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An urban emergy footprint: Comparing supply- and use-extended input-output models for the case of Vienna, Austria

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ABSTRACT

Urban activities currently consume 75% of global final energy demand, which is expected to increase given absolute and relative population growth in cities. Assessments of both producer (upstream) and consumer (downstream) ecological and socioeconomic impacts of urban inter-industry exchanges are needed to reduce energy consumption and resource use behind the industrial footprints of cities. Environmental extensions in the input-output analysis are designed from the user side perspective, focusing only on commercial energy supply and use. This study introduced emergy-evaluated supply-extended and use-extended carbon footprint models for Vienna and compared their empirical and conceptual implications. Emergy-evaluated footprints of Vienna's urban consumption were estimated by combining industrial and systems ecology approaches as per the research question, based on previous investigations of GHG emissions and energy supply- and use-extensions. Results showed that the ranking of footprints of final product categories is sensitive to the evaluation method, with products of extractive and manufacturing industries differing by more than 10% depending on whether emergy or carbon evaluation is chosen. The emergy-based comparison further reveals that for products of extractive industries, the difference between use and supply extension results can be more than 20% as opposed to carbon-based comparison with the difference between supply and use extension results for services not even amounting to 5%. Future studies could address the over-estimation of direct energy supply to the economy, under-estimation of product and service, inconsistency in standard use-extension design, and challenges in assembling emergy-evaluated supply and use extensions. Fundings are relevant for unified responsibility assessment of upstream and downstream sectors without prioritising structural features.

1. Introduction

Cities directly and indirectly consume around 75% of the world's final energy and future final energy demand is projected to increase (*World population prospects 2022: Summary of results, 2022*). Clearly, urban social-ecological systems need to be reorganized in a more sustainable manner, to decrease energy consumption as well as the economic-driven growth in resource use and industrial footprints (Bahers and Rosado, 2023). Taking into consideration the ecological and socioeconomic impact arising from exchanges between and within urban sectors, an assessment of industries' impacts on both the producer (upstream) and consumer (downstream) perspectives is needed.

One method widely used for urban sustainability assessments is environmentally extended input-output (EE-IO) analysis (Yetano Roche et al., 2014). EE-IO is often used for consumption-based accounting formed by complementing traditional monetary input-output accounts with physical extensions, representing primary inputs from the environment or direct demand of households. In this manner, it is possible to evaluate the total environmental footprint of final products or final demand categories (Kitzes, 2013).

Outstanding critical issues for EE-IO remain, such as 1) how environmental extensions (supply and use) are actually derived from the underlying data, 2) what principles are used, and 3) what are the implications for interpreting and applying the results (Owen et al., 2017; Schaffartzik et al., 2015). In this literature, two types of principles for building extensions have been identified. Already Costanza and

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Herendeen (1984) identified different outcomes from the use of both supply and use extensions. Many studies since then have applied either supply or use extensions. The majority of researcher used supply-extension design to address diverse unrelated issues such as footprint reduction based on lifestyle choices (Koide et al., 2021), global energy footprint of natural gas (Kan et al., 2019), and supply pattern of energy and water footprints. Another group of authors focused on methodological improvements and investigation of supply-extension designs. Some endogenized human labour inputs into supply-extension design (Rocco and Colombo, 2016a, 2016b). Other researchers disaggregated product footprints to identify multi-regional footprints of final demand and associated categories (Chen and Wu, 2017; Wu and Chen, 2017a, 2017b). The use extensions were applied to issues where supply-extensions were not reliable enough such as ranking of countries based on their level of decoupling of energy consumption (Akizu-Gardoki et al., 2018), identification of technology and consumption drivers inducing Spanish carbon emissions (Cansino et al., 2016), identification of regions and economic sectors behind wastewater footprint in China (Han et al., 2021), separation of regions with dominant consumption-based emissions from regions with dominant production-based emissions in Japan (Hasegawa et al., 2015). Other scientists worked on combined use of use-extended IO model and network science methodology to the study relationship between internal process, use-extended footprint, and the condition of the metabolic systems. Some scientists developed network models to analyse relations and systemic activities of economic sectors contributing to the use-extended footprint such as Guangdong carbon network model (Li et al., 2018), energy, water, and carbon models of China (Xu et al., 2021), Beijing's energy network model (Zhang et al., 2014a) and study contribution of regions and economic sectors to stability and sustainability (robustness) of China's national metabolic system (Zheng et al., 2021a). Recently, studies directly compared supply and use extensions (Owen et al., 2017) and scrutinized the underlying methodological choices (Schaffartzik et al., 2015), usually at national to international scales.

The analysis of urban energy and carbon flows as embedded into globalized networks of production and consumption has gained increasing attention in recent years, (Fry et al., 2021; Wiedmann et al., 2020; Jin et al., 2021). Some studies analysed city-scale energy footprints with use-extensions (Zhang et al., 2014b; Zheng et al., 2016, 2019; Zhai et al., 2019).

Another important issue is that existing energy analysis and derived supply- and use-extensions are usually confined to standard definitions on technical energy use and do not include anything preceding the extraction phase of the energy carriers (e.g., mining of coal) (Bullard and Herendeen, 1975a; Bullard and Herendeen, 1975b; Heun et al., 2018). The boundary and temporal limits of use- and supply-extensions employed across most studies do not include direct solar energy inputs into ecosystems and indirect solar energy embodied in ecosystem processes and socio-economic activities to produce products or services.

Emergy is an accounting approach that records direct and indirect solar energy used up across all transformations over time, which were involved to make an ecological product or human service. This method was invented by Odum (1971) to measure energy quality of natural and anthropogenic inputs (Pincetl et al., 2012; Patterson, 2014). During the 1970s, Odum used fossil fuel and coal equivalent as numeraire before adopting solar energy equivalent in 1980. It was not until 1983 that 'emergy' and 'transformity' terms started to be used by D. Scienceman and H.T. Odum in order not to confuse them with 'available energy' counterparts (Patterson, 2012).

Cities have been widely studied using emergy synthesis, with Chinese cities being the most widely studied (Amaral et al., 2016). Studies integrated this approach with carbon footprint to extend it to include ecosystem loss of emergy invested by nature, the human society to sustain households, as well as carbon flows resulting from household consumption (Yang et al., 2013; Ali et al., 2018). Other studies used emergy-based ecological footprint (ecological economic footprint) analysis to evaluate sustainable performance of urban social-ecological systems based socio-economic and social ecological pressures on energy (Pan et al., 2019), and water resources (C. Liu et al., 2021), or ecosystems (Zhang and Ma, 2021). Some studies also evaluated the socio-economic (labour force or investments) and ecological causes (biological, energy resource and food consumption) of pollutant emissions (Geng et al., 2014; He et al., 2016; Pan et al., 2019). Therefore, emergy-based ecological footprint approach has been widely used since 2005 to estimate social-ecological footprint of cities (Zhang et al., 2010; Amaral et al., 2016). However, only a single attempt has been made to integrate input-output analysis with emergy synthesis on national scale (USA) (Baral and Bakshi, 2010). In this study, however, footprint of final demand categories has not been estimated. Thus, the study did not encompass the whole supply chain, thereby, not allowing to trace downstream destinations of upstream sources.

Herein, emergy results from supply- and use-extensions for the city of Vienna were estimated based on previous investigations of Vienna's GHG emissions under production- and consumption-based perspectives (Schmid, 2020). Thus, the research question is formulated as follows: How to determine emergy costs of urban consumption, by combining industrial and systems ecology approaches? The answer to this overarching question requires the following sub-questions to be addressed: 1) How to develop supply-extended and use-extended emergy footprint models? 2) How to compare these model results with carbon footprint results using Vienna as case study?

To address this problem, social-ecological footprint framework integrating environmentally extended IOA and the emergy accounting approach is proposed. The rest of the article is organized as follows: Section 2 explains the methods and data used in this study. Section 3 discusses the results of this work. Finally, the article concludes in Section 4 and discusses important implications, limitations, and future recommendations based on this work.

2. Methods and data

The method section proceeds with an explanation how the supply and use extensions were derived, before summarizing how the emergy evaluation was conducted. Then, a summary is given how the monetary and physical IO tables and the final demand data for Vienna was developed. Finally, data sources were summarized. Fig. 1 illustrates the development of emergy-based carbon footprint model which we used to guide our research.

2.1. Derivation of supply and use extensions

The downscaled vector of total sectoral energy supply and use as supply-extension was used. The downscaled energy supply table contained information on natural inputs, wastes, and imports to source sectors. Information on the methodology used to downscale physical energy flow accounts can be found in Section 2.3.4. To construct the supply extension, several steps were necessary. Firstly, direct primary and secondary energy use were allocated to end-users (e.g., gasoline to households), government, investments, and exports. This corresponds to the own consumption of energy industries (Ue), final energy use and non-energy use of industrial sectors (u_{in}), transformation and transportation losses (L) as well as direct energy use of households (F_h). Then, transportation losses were also allocated to each energy consumers among 16 NACE sectors and final demand categories (i.e., households, exports) (Owen et al., 2017).

