, is crucial to increase recycling material rates and to promote the substitution of virgin building material. Also important are specific actions taken on construction sites in terms of the reuse of construction elements, which represents another important policy objective expressed e.g. by the waste hierarchy (EUROPEAN PARLIAMENT AND OF THE COUNCIL, 2008). The extent to which these policy objectives are already fulfilled within the case study are demonstrated.

The main objective of the paper at hand is to investigate material flows and stock changes of subway infrastructure associated with its refurbishment. Specific attention is given to the relation between recycling, reuse and virgin material flows in a case study. Furthermore, the extent to which policy targets are achieved in a specific refurbishment process is investigated. Thereto the refurbishment of a subsection of Vienna's subway network was chosen as a case study. To fulfill the objective a bottom up material flow analysis (MFA) of the refurbishment process on the subsection was performed. For the investigation, the materials were assigned to the three main categories mineral (e.g. gravel, stones, concrete, soil), organic (e.g. wood, plastics) and metals (e.g. iron and steel, aluminum, copper). These general categorizations represent both materials that make up the bulk of the total material input, material output and stock (i.e. mineral) as well as materials having a high secondary raw value (Lederer et al., 2016). For the investigation real inventory data from the public transport provider (Wiener Linien GmbH & Co KG) was used.

First, the case study investigated is presented in section 2.1, followed by a description of the methods and materials used in sections 2.2 and 2.3. An insight into the material inventory of the built up material stock is given in section 2.4, and calculations of flows (built-in, reuse, recycle, and waste) are summarized in section 2.5. Finally, results are presented (section 3) followed by conclusions (section 4).

2. Method and materials

2.1. Case study description

The system investigated is the subway network in Vienna, with five subway lines totalling 87 kilometres in length, including main and shunting tracks. A subsection of the line U4 was refurbished in 2016. The refurbished part consists of parts of the line constructed in the 1890s, of which some parts (station buildings, viaducts) are cultural heritage monuments. In Vienna the subway infrastructure of the line U4 is largely based on the former *Stadtbahn* (urban railway), which had already been built at the end of the 19th century. This historic infrastructure has constantly been refurbished and modified, particularly after Second World War damage in the 1950s and when being upgraded to a subway line in the 1970s (Schlöss, 1987). These processes of refurbishment and modification led to a change in the quantity and composition of the material stock, but also to changes in the wastes generated during these processes. Depending on their quality and quantity, these wastes can serve as a potential anthropogenic resource of secondary raw materials (Lederer et al., 2014). However, neither the changes in the material stock nor the generation of wastes and their recycling has been recorded in the course of these previous refurbishment and modification processes. For this reason, an attempt is made to do so by carrying out a material flow analysis on the present refurbishment project of the U4, termed *NEU4*.

Small improvements in subway tracks (e.g. signal and communication system or passenger information displays) are carried out while constantly maintaining train service; however, for major refurbishments the train service has to be interrupted. Such a major refurbishment process was carried out on a subsection of the subway line U4. In the paper at hand, this rehabilitation process over a total length of 3,500 m was investigated in terms of stock changes and material input and material output flows. The rehabilitation took place from the kilometer pole 10.7 to km 14.2. The standard cross section for the open track within the subsection is presented in Figure 1, including a comparison to the standard cross section before refurbishment.

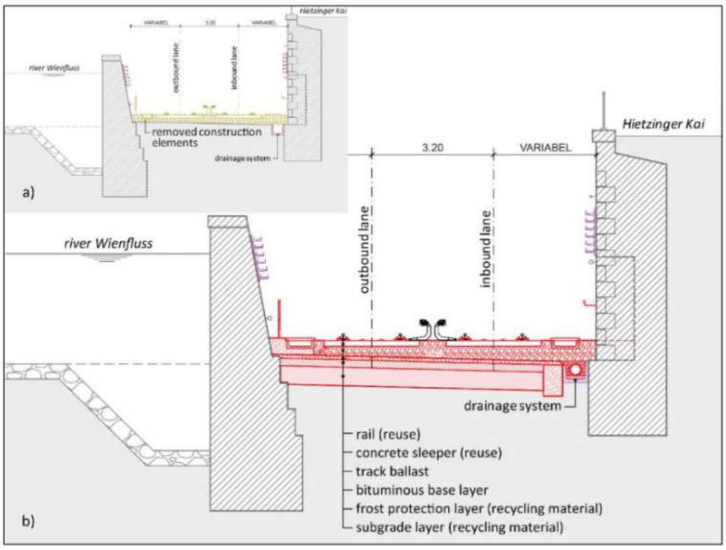

Fig. 1: Open track standard cross section before (a) and after (b) refurbishment

The subsection investigated is built above ground level. Following construction measures based on tender documents were part of the refurbishment process investigated:

Track substructure

The track bed was removed until the subsoil (natural ground) was reached (average depth of 0.8 m – 1 m). The drainage system of the track substructure has been kept in place. From the subsoil, the new track substructure was built. For the subgrade recycling construction material, such as excavated asphalt, road surface material mixed with parts of the removed track ballast was used. Furthermore, recycling construction material was used to build the frost protection layer. A 10 cm bituminous base layer completed the track substructure (see Figure 1).

Track superstructure

On the rebuilt substructure, a new track superstructure consisting of cable channel, track ballast, concrete sleeper, rail, electric cabling, and power rail was built (see Figure 1). The rail and the concrete sleepers were assessed to have an additional lifetime of around 10 years. Therefore, these components were stored in the stockyard during the track substructure refurbishment and could be reused in the newly built superstructure. The conductor rail, made of steel, could be partly (~50%) reused, the other 50% were replaced with a conductor rail made of aluminum. The electric cabling was renewed.

Renovation and extensions of buildings above ground level

There are four stations (Ober St. Veit, Unter St.Veit, Braunschweiggasse and Hietzing) and one train reversing facility within the subsection investigated. The station Ober St. Veit is a cultural heritage monument, therefore building materials such as historical stoneware had to be renovated and reused. Within the buildings, the following construction work was undertaken: retrofitting of the train platform, retrofitting of interior spaces, new construction of operation rooms, retrofitting of stairways, and the modernization of operational equipment.

Viaduct rehabilitation

The U4 line crosses the river *Wienfluss* on a steel bridge. Subsequently, the route leads over 10 vaults over a length of about 100 m. The stock is about 110 years old and consists of bricks that were covered on the sides with natural stone. As a result of the traffic loads of the past few years, the moisture seal was found to be torn, and surface water penetrated into the building. To secure the building, a new improved waterproofing made from seal concrete was installed.

2.2. Material flow analysis (MFA)

Material Flow Analysis (MFA) is a widely applied analytical tool for modelling, understanding and optimizing material flow systems by means of comprehensive investigation of material flow input within and out of a defined system. MFAs include processes (transformations, relocations or storages of materials) and flows as connections between processes. A process that stores a material includes a so-called material stock. This stock changes over time depending on the balance of all input and output flows of the respective process. MFA is used to provide information on metabolic systems. The method has been largely harmonized (see, among others, Baccini and Bader, (1996); Brunner and Rechberger,(2016), (2004)).

The system investigated in the study at hand is presented in a schematic survey in Figure 2, which should provide a clear overview of the system under investigation. Thereby the section is split into two processes (before and after refurbishment), which does not fully represent real circumstances. The "more accurate" system is presented in Figure 4 in the results section. All material flows are presented in the mass unit "metric ton (t)"; and the reference period selected is one year (2016). Three material categories are considered: minerals, organics and metals. However, for the detailed investigation of flows 22 material categories were differentiated in order to reflect changes in the material composition of building components (e.g. the change from a third rail (conductor rail) made of steel to one made of aluminum).

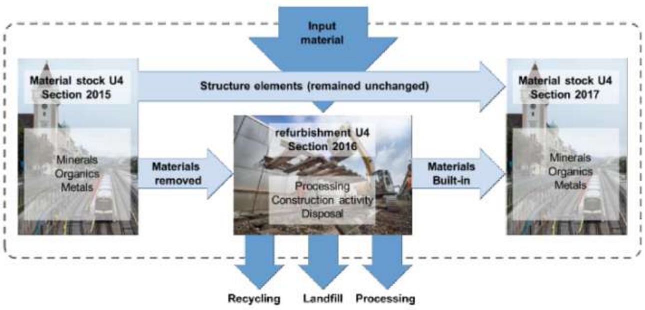

Fig. 2 Schematic illustration of the stocks and flows investigated

2.3. Procedure

The investigation was carried out in two steps. First, the material stock of the subsection investigated was calculated using the same bottom-up approach as applied by Lederer (Lederer et al., (2016). Thereafter, publicly available data from literature was used together with articles and books that described the subway network, especially those parts based on the former *Stadtbahn* (Duniecki et al., 1991; Gerlich, 1980; Hinkel, 1982; Lederer et al., 2016; Schlöss, 1987). In addition, data from the operator WIENER LINIEN GmbH & Co KG, i.e. current and historic construction and engineering plans of construction elements, buildings and track bed were all used.

In the second step, the flows of built-in materials and recycling materials/wastes were calculated. Thereto company data were used. To clarify and complete some of these data, expert interviews with persons in charge for the specific refurbishment process were conducted. The main data sources to calculate built-in materials and flows of recyclables were tender documents (including e.g. construction plans, contract specifications, technical reports), while output flows were determined based on the waste management report of the construction site, tender documents (e.g. detailed information about demolition activities) and soil samples, the latter being mandatory in accordance with the Austrian landfill directive (BMLFUW, 2008).

2.4. Investigation of the stock

In order to characterize the initial state of the system, the material stock was calculated. The material stock of the subsection investigated was divided into the following categories: open track, stations, and viaduct. In each of these categories, individual data sources and calculation methods were used.

