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A multi-criteria framework for assessing urban socio-ecological systems: The emergy nexus of the urban economy and environment

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ABSTRACT

The social and ecological impacts of urbanization require integrated management of cities and their resource metabolism for long-term sustainability and economic prosperity. Traditionally, network models are used to study internal metabolic processes in cities, complementing the traditional "black box" urban models to account for the input of material and energy resources and the output of final products and wastes. This study introduces a multi-criteria assessment framework by integrating a unique hybrid-unit input-output model with the emergy accounting method to estimate the environmental support provided to urban socio-economic systems, applied here to the case of Vienna, Austria. By focusing on the internal organisation and functioning of urban socio-economic systems, the proposed framework strengthens the understanding of ecological and socio-economic flows exchanged among industries and the environment. The results suggest that resources can be saved by applying supply-side and demand-side interventions and improving share of renewables. The multi-criteria assessment framework developed in this study allows to investigate the urban metabolism of cities and regional contexts through the identification of sustainable pathways rooted in material circularity and resource efficiency, supporting the design of policies in line with the "integrated wealth assessment" and "circular economy" principles.

1. Introduction

In the last century, urbanisation has caused an increase in the demand for ecosystem services while altering the ecological structures and functions (Frank et al., 2017). The current trajectory indicates that nearly 68% of the global population will be inhabiting cities by 2050, showcasing further damage to socio-economic and life-support systems (Ritchie and Roser, 2018). These social and ecological alterations have helped recognise the need for sustainable urban management, and their surrounding areas, for safeguarding the long-term sustainability of urban ecosystems (Kalantari et al., 2019). Such management strategies could, similarly to the marine, coastal, and watershed studies, consider cities as a complex techno-economic system comprising complex human-nature interactions (Frank et al., 2017; Herrero-Jáuregui et al., 2018). Contrary to the traditional "black box" urban models, this multi-faceted integrated approach accounts for the input of material and energy resources and the output of final products [i.e., generated gross domestic product (GDP) and supported population] and waste, thus creating network models capable of unfolding the intricate urban metabolism (Zhang et al., 2009; Musango et al., 2017).

Most of the research before 2006 was dedicated to the metabolism of urban systems with less emphasis on ecological considerations (Bodini and Bondavalli, 2002; Chen, 2003; Bailey et al., 2004). Most of these studies focused on a single-criterion analysis representing the whole system from an ecological perspective instead of an integrated (multi-criteria) socio-ecological perspective. To address this limitation, a conceptual model for metabolic processes in an urban socio-ecological system was developed by Zhang et al. (2006). Zhang et al. (2009) developed a network model for the urban economy and environment a few years later. However, this model was highly aggregated, and the

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analysis of ecological and socio-economic flows among economic sectors (i.e., compartments) was also overlooked. Chen et al. (2010) introduced a more comprehensive model characterised by ecological flows among industries. Later, Liu and Zhang (2012) used a disaggregated network model based on a physical input-output table comprising 45 economic sectors. Nevertheless, their model did not account for free environmental inputs, human labour, and economic services, thus, leaving out consumption patterns crucial for the urban economy and metabolism.

More recently, studies by Zhang and colleagues (2014) and Li et al. (2018) have focused on material consumption patterns for improved estimation of material intensity factors. Using the matrix inversion formula, both studies determined the embodied material intensity of each economic sector per $ of economic service. The first study employed a disaggregated physical input-output table of Beijing comprising 32 sectors (Zhang et al., 2014a), while the second used a more aggregated 13-sector data for Guandong province (Li et al., 2018). However, both studies did not investigate the total material use by each industry and environment or their contribution to the urban economy. Other recent studies still do not account for the indirect economic contribution (i.e., services) to each component of the urban socio-ecological system (Zhang et al., 2018; Xia et al., 2019) and the carbon flows/supply from the environment to different sectors of urban economy (Chen et al., 2020). According to the literature review, most studies continue to rely on a single-criterion analysis while disregarding the usefulness of multi-criteria analysis (Chen and Chen, 2012; Zhu et al., 2019; Chen et al., 2020). Although a recent study by Morris et al. (2020) has investigated the impacts of energy, agriculture, construction, and natural compartment on the overall emergy cycling, the emergy use patterns in a whole urban socio-ecological system are yet to be identified.