This method of allocation of transformation losses to final consumers was chosen because the allocation could be performed in just two steps (Owen et al., 2017; Wieland et al., 2019). Namely, Owen employed two-step allocation procedure, in which transformation losses were allocated directly to the consumption industries along the supply chain. This approach resulted in the removal of second order energy

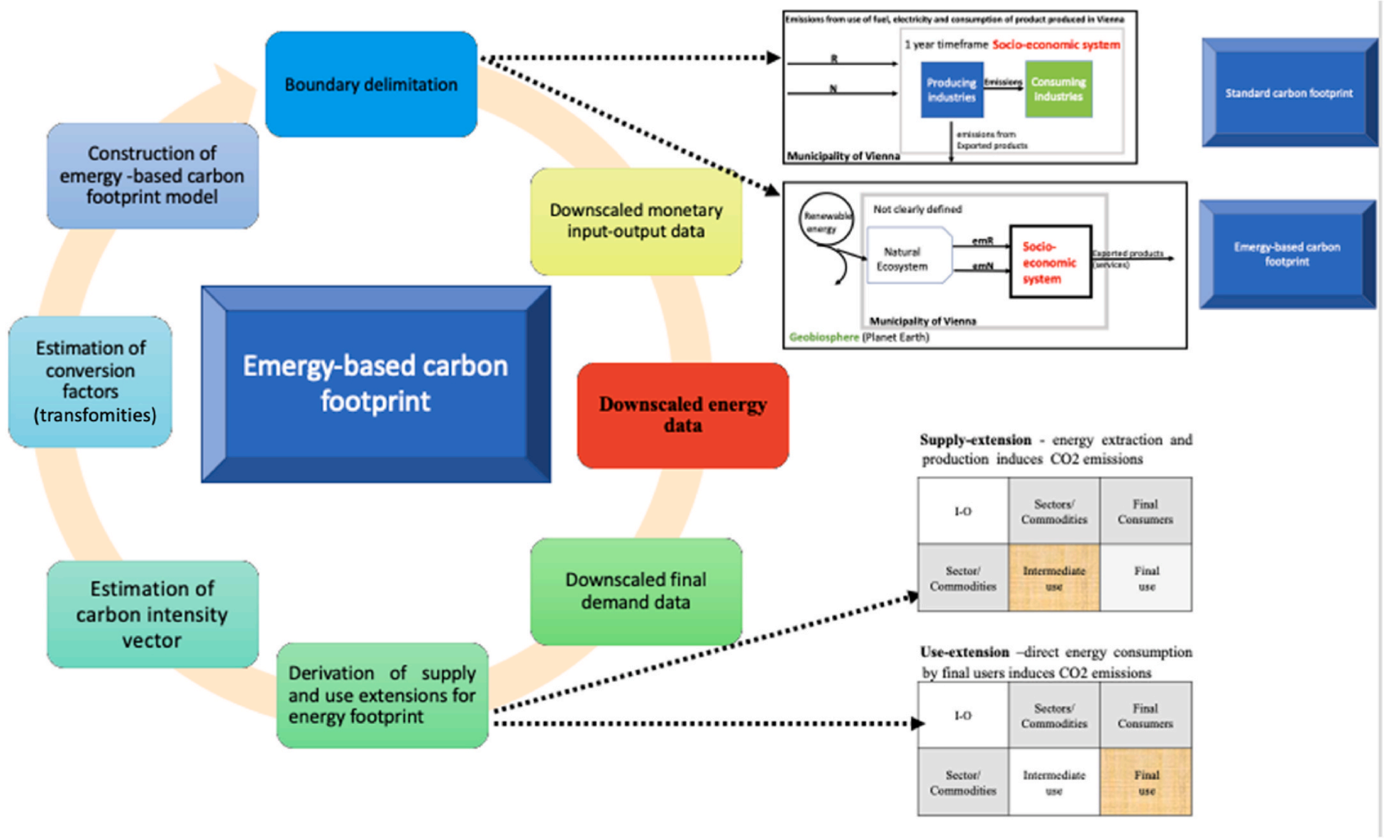

Fig. 1. The development of emergy-based carbon footprint framework. R and N represent renewable and non-renewable primary energy inputs, respectively, and emR and emN represent emergy-evaluated primary renewable and non-renewable inputs, respectively.

requirements from the allocation procedure. For example, final energy consumption (final energy and non-energy use) was not allocated to energy consuming industries but used as starting point to build use extension. The same balance between total energy supply and use was reached (both equal gross inland energy consumption). In Wieland's and our study, energy supply and use were balanced using Energy Accounts (EA).

After constructing energy extensions, the energy supply and use extension should be equal to ensure that the energy supply into Viennese economy conforms to the energy used by the economy; see Equation (1) (Wieland et al., 2019):

$$E + P + IM + S_{with} = (u_{in} + F_h + S_{add} + EX + L + O) \quad (1)$$

Where E-local (renewable and non-renewable energy products), P-wastes, IM-imported energy products, EX-exported energy producers, F_h-direct household consumption, S_{add}-addition to stock, L-transportation and transformation losses, O-energy industry own consumption, u_{in}-industries energy and non-energy use.

To estimate the carbon footprints, energy supply and use were converted into g CO_2 equivalents. Then, carbon intensity vector was estimated by dividing a carbon emission vector (C) obtained from Air Emission Accounts (Statistik Austria, 2015) by total energy industrial output in TJ obtained from physical energy flow accounts (Statistik Austria, 2015); see Equation (2).

$$e = C/G \quad (2)$$

where *e*-carbon-intensity vector, *C*- vector of carbon emission by economic activity (NACE classification), and *G*-total energy output by economic activity (NACE classification) in TJ.

This vector was aggregated to align with the total energy output of 16 industrial sectors we had after downscaling was performed.

Then, this carbon-intensity vector was multiplied by energy extension data (Pe) to arrive at carbon-evaluated version of environmental extension (Pc); see Equation (2):

$$P_C = e \times Pe \quad (3)$$

Final energy demand was then converted to CO_2 equivalents using the same formula since Air Emission Accounts contain the data on CO_2 emissions from households by economic activity in NACE format. However, the households' emissions are reported as a single total number. Therefore, the same proportions of carbon emissions to households as for economic activities were assumed. Thus, the biggest uncertainty of the model that affects the results obtained from standard environmental extensions (Owen et al., 2017; Wieland et al., 2019) stems from the use of national carbon intensity vector and from the assumption of equal share of emissions from households as from economic activities. The carbon-evaluated version of environmental extension is presented below; see Equation (4):

$$F_C = e \times F_{use} \quad (4)$$

Using the carbon-evaluated version of environmental extension and fuel use in households allowed authors of this study to estimate carbon footprints using supply and use extension design. Firstly, direct carbon requirements matrix was estimated; see Equation (5):

$$q = Pc \times x^{-1} \quad (5)$$

where q refers to carbon emitted in direct energy consumption (environmental extension) per € of total purchase, Pc represents the carbon-evaluated environmental extension, and x refers to the total monetary industrial output in €**.**

A single region IO model following commodity-by-industry approach (Miller and Blair, 2009) was constructed following approach by Wieland to derive energy supply and use extensions. The only difference was that he constructed this model using Austrian monetary supply-use tables (MSUTs). In this work, on the other hand, Viennese monetary supply-use tables were used. An industry-by-commodity total requirement matrix is presented below; Equation (6):

$$L = D \times (I - BD)-^{1} \tag{6}$$

where D, is the matrix of commodity output proportions, B-the commodity-by-industry coefficient matrix, and $(I-BD)-^{1}$ is commodity-by-commodity total requirements matrix derived from MSUT tables on basic prices (OECD Statistics, 2015a).

BD carries the same meaning as input requirements matrix (A), the matrix of technical coefficients in the traditional industry-by-industry-approach (Miller and Blair, 2009; Wieland et al., 2019). Therefore, matrices of commodity-by-commodity total requirements and industry-by-commodity total requirements are equivalent to the Leontief Inverse $(I-A)-^{1}$. Then, multiplying direct carbon requirements matrix by commodity-by-commodity total requirements $(I-BD)-^{1}$ the supply -extension can be derived; see Equation (7):

$$Q_{is} = q \times D(I - BD)\ -^{1} \times F_m \tag{7}$$

where Q_{is} represents carbon footprint of final products.

In this way, the standard supply extension was derived. In addition, by summing along the rows of matrix Q_{is}, the author calculated carbon emitted from energy consumed by source industry (Owen et al., 2017).

To build standard use-extension, we added emissions from direct energy consumption by final demand (Viennese households, exports, and stock) to Equation (4); see Equation (8):

$$Q_{iu} = Pc \times D(I - BD)^{-1} \times F_m + Fe \tag{8}$$

where Q_{mu} represents carbon footprint of final products. Here, author also calculated the emission from energy consumed by source industry following the same principle (Owen et al., 2017).