Open track
The construction elements at the track section investigated were mainly built in the 1890s. In this section, the trains run above ground level. The construction elements consist of two walls made of natural stone (see Figure 1). The north wall demarcates the rail track from the riverbed of the river *Wienfluss*. The drainage of the rail track passes through the wall and ends in the riverbed. However, the south wall demarcates the rail track from the street *Hietzinger Kai*. The river is located below and, in some sections, at the same level as the track bed; however, the street level is at around 5 m to 8 m. Both construction elements are completely preserved. To calculate the material stock, different standard cross sections for the sections investigated were considered. The volumes calculated were combined with the specific material intensity (2.5 t natural stone per m³). The material stock was calculated taking the track lengths of the different standard cross sections into consideration, as presented in Table 1. Not included in the stock calculation was the track bed as these construction elements were investigated in detail in the flow analysis (see section 2.3); moreover, the removed materials were added to the calculated stock to represent the overall material stock before refurbishment. For this reason, the only material category considered for the open track are minerals. Metals and organics were used only in insignificant amounts in these construction elements.

Table 1 Material stock calculation (using specific data on the material intensities (m³/m and t/m) and information about the track length in m of applied standard cross sections)

standard cross section	wall-river	wall-street	mineral	track length	stock
unit	m³/m	m³/m	t/m	m	t
Open track (km10.7 - km 11.1)	15	7	55	419	22,836
Open track (km 11.1 - km 14.2)	14	14	71	1,682	119,002
Open track including rescue niche (km 11.1 - km 14.2)	14	12	64	368	23,552
Track station area	12	11	98	770	75,075
Track – train reversing facility	14	14	71	261	18,531

Stations
To calculate the material stock of the station and operational buildings within the subsection investigated, firstly the gross cubic volume for each building was calculated using data from construction plans. The calculated gross cubic volumes were then multiplied with the specific material intensities (given in t/m³) and taking the period of construction into consideration. The specific material intensities were taken from Kleemann et al. (2016) using the therein generated data for the utilization category "industrial" as this seemed to be the one that corresponded best to the existing structures.

Table 2:Gross volume per building (own calculation) and specific material intensities (adopted from Kleemann et al., 2016)

Buildings	**Construction period**	**Gross volume m³**	**Mineral t/m³**	**Organic t/m³**	**Metal t/m³**	**stock t**
Ober St. Veit – transformer substation	1977-1996	4,222	170	1	15	760
Ober St. Veit (west)	-1918	2,761	280	5.8	8.8	801
Ober St. Veit (east)	1977-1996	1,624	170	1	15	292
Unter St. Veit	1977-1996	3,372	170	1	15	607
Braunschweiggasse (west)	1977-1996	3,175	170	1	15	572
Braunschweiggasse (east)	1977-1996	3,528	170	1	15	635
Hietzing Station Building	1946-1976	9,131	340	7.6	13	3,169

In addition to the material stock of the buildings, the material stock of the standard railway platform roof was calculated. In this standard railway platform roof 7.8 kg of metals per m² roof are built-in. The overall roof area covered on the above-mentioned stations is 4,165 m². Additionally, for the roof of the Hietzing station 1,395 t of concrete was built-in.

Viaduct

The viaduct has an overall length of 102 m, decreasing from a height of around 3 m to street level. The calculated gross volume of the construction element amounted to 6,090 m³. To determine the specific material intensity, values from Kleemann et al. (2016) were adopted. Per gross volume 530 kg of minerals, 3.7 kg of organics and 4.3 kg metals were assumed. A bridge made of steel with an overall length of 17.6 m interrupts the viaduct. For the bridge, a total metal amount of around 100 tons was estimated.

2.5. Investigation of flows

For the investigation of the material flows, first detailed knowledge about the construction activities undertaken had to be acquired. Usually these data can be found within the tender documents, in which all planned construction activities are described in detail. Within these documents, e.g. detail executive plans, material specifications, as-built plans and descriptions as well as technical reports are included. Furthermore, these data were extended with expert interviews and literature data. However, the tender documents were provided before the construction activities started; therefore, not all contingencies (e.g. soil characteristics of the natural ground, damage due to construction activities) are included. This mainly effects output and recycling flows. Therefore, the waste management plan, which contains all waste flows of the construction site, was used as the data source.

Within the present study the construction phases "track substructure", "track superstructure" and "building" were distinguished. Within the process termed "building", the renovation and extensions of buildings above ground level and the viaduct rehabilitation were considered together. In addition, there is the process "stockyard", where recycling material is produced (out of waste) and construction elements are stored for reuse purposes.

The built-in material flows were calculated with the specifications included within the tender documents, considering only positions that cause a significant input of materials. Not included were other services such as, for instance, final cleaning of the construction site. Within the positions, the expected amount of materials are included for most building materials (e.g. m³ of concrete, kg of reinforced steel). However, other positions were given in quantity without referring a mass unit, for instance railway sleepers or square meter floor covering. In that case, the material mass was estimated using technical data sheets of the products and literature data.

For the output flows, real data from the construction site was used. Due to legal reasons, construction companies have to report all waste flows from a construction site. These data were used within the study at hand. Furthermore, material flows due to recycling and reuse were identified. In the case that recycling building materials were used, these materials had to be certified and reported. These data were used to calculate the recycling material used for both recycling material obtained from the construction site itself (e.g. track ballast) and for recycling material from other construction sites (e.g. road surface material). Reused construction elements were listed in the tender documents for the refurbishment.

3. Results

3.1. Material stock

The overall material stock of the subsection investigated was around 360,000 t. The by far biggest part could be assigned to the material category minerals (~97%), followed by metals (~3%), and organics (<1%).

The open track shows the largest material stock in comparison to the buildings of stations and viaduct, as presented in Figure 3. The normalized material stock per meter subway track (both directions) for this specific section was around 100 t/m.

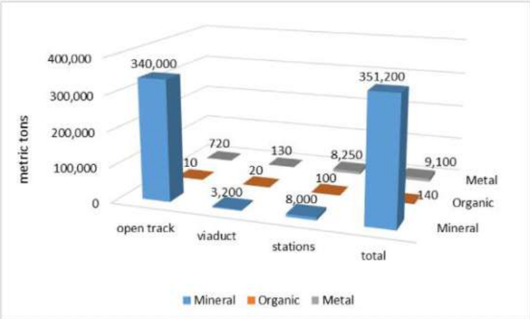

Fig. 3 overall material stock of the subsection investigated before refurbishment

3.2. Material stock changes and aggregated material flows

Through the refurbishment process around 84,000 t of construction materials were built-in in the section, of which two thirds were virgin material and one third recycling material (i.e. road surface material from a construction site in Vienna). Around 74,000 t were demolished and removed from the construction site and brought to landfill, waste treatment and recycling facilities. Since the amount of built-in material was considerably larger than the material removed, the overall material stock increased by around 11,000 t. Per meter of track the value rises by 3 t/m to around 110 t/m.

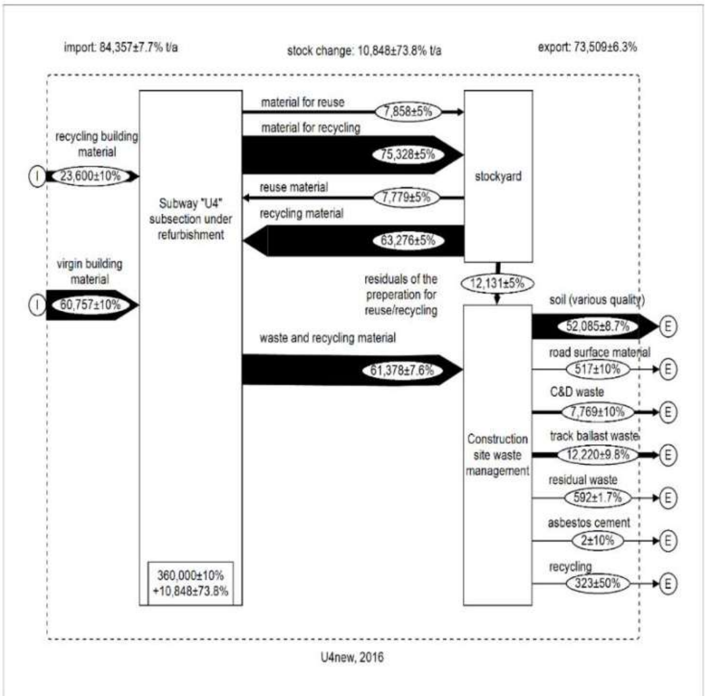

Fig. 4: Stock changes and aggregated material flows due the refurbishment

For the overall material input, a significant share of construction elements were also reused (mainly railway sleepers including rails). Moreover, an even larger amount of materials was recycled on-site. This material remained within the section with either the same or a different function. As presented in Figure 4, the overall mass of recycled material exceeds the mass of the virgin material used during the refurbishment.

3.3. Material flows

In total 22 different material categories were considered. In terms of mass, the main materials brought into the system were gravel (57%), concrete (30%), and asphalt with around 11%, all of which are related to the category minerals. Around 400 t of metals were built in the subsection, of which around 73% were iron/steel, 16% copper, 10% aluminium, and <1% others. In terms of mass, however, the usage of metals (<1% of total amounts of built-in materials) is negligible. The main part of the built-in materials was used for the track substructure (53%), followed by track superstructure (36%), and buildings (11%). When considering the reused and recycled materials, the share increases to 69% track substructure, 24% track superstructure, and 7% buildings. All reused, recycled, built-in, and waste material flows are summarized in Fig. 5.