2.2. *Derivation of emergy-based supply and use extensions*

To build emergy-based supply and use -extension this study carried out the estimation of transformities (energy quality factors) based on carbon network data. The transformities were estimated using the matrix inversion method. The vector of transformities in this method is estimated by multiplying solar energy inputs into industrial sectors by total direct and indirect economic requirements of industrial sectors (Patterson, 2012, 2014). In this study, on the other hand, solar energy inputs were converted into carbon equivalents by through appropriate conversion factors, namely 50 g of CO_2 equivalent per kilowatt hour generated by solar panels (Bilek et al., 2008). The mean value of lifecycle GHG emission estimates generated by solar panels from these two data sources was used assuming 50% of electricity generated from PV technologies during their lifecycle (Bilek et al., 2008). Therefore, it was assumed that around 50% of electricity generation capacity by PV technologies is used in Vienna.

The matrix inversion approach is presented below; Equation (9).

$$p = g(U - V)^{-1} \tag{9}$$

where “U” is the Vienna’s monetary supply matrix (m × n), “V” is the Vienna’s monetary use matrix (m × n), “g” is the numeraire vector (1 × n) of indirect emissions from manufacturing the solar panels used by industries to “harvest” solar energy, and “p” is the transformity vector (1 × m).

Transformities in this study are the same for both the supply and use extensions. The estimation of use-based transformities required the disaggregation of single value of solar energy input to final demand by final demand categories and then, by end-product to arrive at direct solar energy input from ecosystems used for generation of each 64 end-product of MSUT. Only after this matrix of total embodied solar energy reequipments (transformities of product) can be estimated.

The emergy-based supply extension should contain emergy directly and indirectly demanded by intermediate industries. Firstly, the direct emergy requirement vector (emergy intensity) that shows emergy implied into direct energy consumption per € of total purchase was obtained. In simple terms this vector reflects direct environmental burden (direct emergy-based carbon emission per € of total purchase). This intensity was estimated from Equation (10).

$$f_d = (\varepsilon \times P_c) \wedge x^{-1} \tag{10}$$

The next step was to derive cumulative (direct and indirect) emergy consumption per € of purchase (embodied solar energy intensity). This matrix was obtained by multiplying direct emergy intensity by Leontief inverse in product and industry terms; see Equation (11):

$$f_c = (\varepsilon\ \times P_e) \wedge x^{-1}(I - A)^{-1} \tag{11}$$

where ε-is is the transformity vector (1 × m) based on “carbon network data”, Pe is n × 1 carbon-evaluated environmental extension, and $(I-A)^{-1}$ is Leontief inverse estimated as commodity-by-commodity total requirements and industry-by-commodity total requirements matrix.

The multiplication of cumulative environmental burden per € of purchase (f_c) by the vector of total monetary consumption by final demand categories F_m yielded emergy-evaluated carbon footprint, which follows supply extension design; see Equation (12):

$$F_s = f_d \times (I - A)^{-}1 \times F_m \tag{12}$$

To archive this transition vector Fe (emissions from direct fuel use by Viennese households) needed to be translated to the embodied solar energy equivalent through its pre-multiplication by the transformity vector (ε-) based on “carbon network data”; see Equation (13):

$$F_{use} = \varepsilon \times Fe \tag{13}$$

where refers F_{use} refers to the solar energy implied in carbon emissions induced by the direct fuel use in households (i.e., electricity and heating).

Then, by adding F_{use} to the emergy-based footprint estimated using supply-extension design, emergy-based use-extension design was derived in Equation (14):

$$F_u = f_d \times (I - A)^{-1} \times F_m + F_{use} \tag{14}$$

In other words, the study determined environmental cost of total CO2 emissions by a Vienna socio-economic system (F_u). This total environmental cost (environmental support) can be viewed as the sum of the environmental costs associated with production CO2 emissions and the cost associated with final demand CO2 emissions.

2.3. *Development of monetary and physical input-output and the final demand data for Vienna*

2.3.1. *The monetary supply and use tables*

For intermediate monetary consumption and final monetary demand categories, Austria’s national monetary supply and use data for year 2015 was downscaled to arrive at Vienna-specific data. Austria’s national monetary use and supply data were regionalized using a supply-side, commodity-by-industry input-output model, also known as the “Ghosh model” and location quotient approach (measure of industrial concentration). Firstly, a direct-output coefficients matrix was obtained by dividing the corresponding row of national monetary use table by the corresponding row of gross commodity output. This matrix denotes a national supply side commodity by industry model. Then, a national monetary supply and use commodity-by-industry model were downscaled based on value added data (earnings generated by production of goods and services) to estimate the share of commodity inflows to the

Vienna region using a simple location quotient (LQ) technique (Liu and Vilain, 2004). Here, aggregation of industrial sectors in the Austrian supply and use tables needed to be performed to match aggregated gross value-added data by NACE industry (Statistik AUSTRIA, 2015e).

To construct regional monetary supply and use tables, the total regional commodity supply (or use) in monetary was a prerequisite. A vector was obtained through a Ghosh "commodity-by-industry model" thoroughly described by Shao and Miller (1990, page 8). The Ghosh commodity-by-industry total requirement matrix and value added were used to estimate this vector of total commodity output. Finally, multiplying the regional proportions derived from monetary supply and use tables by the vector of total commodity output (total supply or use) yielded Vienna's regional monetary supply and use tables (Miller and Blair, 2009).

2.3.2. *Monetary household consumption data*

The next step was an estimation of urban monetary household consumption. Consumption data for Viennese households, containing detailed expenditure data on goods and services, were taken from the household budget survey 2009/2010 (AUSTRIA, 2013), which was compiled and prepared for IO analysis in previous work (Smetschka et al., 2019). This source rather than a more recent survey was used because such data are not openly accessible free of cost. To estimate SRIO-based monetary vector of household consumption, the study linked the household budget survey, which is compiled using the COICOP nomenclature to SRIO, which is based on CPA 2002 classification. Therefore, a concordance matrix between COICOP and CPA2002 classifications from previous work was used (Smetschka et al., 2019). The total regional household consumption was reallocated from the household budget survey to the CPA classification. The resulting vector represents the final demand of household consumption (F_h).

2.3.3. *Monetary governmental consumption and capital formation for Vienna*

To estimate the Viennese government consumption and capital formation, monetary final demand vectors from national accounts were used as a starting point (Austria 2015). Two approaches to overcome data constraints were combined because city-scale data for these two final demand categories were not available (Millward-Hopkins et al., 2017). First, like previous studies, researcher adopted an approach to downscale these two final demand categories, which assumes that every Austrian citizen benefits from government expenditures in the same way. Thus, the downscaled government consumption from national to local level on an equal per capita basis (Minx et al., 2013; Millward-Hopkins et al., 2017; Schmid, 2020). Second, the alternative estimate for local government consumption was collected from annual balance sheets of government spending contained in Statistical Yearbook of the City of Vienna for the year 2016 ("Statistisches Jahrbuch der Stadt Wien, 2016") (MA 23 2016), which however does not contain all federal/national spending occurring in Vienna. Consequently, the mean value of these two data sources (per capita downscale of national final demand vector and balance sheet of the Vienna's government expenses) was used to estimate government consumption, considering statistical uncertainty of data and questionable assumption that every Austrian citizen benefit from government expenditures in the same way. The same downscaling approach was also applied to fixed capital formation due to the lack of the respective statistical data (Schmid, 2020). Summing across categories household consumption, government consumption, capital formation, and exports yielded final demand vector F_m.

2.3.4. *The physical energy flow accounts and physical extension data*

For energy extension and final energy demand of households, physical energy flow accounts (PEFA) were downscaled. For this purpose, scientists needed to align the more detailed PEFA classification (88 sectors) with MSUT classification (64 sectors). The concordance table developed by Wieland et al. (2019) was used for this purpose. The simple LQ (location quotient) approach was used to determine the shares of production by NACE industry in the region, in order to downscale physical energy flow accounts (physical energy use and supply tables). To calculate the footprint's physical extension and intermediate monetary consumption should have the same number of NACE industries. Therefore, Wieland et al. (2019) aggregated physical energy supply data and use until 16 industries remained. Total energy and use by product were taken from Vienna energy balances (VEB, 2015). The total regional energy supply and use by product (total commodity output in TJ) were obtained from the regional energy balances (VEB, 2015). The author used this total supply (or use) as energy extension in this study. The regional energy supply and use tables were then built using the supply side model (Ghosh "commodity by industry model") to estimate the proportion of commodities used by various industries in Austria. Then, multiplication of regional proportions derived from energy supply and use tables by the by total energy supply (or use) from Vienna energy balances (VEB, 2015) yielded Vienna's regional energy supply and use tables (Miller and Blair, 2009). Then, energy supply and use data was used as a physical extension. This physical extension used in this study represents value added by each industrial sector value added from energy extraction and production by each industrial sector.

2.3.5. *Final energy demand data*

Renewable energy sources and some of energy products used in households were taken from Vienna's regional energy balances (VEB, 2015) as it already contains data on total consumption of households, energy exports, and stocks. The data contained in energy balances were based on the territory principle: all energy commodities used by residents and non-residents in Vienna are accounted for. To calculate the other part of direct energy use vector by households, the annual total expenditure of gasoline, diesel, heating oil, natural gas, and electricity direct energy consumption of households as well as national average energy prices for years 2014/2015 (Statistik Austria, 2015) was a prerequisite. The average energy price for gasoline was further estimated using the Austrian annual total spending on each fuel ("Austria- Petrol sales till 2019 for 2015 | Statista," 2020) to quantify the total gasoline consumption of final consumers in physical units. Moreover, the energy content of total gasoline used by household using calorific values of each fuel (Smetschka et al., 2019). Then, data on energy exports and stocks by product were also obtained using regional energy balances (VEB, 2015). To match the data obtained from EB with the data on product classification reported in PEFA (39 energy products) data were aggregated by summing the products categories from EB. Some data in energy balances were not available (i.e., coal-based energy is not used in energy conversion chain anymore) or missing to differences between Vienna's energy structure and national one. Finally, summing across direct energy exports, stocks and households' energy consumption categories yielded vector of direct energy consumption by final demand (F_e). This vector was needed to derive use-extension from supply-based one.

2.3.6. *Air Emission Accounts*

For carbon intensity vector, carbon emission vector by economic activity was obtained from Air Emission Accounts (OECD Statistics, 2015b). The procedure used to estimate this vector is presented in Section 2.1.

2.4. *Overview on all data sources*

For this study, data on energy extension, final energy demand of households, intermediate monetary consumption, monetary as well as final monetary demand categories associated with Vienna municipality was used. In addition, carbon intensity vector was used. The summary of sources used to build emergy-based carbon footprint model is presented in Table 1.

Table 1
Overview of data sources for emergy-based carbon footprint model of Vienna.

	Temporal coverage	Population Covered	Sample size	Number of categories	Source
Austrian household budget survey-households inside Vienna	04/2009–05/2010	Vienna’s households	1246 households, Sample	53 categories, derived based COICOP classification	Statistics Austria −2013
Vienna physical supply and use tables-downscale of national data	2015	Austrian territory	Complete representation of national economy and its energy exchanges with environment 88 sectors	NACE*88	Statistics Austria (2015a)
Vienna monetary supply and use tables- downscale of national data	2015	Austrian territory	Complete representation of national economy 64 sectors	CPA*64	Statistics Austria (2015b)
Vienna government consumption vector – downscale of national data	2015	Austrian territory	Complete representation of national economy 64 sectors	CPA*64	Statistics Austria (2015b)
Vienna gross fixed capital estimation vector– downscale of national data	2015	Austrian territory	Complete representation of national economy 64 sectors	CPA*64	Statistics Austria (2015b)
Vienna’s energy balances-use of fuels in Household	2015	Vienna Municipality	Complete energy use in regional economy 88 energy sources and 24 final energy users	IEA*88	Statistics Austria (2015c)
Austrian Air Emission Accounts-	2015	Austrian territory	Complete representation of national economy 64 sectors (industries and households)	NACE*64	OECD Statistics −2015

3. Results

This section discusses and compares the results derived for emergy footprints based on supply- and use-extended SRIO models with their carbon counterparts, for an industry-by-commodity model. Emergy and carbon consumption-based accounts (CBA) by final products, and final demand categories by final products were aggregated by source industry categories to determine if there any considerable differences in the carbon footprints of final demand categories. Then, emergy and carbon footprints by source industry were assessed if any empirical differences in the energy consumed to satisfy Vienna consumption by source industry stems from emergy and carbon evaluation methods used in footprint analysis.

3.1. Total emergy footprints by product groups in supply- and use-extensions

The footprint ranking changed dramatically when carbon footprint is evaluated in emergy terms (see Fig. 2). The products of agriculture, hunting and related services (A01) have a highest difference, with emergy footprint (20.06%) exceeding carbon footprint (3.58%) by 16.5% for this product. This product changed its rank from 2nd to 1st, reflecting the largest emergy footprint of agricultural products in the emergy extensions. The footprint with the second largest difference is the electricity, gas, steam and air-conditioning (D + E) where emergy footprint (9.49%) exceeds carbon footprint (0.81%) by 8.7%. The rank of this product grown from 17th place to 2nd place. This product follows by public administration and defence, social security services (O), which climbs from 9th to 4th place, overshooting carbon footprint by 3.5 %. In general, it was found that products of extractive industries and services

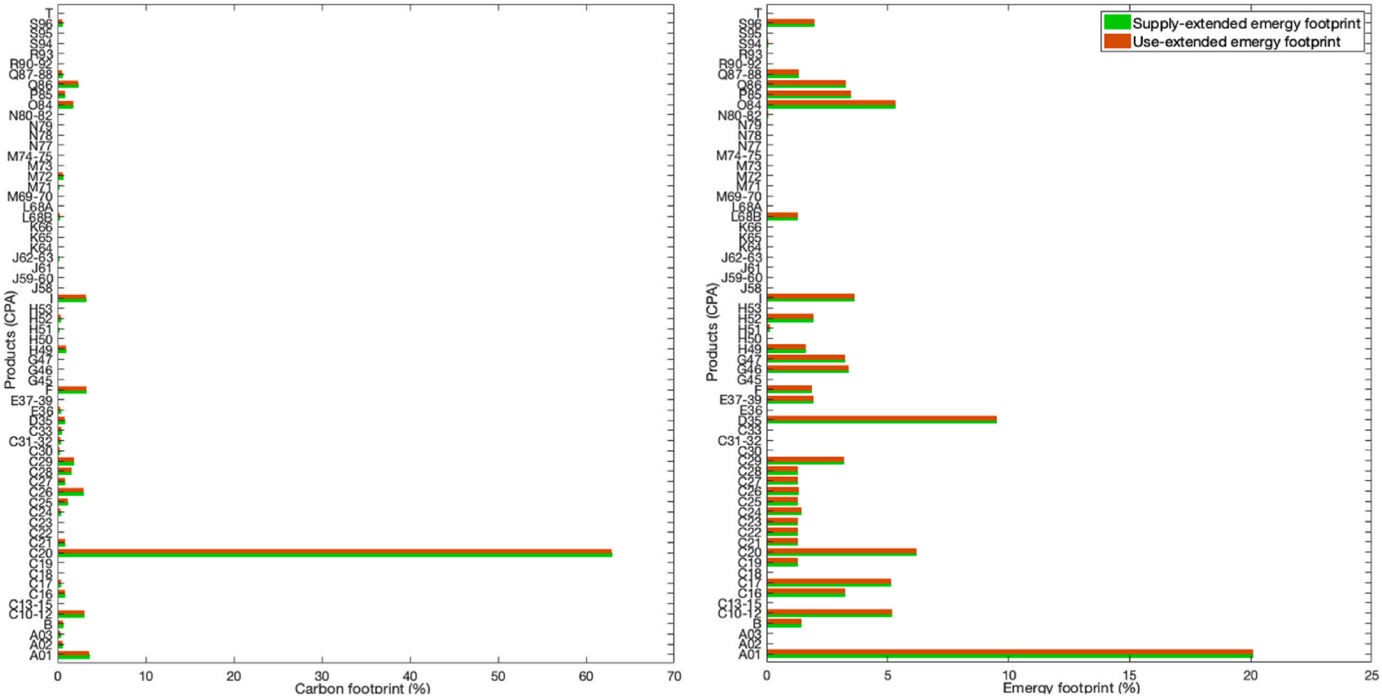

Fig. 2. Carbon footprints (left) and emergy-based carbon footprints (right) for final goods and services, estimated from a commodity-by-commodity IO model, showing the difference between the supply-extended (green) and the use-extended model (red), for Vienna 2015. The complete carbon footprint and emergy-based carbon footprint details are found in the supporting information “S2 in Table S-A and S-B, respectively. Product categories follow CPA classification. Names, abbreviations of products are presented in Tables S–C in the supporting information. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

became larger in magnitude compared to the manufacturing products when emergy footprinting is chosen. Fig. 2 shows that among services the highest increase is found in *public administration and defence services, social security services* (O84), education services (P85), human health services (Q 86) 6.14 E+07 Tera seJ, 3.84 E+07 Tera seJ, and 3.84 E+07 Tera seJ, respectively. The product that deviates more strongly from this pattern is chemical *and chemical products* (C20). Here, the emergy footprint ranks 3rd position, moving down from 1st place in the carbon footprint ranking. This footprint is also characterized by the largest difference with carbon footprint (62.9%) exceeding emergy footprint (6.2%) by 56.7% for this product.