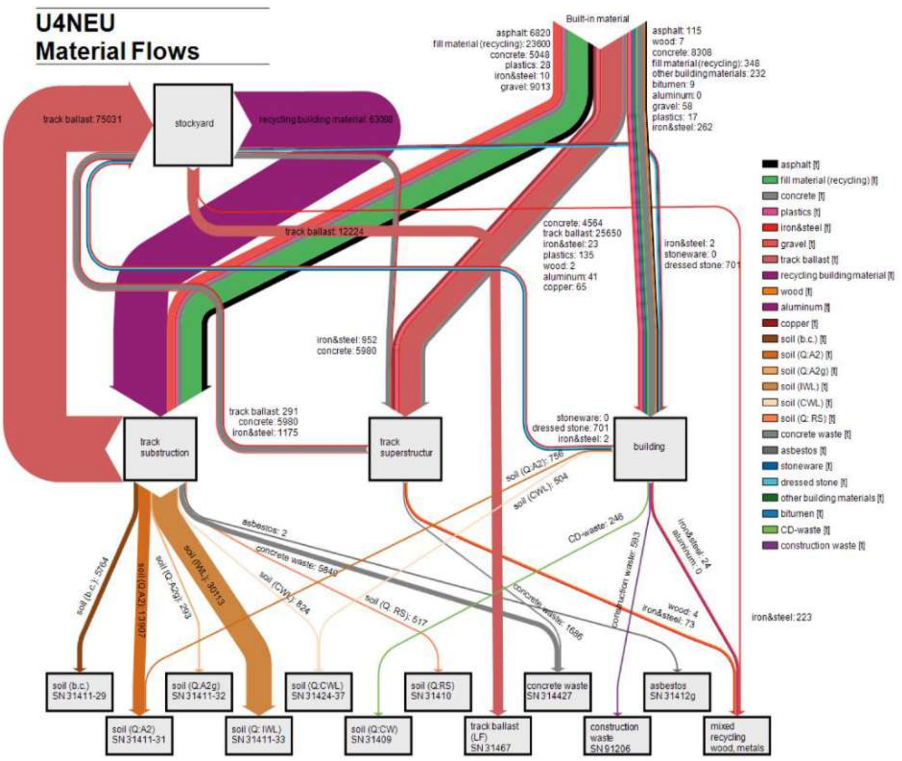

Fig. 5: Material flows during the refurbishment of the line U4 (U4New)

3.4. Ratio – reuse and recycled material

During the refurbishment, materials with a total mass of around 155,000 t were built-in, which equals around 44 t/m track. The share of recycling material was significantly higher than the use of virgin material. 63,000 t of recycled track bed material were mixed with 23,000 t of recycled filling material to form the earthwork structures and the frost protection layer. In total these two material categories account for about 55% of the overall built in materials.

Furthermore, the present study shows that there were also materials reused. In practice, components/elements were removed, stored at the stockyard and then re-installed (having the same function as before their removal). It is worth mentioning that reuse is more highly ranked within the waste hierarchy than recycling (EUROPEAN

PARLIAMENT AND OF THE COUNCIL, 2008). In total components with a mass of around 7,600 t were reused. The far biggest amount was due to the reuse of railway sleepers, including rails. In terms of materials this resulted in the reuse of 6,000 t (78%) of prefabricated concrete and 700 t (9%) of steel. Due to the fact that the station Ober St. Veit is a cultural heritage monument, historic stoneware (0.29 t; <1%) was carefully removed and re-installed after the platform had been refurbished. The same applies for the viaduct, where natural stone parts (700; 9%) were reused as well.

4. Conclusions

Regarding the policy objectives presented at the beginning of the study, it can be stated that the target to reduce the usage of virgin building materials (e.g. BMLFUW, (2016); City of Vienna, (2014); Eisenmenger et al., (2015)) was reached in the case study investigated. In fact, in terms of overall built-in materials, 15% recycling material, 41% on-site recycling material and 5% reused construction elements were used. Hence, the share of virgin construction material built-in was below 40%.

Although the lifetime of each specific subway network and its components needs to be investigated individually, the present study demonstrates that lifetimes commonly used in environmental assessment studies are to be questioned. For instance, Chester and Horvath (2009) assumed for rail modes 80 years for stations and 50 years for concrete components; Anderson et al. (2015) had assumed a lifespan of 100 years for a tunnel shell and 60 years for a tunnel base; Li et al. (2016) only assumed 50 years of service life time. In other words, there is a broad range of expected lifetimes for subway networks given in the literature. However, in the case study main network construction elements have been in use for 119 years and will continue to be part of the network in future, thereby demonstrating that although a broad range of lifetimes is used, real lifetimes might be even beyond the currently assumed ranges. In total >75% of the material stock of the section investigated maintained their function after refurbishment. In terms of mass, the majority of this stock are historical components which were built-in at the beginning in 1890. Even though this is an individual case, there should be further research conducted, in particular if various transport modes are compared. It can be stated that the predicted lifetimes mentioned above will be exceeded significantly.

Furthermore, the results of the present study show that the refurbishment process increased not only the overall material stock but also its complexity. The waste flows indicate a removal of historical bulk material (soil in various qualities). Such materials always carry the risk of being polluted through the more than 100-year use phase. Even if no significant amounts of pollutants were found, the environmental risk could be reduced through the rehabilitation. After the refurbishment, the rail bed is uniform in structure, which simplifies future maintenance and future renewal. The material intensity and material compositions in the section investigated has increased. This is especially true for components of the open track (in particular the track substructure), whereas in the stations mainly building components were replaced with equal materials. Within the open track, the material intensity and composition changed significantly within the track substructure, however, remained unchanged within track superstructure. Because the track superstructure were built in the 1970s and has been continuously updated in recent years. The track substructure was not changed in the 1970s and is not state of technology. The newly built substructure has a significantly stronger subgrade layer and frost protection layer (mainly from recycled material). Additional layers, for instance, a continuous bituminous base layer as a moisture seal, were added to the substructure (see Fig. 1). As a consequence there was an increase in both the material intensity and material diversity.

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Paper IV

Extended ecological footprint for different modes of urban public transport: The case of Vienna, Austria

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Extended ecological footprint for different modes of urban public transport: The case of Vienna, Austria

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ABSTRACT

Urbanization and population growth in urban areas are linked to increasing passenger transport and decreasing land availability. One option to cope with the negative impacts associated to this growth (i.e. emissions from and land use by traffic) is to strengthen public transport, as it has lower land requirements and higher transportation capacities if compared to private passenger transport by cars. Besides the direct land use within the city borders, transportation systems also cause land use in the hinterland, particularly for the extraction of raw materials, for energy supply, and for the sequestration of greenhouse gas emissions. The study at hand investigated these types of land uses of a multimodal public passenger transport network consisting of subway, tram, and bus transport, taking the case study of Vienna. The land uses distinguished were the direct land use in the city, 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 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 under consideration of the life cycle of used goods and materials. Results were expressed in global hectare (gha/a) for one year and further normalized to the transport capacity and performance of each transport mode.

Results indicate that the operational energy CO_2 hinterland use contributes most to the overall land use (55,000 gha/a), followed by the embodied CO_2 energy hinterland use (15,000 gha/a), the direct hinterland use (1,660 gha/a) and the direct land use within the city (620 ha). This sums up to a total of 72,500 gha/a, which, considering Vienna's population of 1.8 million inhabitants, equals 0.03 gha/capita.a. The direct land use within the city corresponds to 1.5% of city area and 1% of the EF. Divided by transport mode, the subway has the largest EF (51%) followed by busses (20%), trams (19%), and services (10%). However, the ranking changes when the transport performance is considered. In general it can be taken from the results that the specific environmental efficiency (specific land use per seat kilometer provided) is increasing with growing offer of service per route. Due to the fact that infrastructural and non-operational energy impacts (e.g. construction materials, station lighting and heating) are not increasing substantially with a higher succession of trains the effect is even higher by rail-bound systems. However, if the required transport capacity per hour falls below a certain limit, subways and trams are not only economical, but also environmental less efficient than bus systems.

1. Introduction

Humankind has been experiencing a shift from a purely rural to a predominately urban living society in which already half of the global population became urban citizens. This percentage will rise even more in coming decades (Grimm et al., 2008). Growing population and consumption of goods and services in large urban agglomerations requires more resources in terms of raw materials, energy, and land. Particularly the latter is a scarce resource in urban areas, as indicated by significant increases in land price in cities over the past few decades.

An increasing population goes along with larger volumes of traffic, which significantly impacts urban metabolism in terms of higher

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emissions, resources and land consumption (Baccini and Brunner, 2012; Barrett and Scott, 2003; Kennedy et al., 2011; Moore et al., 2013; Wackernagel and Rees, 1996). As public transport not only causes lower environmental impacts and offers higher transport capacity in comparison to individual transport, but also requires less space in the city, it is regarded as a major means of providing sustainable transportation in urban agglomerates (Chester and Cano, 2016; Codoban and Kennedy, 2008).

Like other modes of transport (e.g. passenger cars), public transport systems, however, not only have environmental impacts within the city boundaries, but also beyond (Clark and Chester, 2016). This not only counts for emissions, but also for land use. Furthermore, it is likely that this land use is not evenly distributed among different modes of public transport. For instance, rail-bound systems have on the one hand 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 bus lines, i.e. for the construction elements (Andrade and D'Agosto, 2016; Chester and Horvath, 2009; 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 "carbon 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, 2012; Matthews et al., 2008). Several studies (e.g., Barrett and Scott, 2003; Bhandari et al., 2014; Chester and Hovath, 2008; Chester et al., 2010; 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. This is remarkable, as different levels of land consumption are relevant for different stakeholders (e.g. district politicians, urban planners, municipal department of the environment and sustainability) (Zeev et al., 2014). In the present study, the term „hinterland" is used as described by Baccini and Brunner, (2012), thus referring to any land beyond the city boundary without indicating any geographical vicinity. With respect of public transport systems, direct land use is directly linked to the chosen mode of transport, particularly whether a network is underground or aboveground. This is of relevance particularly for urban stakeholders, as underground networks for instance ensure a high transport capacity by avoiding traffic jams while requiring less aboveground land which can be used for other purposes. Contrary to that, indirect land use depends on the quantities of raw materials used and thus effect stakeholders in the proximate hinterland of the cities supplying these raw materials. Moreover, the land required for CO_2 sequestration caused by GHG emissions by energy generation, raw materials extraction and production of goods which are required for the provision of the urban transport service have a global relevance. Cities are increasingly becoming aware of these multidimensional impacts of their transport systems, expressed by the growing number of smart or sustainable city initiatives (e.g., City of Vancouver, 2015; City of Vienna, 2014) and respective indicators to measure how the objectives set by these initiatives have been achieved (Ahvenniemi et al., 2017). With respect to these aspects, the overall objective of the study at hand is to provide a multi-dimensional analysis of land consumption of an urban public transport system, addressing the following research questions:

- What is the total (divided by transport mode)

i direct land use of Vienna's public transport system within the city – subsequently referred as "direct land use",
ii direct hinterland use to provide materials, goods and energy for the infrastructure of the urban public transport system – referred as "direct hinterland use",
iii consumption of land to sequestrate CO_2-emissions associated with the provision of materials and goods for the infrastructure – referred to as "embodied CO_2 hinterland use"
iv land required for the sequestration of CO_2- emitted due to the energy consumption of the public transport provider – called "operational energy CO_2 hinterland use"?