Fig. 3 shows that carbon supply-extended and use-extended models vary depending on whether an emergy-evaluated or carbon-evaluated approach is chosen. The most pronounced difference among supply-extended and use-extended models was found in the products of agriculture, hunting, and related services (A01), printing and recording services (C18), and fabricated metal products, except machinery and equipment (C25), where use-extension exceeds supply-extension footprint by 4.9%. Publishing services and motion picture, video and television programme production services, sound recording (code J58), and music publishing; programming and broadcasting services (code J59-60) also differ the highest among carbon supply and use extensions, with supply-extension exceeding use extension footprint by 4.9%. In general, it was found that services differ by a larger extent when carbon supply-extended design is chosen as opposed to products of extractive and manufacturing industries having a larger difference when use-extension is chosen. Fig. 3 shows that emergy supply-extended and use-extended model distributes emergy to final products according to a more homogenous pattern. The products of agriculture, hunting, and related services (A01) vary the most with supply-extension exceeding use extension footprint by 21.5%. This product is followed by electricity, gas, steam and air-conditioning (code D35) where use extension exceeds supply extension footprint by 15%. In general, the supply and use extended model when evaluated in emergy terms allocates more emergy to services and extractive industries at the expense of manufacturing products. The more emergy was allocated to services when supply extension is used as opposed to extractive industries when use-extended design was chosen. The product that deviates more strongly from this pattern is publishing services (J58) and motion picture, video and television programme production services, sound recording and music publishing; programming and broadcasting service (J59-60). Here, the use extension exceeds supply-extension footprint by 14.9%.

3.2. *Emergy footprints by final demand categories*

This section presents results of the carbon and emergy-based footprint of final products disaggregated by final demand categories.

The strongest divergence between emergy evaluated and carbon evaluated models, in absolute terms, is found for footprints of households (Fig. 4). The household's footprint estimated using emergy-evaluated IO model exceeded its counterpart in the carbon evaluated IO model by 45%. This category ranks 1st, reflecting its largest emergy footprint in the emergy extensions. Exports followed as next strongest divergence with a 37% difference between emergy and carbon extensions. The variation in the footprint of other final demand can be attributed foremost to differences in the footprint of government consumption, with 50% when using emergy-evaluated IO model and 21% when applying carbon-evaluated IO model. The lowest divergence in relative terms was found for the footprint of capital formation with 50% and 41% divergence when using emergy and carbon evaluation

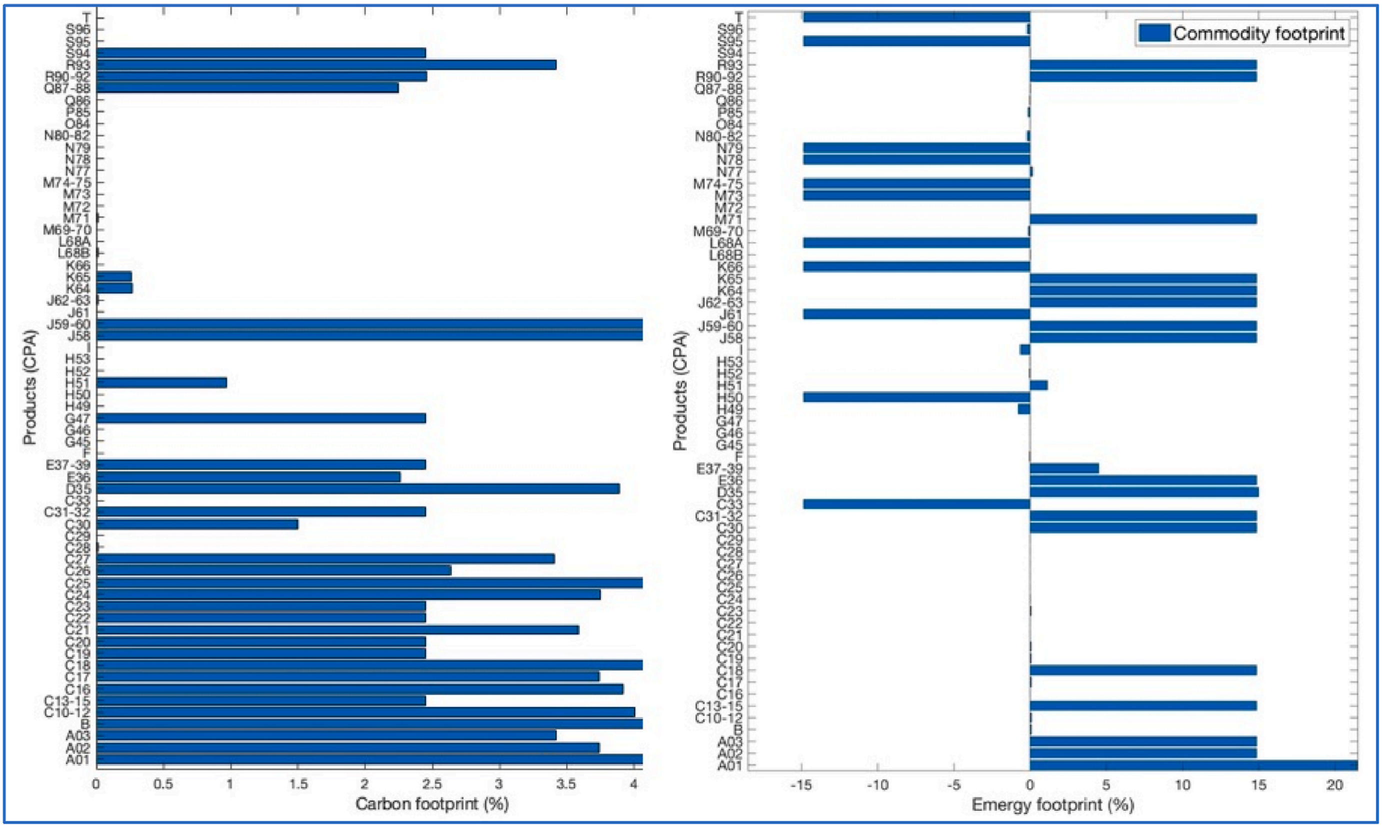

Fig. 3. Differences between the supply-extended and the use-extended model based on carbon footprint (left) and emergy footprint for final goods and services (right), estimated from a commodity-by-commodity IO model for Vienna 2015. The complete carbon footprint and emergy-based carbon footprint details are found in the supporting information "S2 in Table S-A and S-B, respectively. Product categories follow CPA classification. Names, abbreviations of products are presented in Tables S–C in the supporting information.

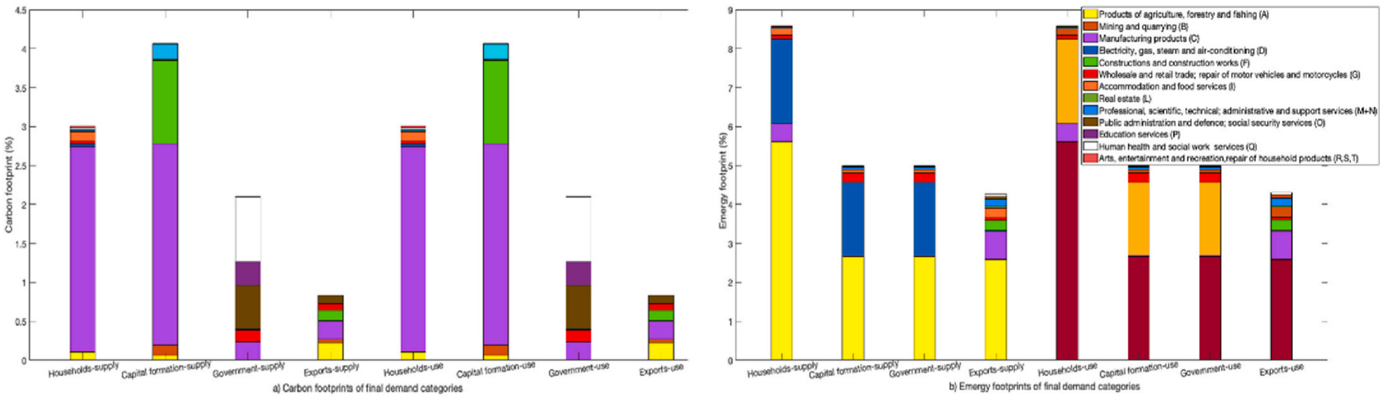

Fig. 4. Carbon and emergy-based carbon footprints of final demand categories broken down by final products and aggregated by intermediate sector categories, 2015; Carbon footprints are shown in the left bar (a) while emergy-based carbon footprints are shown in the right bar(b). In the both bars the total footprints of products by final demand categories based on supply-extended model is shown on the left and footprints based on use-extended model on the right. The initial data are found in Tables S–E in the supporting information "S2". Note: The households-supply and households-use bars were divided by 10 to display all bars in a common scale.

methods, respectively.

The relatively strong divergence in the household footprints led to different rankings of the footprints of the government consumption category in emergy extension. When applying carbon evaluation Household consumption occupied the first place. This category was followed by Capital formation government consumption, and exports. When applying emergy-extension households and export categories retained their ranks., while both capital formation and government consumption shared the second position. Although both the capital formation and government consumption were equally sharing second place, the relative differences between emergy-evaluated government consumption and carbon counterpart were larger than the relative differences of capital formation: 29% and 9%, respectively. This could be related to the higher indirect solar energy cost required to produce energy (i.e., electricity) directly consumed by government, including the nature of the source (i.e., its ability to produce work), distance to the source to the final user and the number of intermediate industries consuming the solar energy from the same source as capital formation.

When researcher compared results obtained emergy (and carbon) supply and use extensions the differences were far less pronounced. The highest difference was found in Export category, where emergy-evaluated use-extension exceeds emergy-evaluated supply-extension footprint by 1.34%. In comparison, emergy-evaluated household footprint estimated using use-extension exceeds its supply-extended counterpart by only 0.2%. The ranking of the footprints of the final demand categories is therefore sensitive to evaluation method used to estimate them.

3.3. *Emergy footprints from consumption by source industry*

The footprint ranking changed dramatically when carbon footprint was evaluated in emergy terms (see Fig. 5). The highest difference was found Manufacturing (C), where emergy-evaluated footprint exceeds carbon-evaluated footprint by 45%. Highlighting the role of this sector as key source. This sector followed by Agriculture, forestry, fishing (A) with emergy-evaluated footprint exceeding carbon-evaluated one by 19% and retained 1st position when industrial footprints were estimated using emergy-evaluated footprint. This sector also retained its second position in the both emergy and carbon-evaluated IO models. The third by magnitude divergence was detected in *electricity, gas, water supply,*

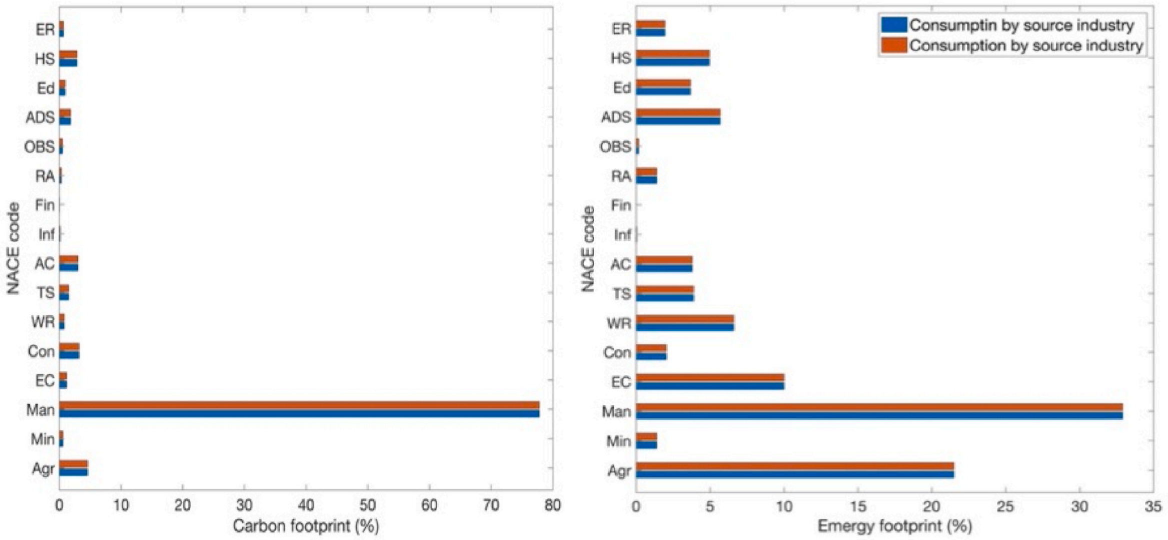

Fig. 5. Carbon consumption (a) and emergy consumption (b) by source industry estimated from the supply-extended (red) and the use-extended model (blue) for Vienna 2015. The complete carbon and emergy footprint details are found in the supporting information "S2" in Table S-G and S-H, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sewerage, waste, and remediation services, which moved up ranks from the 6th to 3rd position when estimations are done based on the emergy-evaluated footprint model. This emergy-based and carbon footprint for this sector differ by 8%. In general, footprints of extractive and productive industries are larger than services. The only exceptions were *electricity, gas, water supply, sewerage, waste, and remediation services* (D + E) and Mining and quarrying sectors (B). Mining and quarrying (B) were three times lower in comparison to services, while footprint of *electricity, gas, water supply, sewerage, waste, and remediation services* (D + E) exceed services by few percent.

Regarding the differences between carbon and emergy evaluated extensions for source sectors, Manufacturing (C) deviated the most, with carbon-evaluated use extension exceeding carbon-evaluated supply-extension footprint by 39% (Fig. 6). The second and third largest divergence was attributed to Wholesale and retail trade; repair of motor vehicles and motorcycles (G) and Human health and social work services (Q): 10 and 9%, respectively. The other sector with considerable difference (8%) was Transportation and storage (H). In general, the largest difference in Manufacturing (C) compared to service sectors can be observed. The differences between emergy-evaluated footprints were less pronounced, as can be seen in Fig. 5. The difference of Agriculture, forestry, and fishing (A) is only 2%, while both the Transportation and storage (TS) and Manufacturing (C) differ by a smallest value (1%). The largest variation between emergy-evaluated extensions was found in *electricity, gas, water supply, sewerage, waste and remediation services* (D + E), where use-extension exceeds supply-extension footprint by 98%. This huge gap in *electricity, gas, water supply, sewerage, waste and remediation services* (D + E) can only be attributed to the indirect solar energy implied in the direct energy consumption of households (i.e., electricity and heat demanded by households).

4. Discussion

The comparison between emergy and carbon footprints revealed that footprints based on the single region input-output (SRIO) model of Vienna Region built from downscaled Austrian monetary supply and use tables (Miller and Blair, 2009) are sensitive to the method applied to estimate them, leading to variations in rankings of the footprints of the final products categories. This is in line with previous research for other countries and cases (Baral and Bakshi, 2010; Li et al., 2018; Park et al., 2016; Sun and An, 2018). In this section, the benefits and limitations derived from the combined approach, which integrates emergy synthesis with supply and use extended energy-based carbon footprint models are discussed in the following order: major findings, conceptual implications and limitations, complementarity of emergy-evaluated models.

4.1. *Methodological implications*

The comparison of results between emergy-evaluated and carbon footprints of final products showed that products of extractive and service industries were larger when applying emergy-evaluated footprint as opposed to the manufacturing products being larger when applying the carbon footprints. There are two main reasons behind these differences. First, when emergy accounting is applied by itself, services are always higher than energy products since they are used indirectly to support infrastructures for any production process to occur from the larger scale of economy (Franzese et al., 2009; Russo et al., 2014; Qu et al., 2017; Huang et al., 2018), to national input-output analysis (Baral and Bakshi, 2010) and to natural ecosystems, where services have the highest transformities (Campbell and Brown, 2012; Z. Liu et al., 2021). Second, products with high share of renewable energies are characterized by lower environmental work required to produce them. Therefore, the question could be posed whether the large share of importing non-local renewable energy products is the reason for footprints of products of extractive industries being larger than for services (i.e., products of agriculture, hunting, and related services).

When footprints are displayed by source sector, sectors engaged in energy extraction and production industries (i.e., Manufacturing and Agriculture, forestry, and fishing) usually have larger footprints than other sectors. However, this was not the case for electricity*, gas, water supply, sewerage, waste and remediation activities* (D + E) and Mining and quarrying sector (B) despite their crucial role as commercial energy producers in the economy. From the statistical data used, it was clear that territorial urban production from these sectors was too small to satisfy final demand of Viennese consumers. The majority of mining ores and energy production facilities as of 2015 are located at distance from Vienna municipality and are in decline in terms of production based on temporal trend of mining production from 2009 to 2019 (Koerbler.com, 2013; Mining and quarrying," 2019; MINLEX - Austria Country Report,