- What are the specific land uses for the four categories if transport capacities (expressed by seat kilometers provided (SKP)) and carried passenger (expressed by passenger kilometers traveled (PKT)) are considered?

For this purpose the public transport system of the Austrian capital Vienna has been analyzed as a case study, as it is multi modal consisting of an extensive bus, tram, and subway network and thus comparable to the public transport system of other cities like Munich, Paris, and Shanghai. Furthermore, the reduction of land consumption has been defined as a policy goal by the city administration of Vienna in its "Smart City Framework Strategy", indicating a high interest in indicators for measuring this policy goal (City of Vienna, 2014). For the study, real inventory and energy-consumption data were used.

2. Methods, methodology and materials

2.1. General methodological setting

2.1.1. Background

The case study city of Vienna covers an area of 41,500 ha and is home to a population of 1.8 million inhabitants in the year 2012. Projections suggest that the 2 million mark will be reached by the year 2028 (MA 23, 2015). Public transport is an important mode of traffic, and the largest provider WIENER LINIEN GmbH & Co KG offers this service with its extensive network of subway, tram, and bus lines including buildings (e.g. stations, garages, workshops). Additionally, service buildings (e.g. administration) are part of the operators assets (Wiener Linien GmbH & Co KG, 2016).

2.1.2. System boundaries

In the study at hand, only the service covered by this provider is considered, and the system under investigation (*Public transport provider – Wiener Linien*) includes all activities and associated infrastructure of Wiener Linien to provide the transport service. Infrastructure not provided by Wiener Linien itself (i.e. roads also used by private transport) are included in this study only in the direct land use, but not for the hinterland uses. This inconsistency is deliberately taken into account to be able to compare the direct area efficiency of all investigated transport modes. Furthermore, due the reason that the provider can influence the direct land use of the bus network through the line management, but has no influence on the road construction and its maintenance. Due road infrastructure is not included in the study at hand no allocation between private transport and public bus transport is needed.

The investigation is carried out on a life-cycle basis, and the life-cycle components included are presented in Figure 1. The inventory data from the Wiener Linien was divided wherever applicable into traffic modes. For services (e.g. administration) which were not applicable to one single transport mode the category "services" were introduced. The reference period selected is one year (2012).

2.1.3. Overall method: ecological footprint

The overall land consumption of Vienna's public transport system

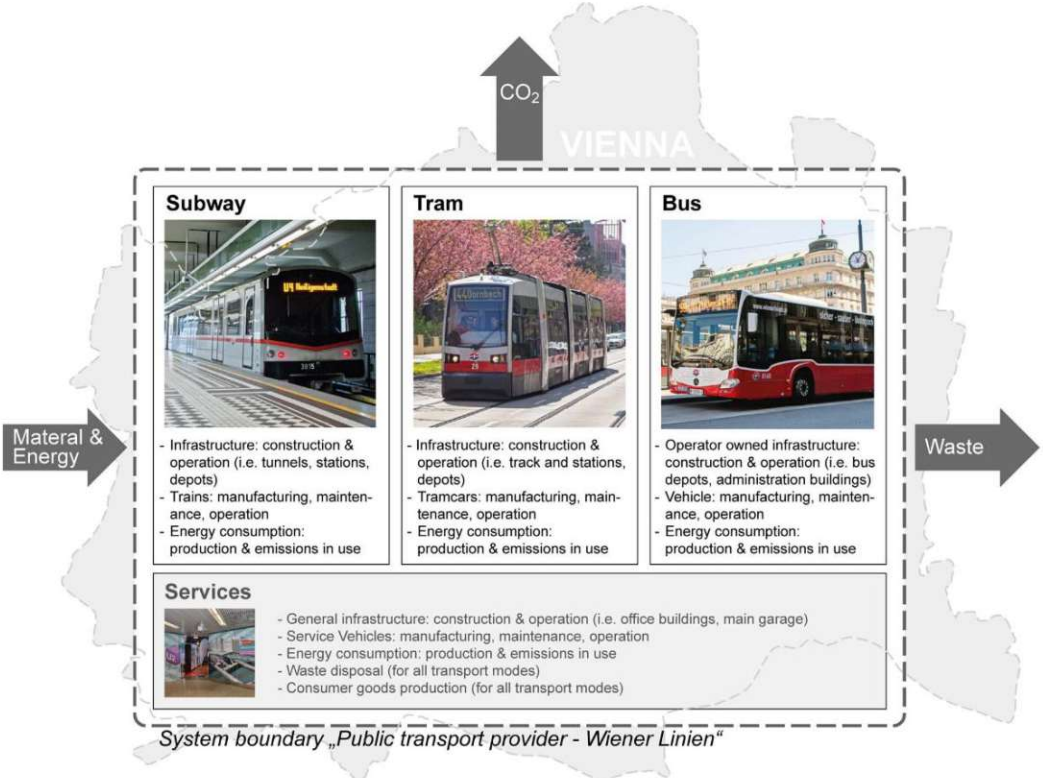


Fig. 1. System boundary "Public transport provider – Wiener Linien".

has been determined using an extended ecological footprint (EF) analysis approach based on several studies (Borucke et al., 2013; European Commission, 2012; Global Footprint Network, 2009; Rees, 1992; Wackernagel et al., 2005; Wackernagel and Rees, 1996). While most EF studies quantify the overall land required on a global scale, the study at hand distinguished i) the direct land use of the transport system within the city (*direct land use*), ii) the direct hinterland use necessary to provide materials, goods and energy for the infrastructure of the public transport system (*direct hinterland use*), iii) the consumption of land to compensate for GHG emissions, expressed as CO_2-emissions associated with the provision of materials and goods (*embodied CO_2hinterland use*), and iv) the land needed for the sequestration of CO_2 related to the direct energy consumption of the public transport system (*operational energy CO_2 hinterland use*). The direct land use was determined using spatial data given by a geographic information system (GIS). Direct hinterland use was determined by establishing a material and energy inventory and applying an ecological footprint (EF) calculation using the software Simapro and the therein implemented database ecoinvent on this inventory. The same material and energy inventory and Simapro were also used to first determine the life-cyle GHG emissions of providing the materials (*embodied CO_2 hinterland use*) and the energy for operation (*operational energy CO_2 hinterland use*), and second to calculate the land use to sequestrate these GHG emissions. The total EF was determined by combining all four land use categories, thus summarizing the direct land use expressed as hectares (ha) and the direct hinterland use and CO_2 hinterland uses expressed in global hectares per year (gha/a) for the period of one year (2012). In EF calculations on a life-cycle basis, the expression of direct land use in ha/a is required to establish a harmonized unit system to indirect land uses expressed as gha/a. To consider the different transport capacities and performances of the modes of transport, all results were finally normalized per seat kilometer provided (SKP) and person kilometer travelled (PKT). Fig. 2 summarizes the methodology, whereas the subsequent subsections (2.2–2.7) describe in detail the methods and materials to determine each land use type.

2.2. Calculation of 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 GIS data provided by the city of Vienna (Federal Chancellery and Vienna City Administration, 2016) 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. For areas not included in the GIS data sets (e.g. bus and tram stops), data provided by Wiener Linien were manually added.

The Municipal Department 28 – Road Management and Construction (MA 28, 2016) holds data on the local road network (*Straßeninformationssystem* SIS) in Vienna. In this GIS dataset the tram network is included (MA 28, 2016). Only objects above ground level are included in this dataset. The GIS data on area used for buildings (e.g. train depots, engineering rooms, social rooms, and other services) was retrieved from the operator. Even though no such GIS data was

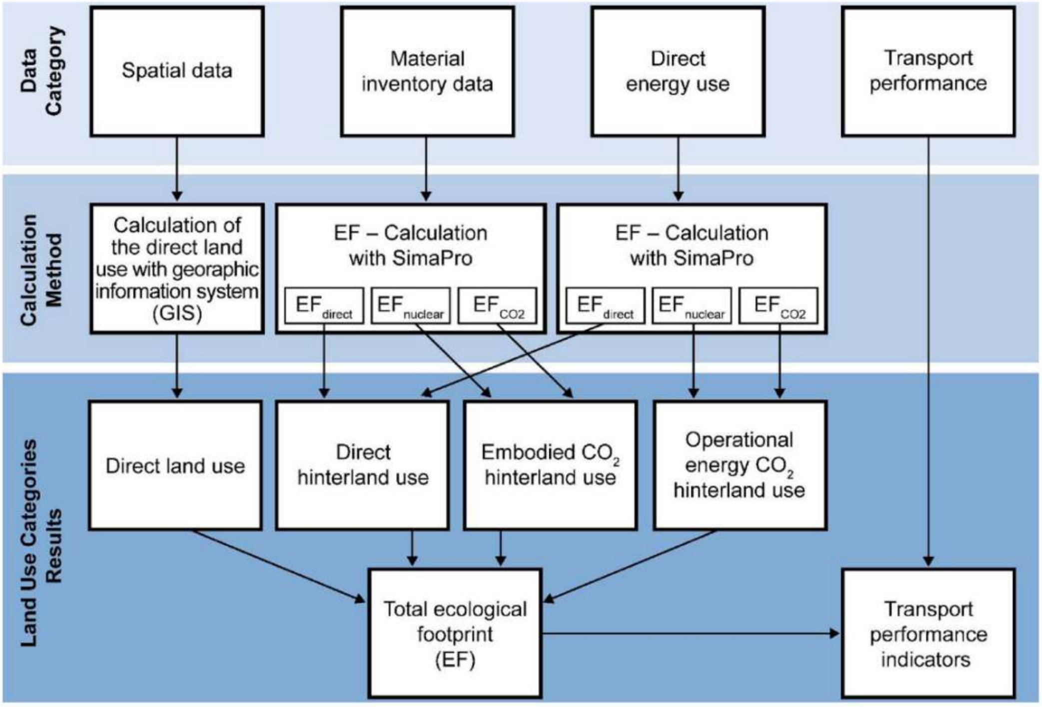


Fig. 2. Data categories, calculation method and resulting land use categories.