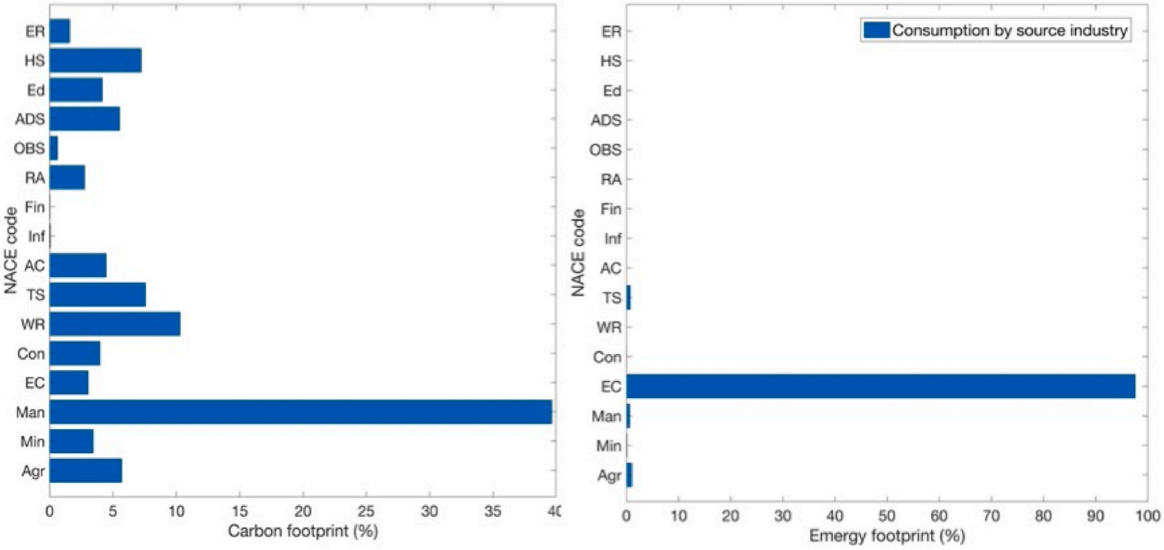

Fig. 6. Differences between the supply-extended and the use-extended model-based carbon footprint (left) and emergy footprint for source sectors (right), estimated from a commodity-by-commodity IO model for Vienna 2015. The complete carbon footprint and emergy-based carbon footprint details are found in the supporting information "S2 in Table S-A and S-B, respectively. Product categories follow CPA classification. Names, abbreviations of products are presented in Tables S–C in the supporting information.

2017). The alternative form of mining (urban mining) based on the recovery of raw materials (electronic waste) is considered a viable alternative for the future (Brunner, 2011). In case of electricity, the Vienna Government is more concerned with the improvement of share of renewable energies in the energy supply chain by equipping building with photovoltaic panels and renewable heating systems (Austria, 2050; Ardak et al., 2020; City of Vienna, 2019). The disaggregation of end-products by final demand categories showed that Exports category in emergy-evaluated extension design had a small difference compared to the supply-extended design. It is obvious that export flows of energy products are also integral, leading to the question about magnitude of direct energy exports. The export of agricultural and energy products contributed the most to the small differences in the category of Exports also pointing to the small direct energy export of biofuels including environmental costs of biofuel production, not of local origin.

4.2. Conceptual implications

The system boundary of the emergy-evaluated extension design compared with the energy one is completely different. The emergy boundary is global and inter-temporal, as it covers all solar energy inputs originally captured in ecological processes during earth's entire history, as it is directly and indirectly embodied in fossil fuels available nowadays. According to this approach, an urban socio-economic system is embedded in global environmental support system (biosphere). In the urban IO analysis, the boundary covers the city and only one year; specifically, the fossil fuels and other energy carriers as utilized within the city, within one year (Dong et al., 2016; Schmid, 2020). These boundaries translate into supply and use extension design via energy quality factors (transformities), making an adoption of new allocation assumptions necessary. While supply extension design applied by Owen et al. (2017) and Wieland et al. (2019) employed straightforward allocation of environmental burden by economic value used in traditional LCA, Owen's allocation assumption for use-extended design differed from that of Wieland. Wieland employed three-step allocation, while Owen employed two-step allocation procedure, in which transformation losses are allocated directly to the consumption industries along the supply chain. Wieland, on the other hand, allocated transformation losses to the energy producers (Wieland et al., 2019). Owen's approach resulted in the removal of second order energy requirements (i.e., energy for processing) from the allocation procedure. For example, final energy consumption (final energy and non-energy use) was not allocated to energy consuming industries but used as starting point to build use extension. In the end, the same balance between total energy supply and use was reached (both equal gross inland energy consumption). In Wieland's and our study, energy supply and use were balanced using Energy Accounts (EA). Which extension is more appropriate for when emissions are accounting using territory versus residence principle, and whether one of these allocation assumptions could lead to double counting, should be addressed in future studies.

The other difference that should be noted is that direct energy consumption by final demand categories (households, exports, stocks) became integral (direct and indirect) when transformities are applied to the final demand. This can lead to the great variation between the results obtained from standard and emergy-evaluated use extension design (i.e., direct, and indirect solar energy implied in electricity use is allocated to households). It significantly affects the results since energy use of fuels allocated to final demand categories is not of first order anymore. It introduces the question of inconsistency of the allocation procedure used in standard use-extension design for emergy-evaluated use-extension design. When transformities are applied to the environmental extension there is no effect on the allocation procedure used to build supply-extension. However, natural inputs and wastes and imports became also integral (direct and indirect). For example, production of natural gas not only includes extraction of natural gas from shale formations but also incorporates biomass production under heat and pressure in Earth's crust. The question of whether standard supply allocation is appropriate for emergy-evaluated supply extension needs to be checked. For example, the solar energy inputs can be allocated to the producer (agriculture) and, then be distributed to other industries based on monetary payments. Therefore, emergy-evaluated extension design questioning the allocation procedures adopted for supply-extension design.

4.3. Interpreting disagreement from a conceptual point of view

Following the stated differences between emergy-evaluated and standard energy extension design, it is noted that both extensions are conceptually different: emergy-based design is used to assess depletion of natural resources (donor side perspective) while standard design is more concerned with footprint of production and consumption activities in cities (user side perspective). The emergy footprint gives more weight to the environmental dimension and thus reflecting the global environmental processes as drivers behind energy supply. Therefore, environmental support to the production of energy generates the same sale of energy and generation of revenue. Particularly, both the energy production and monetary consumption of final users (i.e., households) in the city stimulate renewable energy supply from global environmental system. The emergy-use design was more focused on direct and indirect consumption of production processes and consumption activities and put more emphasize on socio-economic dimension and reflects the final users as drivers behind energy use, which exploit global environmental system. In this case, global environmental support to final energy users generates direct and indirect energy consumption. Therefore, this extension ignored the monetary dimension, namely production factors such as labour and services (indirect monetary contribution such as investments) to production and consumption activities. In other words, this extension better captured direct emergy consumption and energy quality of direct energy products sectors in urban economy, while the first extension better reflect indirect monetary support and energy quality of services. However, the emergy-evaluated extension was better suited to evaluate total environmental pressure of each energy user. Thus, results of both extensions provide completely different type of information despite the both being based on matrix algebra and input-output analysis.

4.4. Limitations of emergy footprint accounting

Homogeneity price assumptions not only influence the divergence between energy supply and use extension (Wieland et al., 2019) but also have a different impact on emergy-evaluated extension. This impact had a different meaning compared to the standard supply and use extension due to conceptual differences stated in Chapter 4.3. Emergy-evaluated supply extension assumes economy-wide average energy prices faced by industries and final consumers (Guevara and Domingos, 2017; Wieland et al., 2019). It is crucial for complete accounting of direct ecological (energy) and indirect socio-economic flows (monetary) to have an information on the prices faced by industries in the MIOT since only actual (direct) energy input from environment and monetary flows among the sectors of urban economy can be converted via transformities to solar energy equivalent flows. In addition, according to the emergy analysis, money is paid in exchange for imported energy products. Therefore, payments for energy products from intermediary sectors should reflect actual energy prices faced by them. In this regard, the exact and approximate hybrid-unit input-output models developed by Guevara and Domingos (2017) based on the both average prices faced by final consumers and economy-wide average energy prices, respectively, are more feasible for integration with emergy approach since the prices faced by intermediary sectors could be estimated using both the models.

The other limitation of the current study was that services that is invested from the larger scale of economy (i.e., national) used in Emergy Synthesis reflect monetary imports category of final demand (Raugei et al., 2014; Schmid, 2020). This led to underestimating investments provided to the Viennese production and consumption activities and the work of environment required to sustain them (Kamp et al., 2016). The consumption-based accounting approach includes indirect emissions from investments from outside of the municipality) (Harris et al., 2020; Schmid, 2020; Lenk et al., 2021). Therefore, to estimate completely the total environmental support (ecological and socio-economic) to the sectors of urban economy in emergy-extended supply design the footprints assessment should be based on consumption-based accounting.

The other uncertainty comes from the downscale the vectors of national monetary government consumption and capital formation on a simple per capita basis as done in three studies before (Minx et al., 2013; Millward-Hopkins et al., 2017; Schmid, 2020). This assumption leads to the underestimation of both supply-extended and use-extended footprint results since Vienna is capital region, the largest GDP contributor to the Austrian economy, and a service-based economy on its own (Vienna, 2020; Statistik Austria, 2020). Therefore, Austrian citizens living in Vienna benefit more from the government expenditures and capital investmnets than national average. Minx et al. (2013) addressing this issue by endogenizing capital formation and government consumtion. The issue, however, that capital formation does facilitate production of industries such as infrastructure replacement and capacity expansion) and, therefore, the formation of capital (fixed assets) can be linked to the to the sectors using capital goods in their production. The government spending, however, does not facilitate production of industries in any way, and, therefore, cannot be endogenizing into the intermediate consumption of monetary use table before downscaling. This issue, thus, should be addressed in the future when more studies that employ footprint analysis of city scale will be introduced.

Other uncertainty of the model stems from the Air Emission Accounts that contain GHG emissions by economic sector at Austrian scale (Statistik Austria, 2015). This uncertainty results in overestimation of carbon footprints estimated using supply-extended and use-extended IO designs. The more uncertainty stems from the assumption of equal share of emissions from households as from economic activities due to the GHG emission data on households being available as an aggregated single, instead of showing the data on carbon emitted in direct energy consumption of households by economic sector (NACE classification). This results in underestimate of carbon footprints of final products and source sectors in the results based on the use-extended IO design. This is the problem with the most of studies that the national emission data is used to estimate direct carbon emission by industry (Schmid, 2020; Fry et al., 2021) or use outdated GHG emission inventories for cities Wiedmann et al. (2020). Rather than inventing new downscaling approach, the data on carbon emissions by economic activity can be obtained from other service-based cities in EU for which data is available (reference cities) such as Stockholm and then, used to estimate Vienna-specific carbon intensity vector (Wiedmann et al., 2020). Therefore, this approach can be used to get better estimation of carbon intensity vector and reduce uncertainty stemmed from the use of national carbon emission vector. The approaches to disaggregate the data on households' emissions need to be proposed for EU cities due to lack of studies employing use-extension design at urban level in EU (Wiedmann et al., 2020) since or Chinese cities (or regions) with detail emission data availability can be used as a proxy for EU cities such as Beijing (Li et al., 2018), Tianjin and Shanghai (Zheng et al., 2021b). This way uncertainty associated with the use-extended carbon footprint results can be reduced.

The vector of solar energy inputs to industries in Vienna was obtained from downscaled energy use tables and Vienna energy balances for 2015. The total solar energy use in Vienna is based on the Energy survey by Statistik Austria (Statistics Austria, 2015). The methodology for calculating renewable natural energy inputs, including solar energy, is based on the territorial principle, which includes solar energy captured by all solar panels for electricity generation within the national territory and the share of imported solar energy for electricity generation purposes out of the total electricity import. However, this methodology leads to the overestimation of direct energy supply to the economy and the underestimation of transformities of products and services aggregated by the economic sector.

The other limitation of this methodology includes the temporal boundary setting, which could lead to the consideration of indirect carbon emitted during the manufacturing of solar panels in the Vienna Region. The actual efficiency of solar panels is not reported for Vienna, leading to uncertainty in the vector of solar inputs into economic sectors. The environment dimension is only defined as a single sector in PEFA, and the solar radiation captured by 'environment' is assumed to be utilized for electricity and heat purposes of energy industries, service industries, and households (City of Vienna, 2022). Therefore, energy flow within the 'environment' is not recorded, leading to uncertainty in accounting of direct solar energy inputs into industries and ecosystems.

The study also used the combined utilization of the location quotient approach (LQ) and commodity-by-industry version of 'supply-side' input-output model to downscale monetary and energy supply and use data. However, this methodology leads to differences in fuel consumption based on the residence principle and its counterpart based on the territorial principle. To overcome this problem, the Austrian shares of sales of each fuel type by land, air, and water transport and sales of other energy products were found by transforming the Austrian physical energy use table into the commodity-by-industry equivalent of 'supply-side' input-output model.

The supply-side commodity-by-industry model was used in this study because it facilitates the separate downscaling of monetary and energy supply and use tables. However, this model reflects export-oriented growth, which can lead to higher stress on local ecosystems due to the dependence on purchased goods and services (De Mesnard, 2009; Aroche Reyes and Marquez Mendoza, 2021). The simple location quotient downscaling approach used in this study also has limitations, such as the assumption of the same technology used in the production process in the targeted region and a country (Miller and Blair, 2009; Galychyn et al., 2022), and the exclusion of biodiesel exports by the transportation and storage sector.

In conclusion, the study's methodology for calculating solar energy inputs to industries in Vienna has limitations, including the overestimation of direct energy supply to the economy and underestimation of transformities of products and services. The location quotient approach and supply-side commodity-by-industry model used in this study also have limitations, such as the assumption of the same technology used in the production process and the exclusion of biodiesel exports by the transportation and storage sector. These limitations should be considered when interpreting the results of the study.

4.5. *Complementarity of emergy-evaluated extensions and future development*

Based on the discussion, this study concludes that both extensions are complementary. According to Owen et al. (2017), and Wieland et al. (2019) both extensions separately provide useful information with the choice biased towards the responsible party: ether producers or consumers, and the origin of energy consumption: upstream energy sources (extractive industries) or downstream energy sources (consumers) in the energy conversion chain. In this regard, both the emergy-evaluated and traditional extension-designs are useful since both the extensions stems from input-output analysis. However, emergy-based supply and use extensions are complementary because each of them can only account for part of the environmental cost of provided to the activities responsible for energy (or carbon) footprints. Total environmental cost (support) to each source industry, or final product can be only captured when direct emergy consumption from use extension is isolated and added to the emergy-evaluated supply-extension design.

This energy (carbon) supply and use extensions can only be used together to investigate distribution of emission responsibilities of economic activities along the supply chain, depending on whether energy use of production and consumption industries or indirect emergy consumption in downstream sectors is prioritized (Du et al., 2011; Zhang et al., 2014a; Sun and An, 2018). Accordingly, it is suggested to discard prioritization and simply consider the responsibility of the both upstream and downstream sectors, bringing the upstream data from supply-extension and use-related data from use extension into a unified framework (Ali et al., 2018; Chen and Chen, 2011; Zhou and Kojima, 2010; Zhang, 2013). Ultimately, the total environmental costs associated with upstream and downstream CO_2 impacts of producers can be effectively assessed and compared with traditional carbon footprint (CF) only when the compatible data from use-extension is extracted. When this step is archived the global environmental support to local impacts manifesting at global level can be estimated using the multi-scale nested MRIO tables (Fry et al., 2021) can be accessed. Therefore, these directions could inform policymakers, and to stimulate environmental policies based on biophysical constraints, consumption efficiencies and global implications of economic activities.

5. Conclusion

In this study, supply and use designs of emergy extensions were introduced. Our empirical comparison of emergy-extended and carbon-extended SRIO models results revealed considerable differences in relative importance between emergy and carbon footprints.

The comparison of emergy-evaluated footprint model results with carbon counterparts based final products revealed a usually high difference in footprints of agricultural products. This difference lies in large imported renewable energy supporting production of agriculture, hunting, and related services (A01). The comparison of emergy-evaluated and carbon footprints by source sector, however, revealed the low difference in footprints of electricity, gas, water supply, sewerage, waste, and remediation activities (D + E) and Mining and quarrying (B) sectors. Mining operations are in another part of country are no longer economically feasible and experience rapid decline in production, highlighting low importance of this sector as a source of energy for Vienna's economy. The recovery of electronic waste holds a great promise for the substitution of traditional mining in Vienna. In the case of electricity, Vienna Government is more concerned with the improvement of share of renewable energies such as adoption solar PV technologies for energy supply and geothermal pumps to heat new buildings. The small difference between use-extension footprint and supply-extension footprints of final demand categories was due to the direct energy use of biofuels by final demand categories (i.e., households) being far less pronounced compared to the final consumption by production (industries).

The Exports category was a little larger using emergy-evaluated use extension design compared to the supply-extended design mainly due to the low contribution of direct energy export of biofuels allocated directly to the final demand category of exports.

The conceptual differences, however, imply that emergy-evaluated supply-extension resembles the structure of traditional monetary IO, and therefore comparable with energy (carbon) supply-extension design. The emergy-evaluated use-extension, on the other hand, differ considerably from energy use-extension design and does not reflect the logic of emergy synthesis. Each extension provides different information despite utilizing input-output tables & similar matrix algebra. Therefore, combining the first step of emergy-evaluated use-extension design (direct energy consumption by final demand) with the emergy-evaluated supply-extension design (primary energy input from environment and contribution of human labour and economic services to industries), and adjusting the allocation assumption to reflect the logic of direct and indirect flows in Emergy Synthesis would result in more accurate estimation of total environmental pressure of each sector in an urban economy. Finally, this study highlights the importance of assembling emergy extensions from the multi-scale nested MRIO tables to promote decision rooted in environmental and economic stewardship and resource-efficient cities.

CRediT authorship contribution statement

O. Galychyn: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **B.D. Fath:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation. **D. Wiedenhofer:** Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **E. Buonocore:** Writing – review & editing, Supervision, Investigation. **P.P. Franzese:** Writing – review & editing, Supervision, Investigation.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clpl.2024.100058.

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