available for tram stops, as they are located on public rather than the operator's property, the operator holds a separate data inventory for these areas to calculate expenses for the winter service. The relevant data was provided by the operator. For the calculation of land use, each stop was counted once, even though different bus and tram lines may be used at the same stops. Different vehicle lengths and thereto resulting stop sizes were considered. In Table S1 from the supplementary material, the stop categories, numbers, specific sizes and total area which accounted for direct land use are summarized.

The direct land use for the subway was determined using GIS datasets provided by the operator. The basic data set includes all civil engineering constructive works (such as tunnels, bridges, elevated track sections). Ground-level sections were added manually. A dataset with other subway buildings (such as subway stations, depots, other services) were added to the file. As for the direct land use, only above-ground level sections were considered, and all objects were manually divided into the two categories above and below the ground level.

The area for the bus network was determined by using vector data for the bus lines from Wiener Linien (Wiener Linien GmbH & Co KG, 2015a). Transversal to the vector of the bus lines, a buffer 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 buffer was chosen at 3.5 m for sections in one direction and 6.5 m for sections used in both directions (MA 18, 2011). Additionally, the operator's dataset for buildings (e.g. bus depots, social rooms, and other services) was used and account for the direct land use demanded by public transport via bus. The area for bus stops was calculated using the same data set (information necessary for the winter services) and approach as for trams.

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 respective data source for evaluating their area was the GIS dataset from Wiener Linien which includes all buildings.

2.3. Calculation of direct hinterland use

In order to assess direct hinterland use, first the quantity and composition of materials (including goods) consumed was determined. Therefore, data provided by the operator were categorized and a material inventory (see Section 2.3.1) 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.

To include the preceding chain of materials used, data from the ecoinvent database is used for the calculation. The database includes not only all preceding chains of materials and energy for manufacturing these materials, but also the associated land uses (Hischier et al., 2010). Not included in the method is the normalization with respect to the land categories, meaning that each impact category is given the weighting factor 1 (Goedkoop et al., 2008). The idea of using six different land-use categories (pasture, arable, forest, water, built-up and energy) applied in several studies (e.g., Global Footprint Network, 2009); (Wackernagel and Rees, 1996) was not considered in the study at hand. 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 (EF_{direct}) and indirect land occupation (EF_{CO2} and $EF_{nuclear}$). The indirect land occupation is related to nuclear energy use ($EF_{nuclear}$) 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 (see section 2.3). 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 (cf. Fig. 2).

2.3.1. Structure of the inventory data utilized

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
vi energy and fuels

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. For this reason, not one but a set of formulae were used, as presented in subsequent paragraphs. In general, the formulae applied have in common that some 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 from the Wiener Linien 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. An overview of the inventory and its structure is presented in Fig. 3, it contains the main inventory assets of each category but it is not a complete list. 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.

2.3.2. Buildings

For all buildings considered, in total an area of about 1 million square meters was in use in 2012. The different buildings were allocated, where possible, to the transport modes. Otherwise they were allocated to services. The following building categories were identified: subway construction, tram lines, storage buildings and administration buildings. Subway construction includes 104 metro stations, the storage buildings include depots for busses (3), subway trains (4) and trams (10) as well as a garage for repair and maintenance works (Wiener Linien GmbH & Co KG, 2015b).

In general, two types of buildings were distinguished: storage and administration buildings. For calculating their material stock the following formula was used:

$$M_i = \sum_{s=1}^{k} m_{i,s} \times A_s \tag{1}$$

where M_i is the mass of material i in tonnes [t], m_i is the material intensity of material i for building type s in tonnes per square meter [t/m^2], A_s is the effective area of each building type s in square meters [m^2], and k is the number of building types [dimensionless]. For the material intensities of buildings, data from Hoffmann et al. (2011) and Kellenberger et al. (2007) were combined, harmonized and converted from tonnes per gross building volume to tonnes per square meter, presented in detail in Table S2 in the supplementary material. The energy used for the construction of the buildings was taken from Kellenberger et al. (2007).

The types and quantities of materials used for subway construction depend on the construction method applied. Lederer et al. (2016a) quantified the built-in materials of the Viennese subway network in detail using the following approach:

$$M_i = \sum_{s=1}^{k} m_{i,s} \times l_s \tag{2}$$

where M_i is the material mass of material i in tonnes [t], $m_{i,s}$ is the intensity of material i for construction method s in tonnes per meter of length [t/m], l_s is the section length of the construction method s in meters [m], and k is the number of construction methods in the subway network [dimensionless] (Lederer et al., 2016a). All data used for the calculation of the material inventory of the subway are based on information provided by Lederer et al. (2016a). The material intensity of tram tracks is based on primary data from the operator and was calculated on the basis of the single-track standard cross-section (Wiener Linien GmbH & Co KG, 2012a), (supplementary material cf. Table S3). In particular the average material intensities were multiplied by the track lengths as shown in Eq. (2) in order to determine the associated material stocks.

2.3.3. Mobile and immobile assets

The database with respect to the assets in use was provided by the financial accounting department of the public transport provider. The allocation of each asset to a specific cost category allowed them to be assigned to the mode of transport (subway, tram, bus or services). In total there were about 36,500 assets in use by Wiener Linien. Excluded were non-physical assets, for instance cash, patents or servitudes. Physical assets were also not taken into account if their economic useful life had been expended. This allowed around 14,000 assets to be disregarded. As the remaining number was still far beyond a manageable figure, similar assets were bundled into categories, for which subsequent compositional data were assigned.

Thereto in a first step, all similar assets were counted and an ABC analysis was performed. All assets of which less than 100 pieces were in use or whose mass was estimated to be less than 1 kg per piece were not taken into consideration. About 4000 assets could be discarded through this constraint. In total 18,000 assets were finally merged to 162 different categories, which have subsequently been evaluated for their composition using literature data, own calculations or expert interviews. Not included in this number are buildings and the rolling stock. A summary of the 162 categories and their assumed material intensities are given in Table S11 and Table S12 in the supplementary material.

2.3.4. Rolling stock

The mass of each material in the rolling stock was calculated using the following formula:

$$M_i = \sum_{s=1}^{k} m_{i,s} \times m_s \tag{3}$$

where M_i is the material mass of material i in tonnes [t], $m_{i,s}$ is the intensity of material i for rolling stock type s in tonnes per ton of rolling stock weight [t/t], m_s is the total mass per rolling stock type s in tonnes [t], and k is the number of rolling stock types [dimensionless].

In general, three main categories of rolling stock types, namely subway trains, tramcars, and busses, have been distinguished. Each of them, however, is further subdivided into different types of vehicles. The total number of 700 subway trains, for instance, divides into three

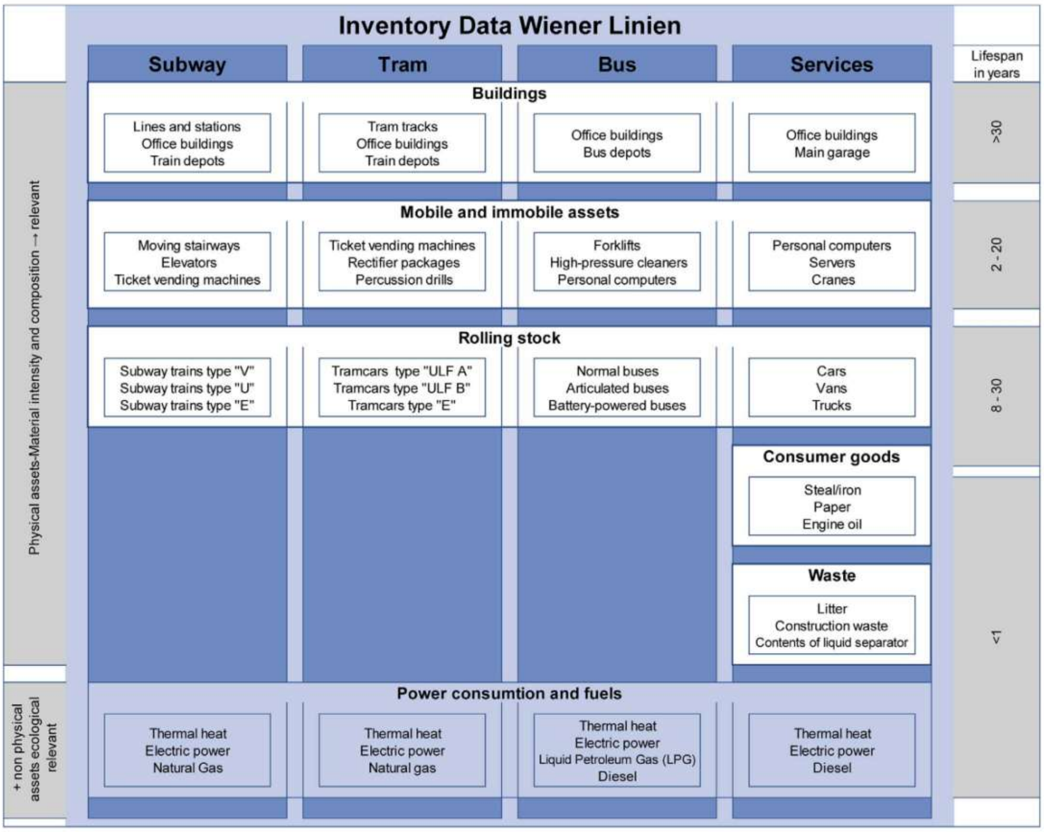


Fig. 3. Inventory categories of the public transport provider Wiener Linien (incl. respective lifespans).

types (types V, U, and T) (Wiener Linien GmbH & Co KG, 2012b). The total mass m_s of each type was 168 t for type V, 157 t for type U, and 138 t for type T (Bomardier et al., n.d.; Siemens AG, 1998; Wiener Stadtwerke Verkehrsbetriebe, 1985). Due to lack of data for the material intensities $m_{i,s}$ for the train types U and T, the material intensity based on composition data provided by Struckl, (2007) was used (cf. supplementary material: Table S5).

Eq. (4) also applies to the 525 tramcars that divide into three types (A, B, and E). Types A and B are relatively new ultra-low floor trams (Ultra Low Floor are therefore called “ULF”), while E is an older type that was constructed until 1990 (Wiener Linien GmbH & Co KG, 2013). The total mass m_s was: Type A 30 t (Siemens AG, 2004a), Type B 43 t (Siemens AG, 2004b) and Type E, including one trailer vehicle around 36 t (Wiener Stadtwerke Verkehrsbetriebe, 1984). Detailed information can be found in Gonzalez, (2016). The corresponding material intensities $m_{i,s}$ were taken from (Type A and B) Pamminger and Adamek, (2010) and (Type E) from ecoinvent (Spielmann et al., 2007) (cf. supplementary material: Table S5).

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) (Wiener Linien GmbH & Co KG, 2013). Their material intensities $m_{i,s}$ and total masses m_s were taken from Gassner, (2013) and Siemens AG, (2012).

2.3.5. Consumer goods

The purchasing department provided data on low-value assets and consumer goods. Due to the fact that not all purchases are linked to a cost center, all consumer materials in this paper are counted as services. For all goods which are stored in the company’s warehouse, the mass of the goods is known. Accordingly, the mass and material is known for the majority of the consumer goods and can be used to establish the material inventory necessary for the analysis intended.

In view of the large number of goods and materials, a selection and categorization was necessary in analogy to the assets. First, all similar goods were counted and duplicates removed so that around 46,000 various articles remained. Second, only relevant articles were chosen. For instance, all non-material goods were sorted out. Third, 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. Another important material category was paper (tickets, reprographic paper, etc.). Therefore, each good was assigned to a consumer goods category. This classification was taken for the inventory. Transport of the goods was not taken into account for the emissions. In categories for which the allocation to a single main material was not reasonable, average material composition from the literature data was used for the determination. 64 consumer good categories were identified. A summary of the identified materials and goods categories, allocated ecoinvent processes and amounts from 2012 is given in Table S9 in the supplementary material.

2.3.6. Waste, energy and fuels

The annual amounts of waste arising were grouped by the type of waste. 63 different types of waste were generated by Wiener Linien in the year 2012. A summary of waste types, allocated ecoinvent processes and amounts from 2012 is given in Table S10 in the supplementary material.

Furthermore, the annual consumption of energy (electric power and heat energy) and fuels were considered using data provided by the operator. A distinction between energy used for traction and general energy use was made. A summary of the energy consumption data from the operator is given in Table S6 in the supplementary material (Keuschnig, 2013; Rumpeltes and Reeps, 2013).

2.4. Calculation of embodied CO_2 hinterland use

By using the material inventory established as described in Section 2.3 and the software Simapro (version: 7.2.3), the hinterland required to sequestrate the CO_2 generated during the production and provision of the materials consumed was calculated, representing the respective EF (Hischier et al., 2010). As described in detail in section 2.2, the method implemented distinguishes between three different environmental impact categories associated with land use, which are direct land occupation and indirect land occupation, related to nuclear energy use and to CO_2 emissions (Hischier et al., 2010). The total embodied CO_2 hinterland use represents the calculated indirect land occupation from materials (and goods) used. Furthermore, no distinction is made between indirect hinterland use for nuclear energy and CO_2 emissions since the share of the former is fairly small in the Austrian energy mix (E-Control, 2016).

2.5. Calculation of the operational energy CO_2 hinterland use

To assess the operational energy CO_2 hinterland use, energy consumption data were used. The respective data comprises the electricity for the subway and tram operations, fuel for busses, heat for the subway stations and electricity for buildings and services (Table S6 in the supplementary material, Keuschnig, (2013) and Rumpeltes and Reeps, (2013)). 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, 2013a). 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 per time [gha/a].

2.6. Calculation of the total area – ecological footprint

The ecological footprint (EF) was calculated by summing up the different land uses calculated as described in Sections 2.1–2.5. The EF was calculated for the period of one year. The direct land use within the city forms the basis. To be comparable, the hinterlands also have to be calculated for the period of one year. Due to the fact that the inventory incorporates materials and goods which are used in different time scales for some categories, a normalization is mandatory.

Not necessary was a normalization for the inventory categories of power consumption and fuels, consumer goods and waste since these categories already consider the annual consumption of goods and energy. However, a normalization was made in categories where materials and goods were used over a longer period than one year. This is the case for the inventory categories: buildings, rolling stock, and mobile and immobile assets, for which the economic life span was used. 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. The respective life span data was taken from the financial accounts department of the operator and is shown per asset category in Table S13 in supplementary material.

2.7. Transport capacity and performance indicators

Finally, to compare the results with other transport systems and literature findings, the results were normalized not only to one year (see section 2.6), but also to the passenger kilometer traveled (PKT), meaning that the total land use per year (tA) was divided by the amount of kilometers traveled by all passengers of the public transport system (Eq. (4)).

$$tA_{specific,PKT} = \frac{tA}{PKT} \tag{4}$$

Information about the PKT was obtained from the Austrian Institute for Regional Studies and Spatial Planning, who quantified the total urban transport performance in Vienna from 1970 to 2013 (Österreichisches Institut für Raumplanung (ÖIR), 2014) (cf. supplementary material: Table S7).

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), as shown in Equation (5). The respective data for this calculation are taken again from ÖIR, which quantified the total seat-kilometer provided by Wiener Linien in 2012, (Österreichisches Institut für Raumplanung (ÖIR), 2013) (cf. supplementary material: Table S8).

$$tA_{specific,SKP} = \frac{tA}{SKP} \tag{5}$$

To compare how efficient the area is used by various transport modes, the direct land consumption within the city is related to the transport performance (see Eq. (6)):

$$AE_i i = \frac{TP_i}{A_i} \tag{6}$$

where AE_i is the area efficiency in million PKT or SKP per hectare for transport mode i, TP_i is the transport performance per year in million PKT or SKP for transport mode i, and A is the area used by the transport mode i in hectare.

3. Results

With 39% of the modal split in 2012, public transport is the most important mode of transport in Vienna (Wiener Stadtwerke Holding AG, 2013b). 85% of the passenger kilometers traveled (PKT) by public transport was provided by WIENER LINIEN GmbH & Co KG (Österreichisches Institut für Raumplanung (ÖIR), 2014) who operates a network of 5 subway lines, 29 tram lines, and 109 bus lines, of 79 km, 172 km and 700 km length, respectively (Wiener Linien GmbH & Co KG, 2016). The remaining 15% are provided by private and public bus operators, as well as the Austrian national rail operator *Österreichische Bundesbahnen* (ÖBB) who operates a number of suburban rail way lines linking the city to its hinterland.

3.1. Different land uses

The total area used in Vienna by infrastructure from Wiener Linien is 621 ha. As presented in Figure 1 in the supplementary material, the network is spread over the entire urban area. Around 80% of the directly land use relates to the network (cf. Fig. 4). Stations need 6% and

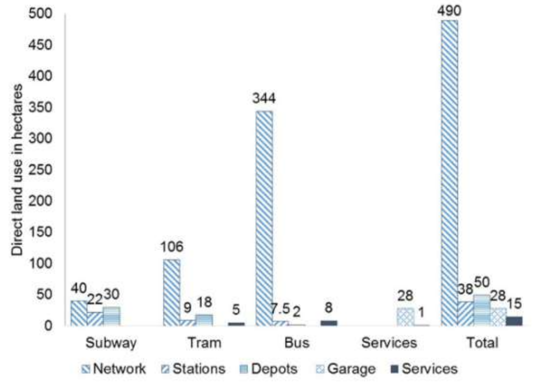


Fig. 4. Direct land use divided by transport mode and use category (network, stations, depot and garage, services).

Depots 8% of the area for direct land use, while 5% are needed for the service of the rolling stock at the main garage. 55% of the subway is below ground and thus not accounted for, while the above surface sections require 15% of the total area. Approximately 22% of the area is used by the transport mode tram. Due to the longest network, the transport mode bus occupied, with 58%, the largest area of all transport modes.

The direct hinterland to produce materials for built-up infrastructure and consumed goods as well as energy is 1,660 gha/a, which is 2.7 times the direct land use. As shown in Fig. 5, the inventory category power is, with 442 gha/a, responsible for nearly 60% of direct hinterland demand, followed by buildings (27%) and consumer goods (12%). Regarding transport modes, 59% of direct hinterland use is caused by material and energy use of the subway, followed by the tram (18%). For both transport modes, power and buildings are the most relevant categories.

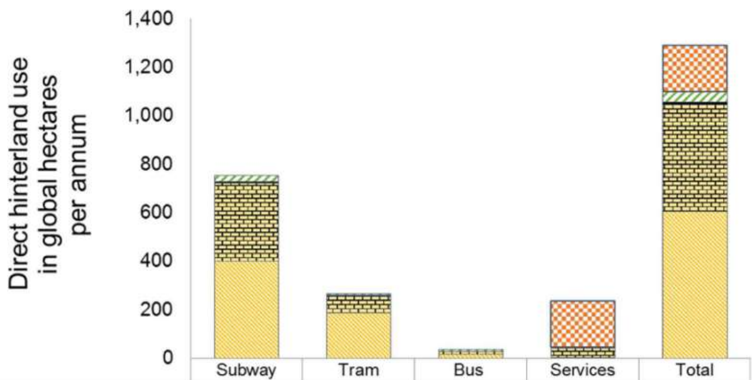
The production of materials and goods required by Wiener Linien causes GHG emissions, i.e. CO_2, mostly from energy generation and material production (e.g. cement). The area to sequestrate these CO_2, named as embodied CO_2 hinterland use, emissions was determined as about 15,000 gha/a (cf. Fig. 6). Therein, the inventory category buildings was the most relevant (65%), as it includes the materials for subway tunnels and tram tracks, which are the construction elements responsible for the highest material input within the two transport modes. The second largest hinterland use in this section is caused by the inventory category consumer goods, with 15%. This category was counted under services as it was not possible to assign it to the three transport modes.

To compensate the CO_2-emissions caused by the direct annual energy use of Wiener Linen, an area of around 55,000 gha/a (operational energy CO_2 hinterland use) is required. In terms of transport modes subway (50%) shows the highest contribution followed by bus (24%) and tram (18%) (cf. Fig. 7). The total land use is mainly caused by energy used for traction (75%), and the remaining quarter is mainly caused by energy for heating and power (for both light and power current). The results for the transport modes subway and tram are dominated by electric power mainly for the operation of the trains, and the one for bus by its fuel consumption. In total, electric power is responsible for around 70% of the overall area use under this category of land use.

3.2. Total area – ecological footprint

The sum of all four areas, namely the EF of Wiener Linien is around 72,500 gha/a in the respective year of reference. To set the different land uses into perspective, all four areas are presented on the map of Austria in Fig. 8. In this map, the inner green circle represents the direct land use, while the hinterlands (direct, embodied CO_2, and operational energy CO_2) are presented as an annulus, so their area is not overlapping. As result, the outermost circle marks the overall area required. If split up by transport mode (cf. Fig. 9), the subway shows the largest EF (51%), followed by busses (20%), trams (19%), and services (10%).

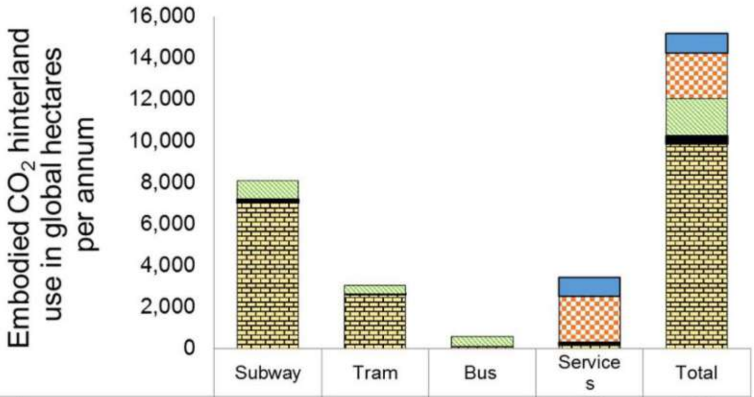
The results indicate that the subway shows the largest EF of all transport modes. However, when looking at the EF per performance unit, this ranking of the transport modes changes (cf. Fig. 10). Due to the high transport performance of the subway and tram, both perform better than the bus. The transport mode bus needs around 1.7 times the area per PKT and 2.5 times the area per SKP compared to the subway



	Subway	Tram	Bus	Services	Total
Waste				2	2
Consumer Goods				191	191
Rolling Stock	27	6	8	0	42
Mobile and immobile assets	5	2	0	4	11
Buildings	323	70	9	40	442
Power	399	187	17	1	603

Power Buildings Mobile and immobile assets Rolling Stock Consumer Goods Waste

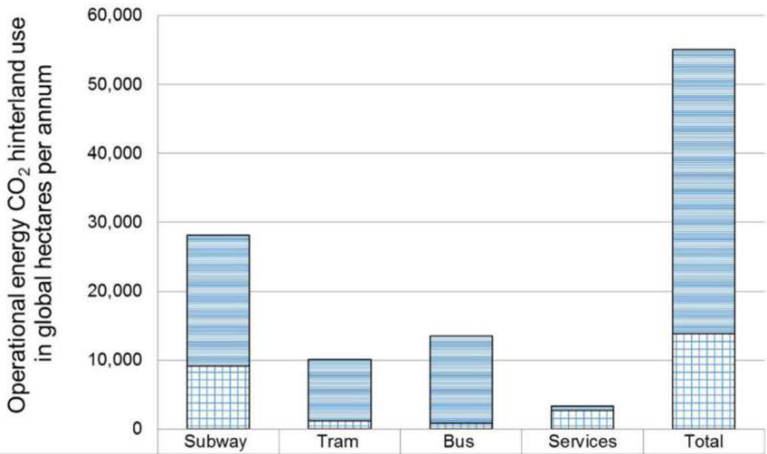
Fig. 5. Direct hinterland use divided by transport mode and inventory category (power, buildings, mobile and immobile assets, rolling stock, consumer goods and waste).



	Subway	Tram	Bus	Services	Total
Waste				920	920
Consumer Goods				2,200	2,200
Rolling Stock	870	400	490	20	1,780
Mobile and immobile assets	190	60	10	150	410
Buildings	7,020	2,590	90	150	9,850

Buildings ■ Mobile and immobile assets Rolling Stock Consumer Goods Waste

Fig. 6. Embodied CO_2 hinterland use divided by transport mode and inventory category (buildings, mobile and immobile assets, rolling stock, consumer goods and waste).



	Subway	Tram	Bus	Services	Total
Energy for traction	19,010	8,910	12,630	630	41,180
General energy consumption	9,140	1,180	840	2,720	13,880

Fig. 7. Operational energy CO_2 hinterland use divided by transport mode.

With regard to the area efficiency of the public transport provider Wiener Linien, defined as PKT per ha of direct land use within the city, the results indicate an average efficiency of around 5.4 million PKT/ha. The subway is the most efficient transport mode, followed by tram and bus. The subway shows with 23.2 million PKT/ha an almost 18 times higher area efficiency than the bus (1.3 million PKT/ha), whereas the area efficiency of the tram (5.5 million PKT/ha) corresponds to the Wiener Linien average.

4. Discussion

In this paper a new approach for the analysis of land use of urban transport systems was presented. The data inventory and categorization presented was used to examine a complex public transport system with scalable results.

4.1. Contribution of each transport mode and services to the result

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. 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) not only underlines the relevance of the study at hand, but also calls for a deeper look at the contribution of the different transport modes and services to the results.

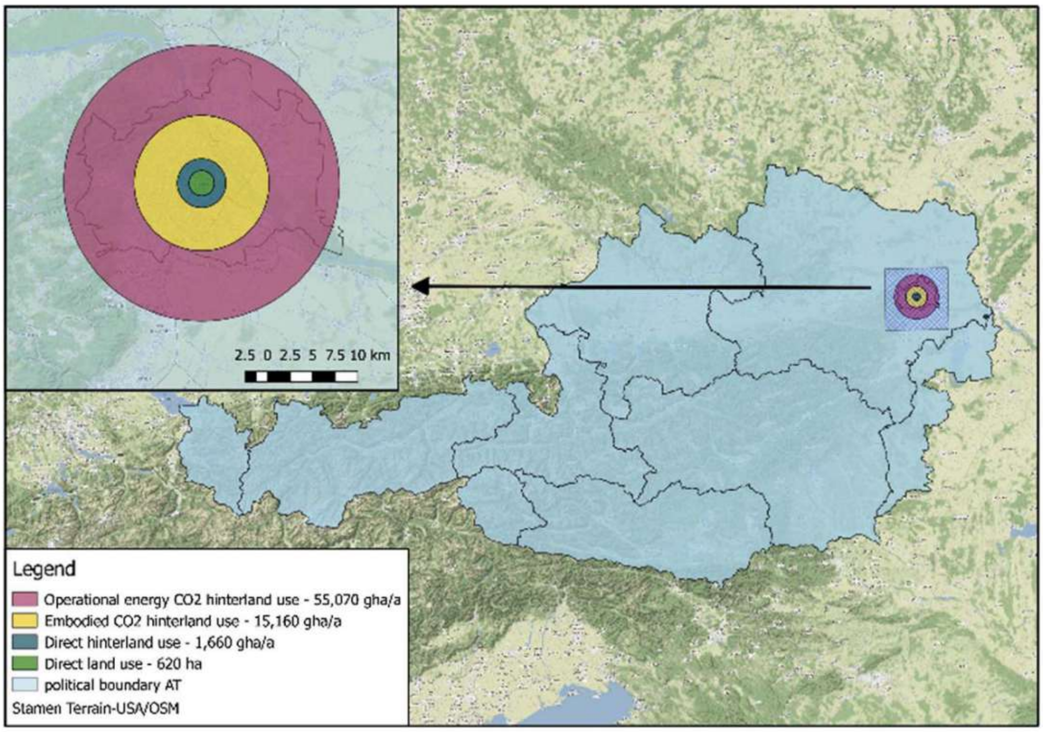


Fig. 8. EF divided by land category and referred to the overall area of the city of Vienna.

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 other authors (e.g., Anderson et al., 2015; Chester et al., 2010; Chester and Horvath, 2009). 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, cannot be easily answered, as the three transport modes are complementary interlinked to each other in a network of main transport axes along densely populated areas (subways, and to a lesser extend trams) and a small boned network of tram and bus lines in less densely populated areas connected to the main axes. When it comes to the

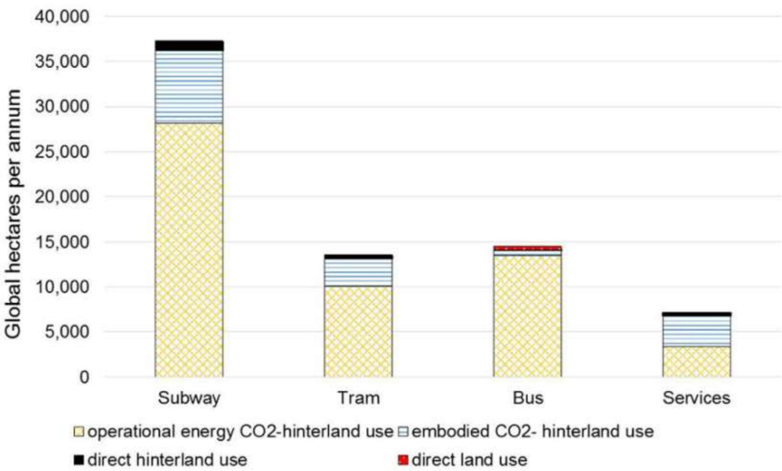
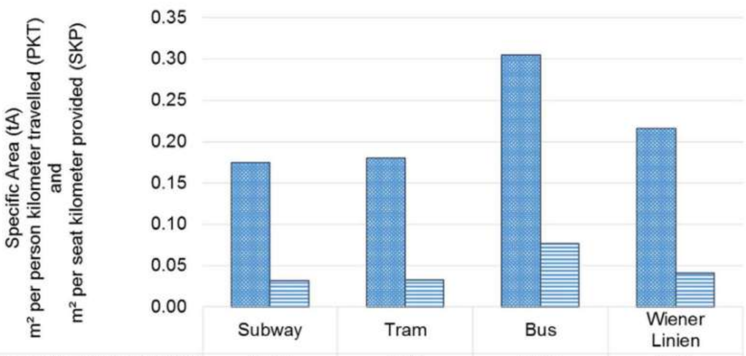


Fig. 9. EF divided by transport mode and land use category.



	Subway	Tram	Bus	Wiener Linien
tA specific, PKT [m²/PKT]	0.17	0.18	0.31	0.22
tA specific, SKP [m²/SKP]	0.03	0.03	0.08	0.04

Fig. 10. Ecological Footprint in square meters per PKT and SKP.

decision whether a main axe in the network should be served by either subway or tram, however, the EF can be used as an add-on to economic and capacity decision tools. Furthermore, considering and distinguishing between all modes of transport covered by an urban public transport provider, as well as taking into consideration the services required to provide that respective mode is helpful for the provider as the results can be integrated in the company's environmental management system (Erdas et al., 2015).

4.2. Classification of land use types and EF components

While the first unique aspect of the study has to do with considering and distinguishing between different transport modes and services, the second unique feature of the study at hand is the classification of land uses. This is important for at least two reasons.

First, as Zeev et al. (2014) have concluded, not every land use has the same relevance for every stakeholder. Stakeholders like local politicians and authorities or urban planners working on the ground may face the challenge of dealing with scarce space in the city more often than they deal with global land use for CO_2 sequestration, while decision makers or NGOs on a national or even international level may be more interested in the latter. 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. Thus, concealing the results behind one single figure might not be a problem for stakeholders at higher levels more interested in, for example, CO_2 sequestration hinterland use for the simple reason that this type of land use dominates the overall results of the EF. However, particularly for stakeholders at lower levels, a clear differentiation is much more important for their tasks of urban planning at local level.

Second, EF is a well-established method used at different levels, from companies or cities, products or services to countries or even the whole world (Borucke et al., 2013; Bruckner et al., 2015; European Commission, 2012; Global Footprint Network, 2016; McDonald and Patterson, 2004; Schanes et al., 2016). Nevertheless, different approaches exist, with some considering CO_2 sequestration exclusively since it often dominates the results (i.e. carbon footprint), while others focus on environmental footprint on a life-cycle basis (Kitzes et al., 2009; Wackernagel et al., 2004; Wiedmann and Barrett, 2010). The strength of the distinction between the different components of the EF as performed in the study at hand is clearly that the results can be compared to and embedded within other studies, no matter which approach they used for the calculation of the EF.

4.3. Area efficiency

As previously mentioned, stakeholders at local level might be more interested in direct land use even though it contributes little to the total EF. An indicator introduced in the study at hand that is derived from this type of land use under the EF concept is the area efficiency of transport systems. The results for the calculation of this indicator show that the subway is the most efficient transport mode, which is due to its high transport performance and the fact that significant parts of the network are below ground. This comparatively high area efficiency is also one of the main reasons why cities and urban transport providers opt for subways over trams, light rails, busses or suburban railways, even though the construction costs of the prior are much higher. However, what is not taken into account in this indicator is the fact that subways consume space – albeit underground. While very often this space is not considered as consumption at all, some cities already face the problem of underground space scarcity, mainly due to the growth and extension of underground network infrastructure (e.g. water supply, sewerage, gas, electricity, ICT, waste collection) (Admiraal and Cornaro, 2016). For this reason, it might be interesting to consider not only surface area efficiency, but also underground space efficiency, if not so much for environmental, but for urban infrastructure planning reasons.

4.4. Reduction potentials of the EF

An environmentally conscious transport provider confronted with the results of this study will likely be keen to know how to reduce the EF of the public transport system under investigation.

One measure would be a reduction in the transport distances per person and day, which would lead to a reduced service (in terms of frequency) and thus a reduced consumption of land use caused by the traction energy demand, assuming only the existing system is considered. Subsequently, it might even be possible that when planning transport networks in the future, less land consuming (on a total basis) modes like trams and busses would be favored over subways. However, this is neither in the hands of the public transport provider, nor in his interest. In striving to meet the demand of a growing city like Vienna while keeping in mind the limitations of more land-consuming transport alternatives (i.e. private car transport), it is likely, and from an EF point of view also desirable, that the total direct land use of the public transport system will increase. For this and other reasons (e.g. the large contribution to the total EF), a significant decrease in the EF of the current public transport system in Vienna can only be reached by reducing the hinterland EF, which is dominated by the operational energy CO_2 hinterland. Three potential measures to do so which were also the city, and no further increase in transport demand could be expected, the tram would have been the better solution in terms of environmental efficiency.

The indicator, however, only takes into account the land use and therefore can only be an add-on to economic and social decision criteria for future network extensions. If this is desired by decision makers, public transport operators, and the public, the presented indicator offers straight forward results which can be easily interpreted by various stakeholders.

4.7. Limitations

The study at hand provides a detailed environmental assessment of a well-established public transport network in terms of land use. However, as an urban public transport system is a complex system, there are limitations and uncertainties which must be discussed.

Firstly, although the presented material inventory has a high level of detail, infrastructure and applicants were clustered in joint categories. As a result of the clustering, uncertainties and simplifications naturally occur. Secondly, the paper investigates the activities of one specific public transport provider. There are both, advantages and disadvantages associated with this focus. Advantages are that the results can used as indicator within the company, which has, considering the relevance of a provider like Wiener Linien, also relevance for the city government and administration to improve the environmental performance of the public transport system. Also the used inventory data were uniform in structure and consistent for all three transport modes, which improved the results and their comparability. However, due to the reason that it is one provider with three modes of traffic not all categories of the inventory could be counted to only one of the three transport modes (e.g. administration). Therefore the category services was introduced. The category services was allocated to the transport modes to calculate the specific land use per transport mode. Thirdly, as system boundaries were limited to assets in the hand or mainly used by the provider Wiener Linien, multi-use inventory categories like roads for the transport mode bus were not included in this study. This fact reduces the comparability to other LCA studies which investigates urban bus transport. Finally, as in every environmental assessment there are uncertainties in the results. Especially the calculation of the global hinterland is based on data from databases and therefore represents an approximation to real environmental impacts. However, the whole complex of supply chains cannot truly be captured by even the most sophisticated outcome model.

5. Conclusions and future research

Based on the results of the study, it can be concluded, that the land use of a public transport provider is dominated by the operational energy CO_2 hinterland use, followed by the embodied CO_2 energy hinterland use, the direct hinterland use and the direct land use within the city. When the land required for the sequestration of CO_2 emissions is included in the investigation of land use, a significant decrease in land use can only be reached by reducing the EF in the global hinterland. The main objective of this paper was to provide a multi-dimensional analysis of land consumption of an urban public transport system and distinguish between local and global land use. With the chosen approach, a detailed investigation was performed and the three transport modes were compared within the introduced land use categories under consideration of the transport performance. The introduced land use categories are suitable for a public transport provider and provide useful information for various stakeholders. The presented study has some limitations because the study focuses on one transport provider. Therefore, real inventory data was investigated in detail, allowing future generations of researchers to include these data in a study with a broader scope that also includes other transport providers in Vienna. Another field of future research is the extension of the study to other modes of transport, especially private motor vehicle transport. A number of studies have analyzed the life cycle impacts of private transport, but there are no studies known to the authors that investigated the land use for both systems private transport and public transport for one region, especially not on the base of real inventory data. The comparison of both systems within the same region would be of great interest to compare the impacts of both transport modes. The results of both systems can be used as a basis for a prediction model, to calculate the future land use under consideration of changing technologies (e.g. establishment of electric-driven vehicles). Another open research question is to include specific supply chains within the investigation. It would be important to know, not only how much land is used within the global hinterland, but also were the hinterland is located and how it is connected to specific materials and goods in use. To answer these questions the hybrid UM-LCA framework of Clark and Chester (2016) proved to be a good approach. For all of these future research questions, the study at hand is a necessary foundation to build on.

Acknowledgment

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landusepol.2017.12.012.

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