In this context, this study could lead to an improved understanding of sustainable urban metabolism by introducing a framework that identifies inefficient or unsustainable emergy use patterns in an urban socio-ecological system while providing a basis for developing sustainable resource management strategies at the regional scale. Therefore, the main research question is as follows: How to develop a multi-criteria assessment framework capturing the complexity of urban metabolic systems by applying biophysical, systems, and network perspectives? To find solutions, we have proposed a multicriteria assessment framework that integrates hybrid-unit input-output and the emergy accounting methodologies to enhance our understanding of environmental and socio-economic flows exchanged between industrial sectors and the environment and characterise the internal organisation and functioning of urban socio-ecological systems.

This study adds scientific contribution to previous research in several critical ways regarding downscaling monetary and energy supply and use data, implementing a two-step approach linking sequentially downscaling based on the supply-side approach with the builing of input-output systems based the demand-side model, introducing hybrid-unit emergy input-output model for urban scale, and combining of matrix inversion and reflexive methods to derive non-negative transformities from under-determined systems of equations.

The application of downscaling approach developed by Liu and Vilain (2004) was extended to national monetary and energy supply and energy use tables. Such application allowed authors to combine supply and use data via demand-side Leontief's model based on industrial technology assumption to build regional energy and monetary input-output tables (Miller and Blair, 2009). Ultimately, joint monetary (energy) production (co-products) was accommodated into the input-output table, thereby avoiding negative monetary (energy) transactions among the industrial sectors and unequal process energy (monetary) efficiencies stemming from joint production (Patterson, 2014). In addition, authors could downscale data on production and consumption of commodities by sectors to obtain more reliable results as compared to downscaling of national industrial input-output data, namely energy (monetary) value-added matrix (energy and monetary losses by industry) and the total amount of valuable products by sector (industrial output). Furthermore, by using this procedure, we ensured that the resulting regional energy input-output table conforms to the first law of thermodynamics (Heun et al., 2018).

The other novelty of this work is that supply-side Ghosh's commodity-by-industry models and demand-side Leontief's input-output models were used sequentially in the same study, considering the strengths of both models. Ghosh's model was used to build regional monetary (energy) supply and use tables, and Leontief's model created a monetary (energy) input-output system from these tables. Here, first-time industry-based technology and supply-side commodity-by-industry model (supply-side make-use model) were applied together in a single study, which Mesnard (2004) explained in terms of the closed economic circuit (industries closed in a loop to be interpreted economically). Then, the resulting regional monetary and energy supply and use tables were combined into economic and energy input-output tables, respectively since energy use and supply tables are only compatible with industry-based technology and demand-side Leontief's input-output model (Heun et al., 2018). The other reason was that the hybrid-unit emergy input-output model could only be constructed if monetary and energy input-output tables were built using the same technology (Guevara and Domingos, 2017; United Nations 2018). Therefore, the introduction of a two-step approach combining the regionalisation procedure (downscaling approach) using the supply-side method (first step) and the construction of input-output systems using the demand-side model (second step).

The third novelty of this work is that the exact multi-factor (hybrid-unit) energy input-output model developed by Guevara and Domingos (2017) was integrated with the emergy accounting approach to account for socio-economic (monetary) and ecological (emergy) consumption by the energy production process and non-energy (tertiary) industries separately. More importantly, both the economic value of services and the emergy value of products provided by the energy industries were incorporated into the analysis (Guevara and Domingos 2017), thereby incorporating the total upstream cost of energy products and economic services exchanged among energy (extraction and production processes) and non-energy industries (the tertiary part of Vienna's economy). The entire environmental support (emergy and monetary criteria) of energy industries to tertiary sectors, and vice versa, has not been explored before in the context of the hybrid-unit energy input-output system (Bullard and Herendeen, 1975; Lindner, S., & Guan, 2014; Shepard and Pratson, 2020). In other words, total emergy used to satisfy the final demand of energy and non-energy industries are separated. Also, both monetary and emergy flows are arranged by the processes of energy use and conversion (Guevara and Domingos 2017). This model allows us to separate and then account for two emergy efficiency indicators (A^r and L^E), thereby allowing us to understand how environmental support affects primary-to-secondary energy conversion efficiency (i.e., the total amount of environmental support to primary energy needed by one energy industry to produce the amount of environmental support to secondary energy by another energy industry to satisfy the consumption of tertiary industries) and direct emergy consumption efficiency (amount of direct emergy demand by each tertiary industries to produce their monetary output). Ultimately, this model contributes to understanding emergy used in primary (LE) and secondary energy production processes (Ar) in the urban economy. In short, this model provides a more detailed representation of emergy use in the economy and supports the identification of urban production and consumption processes characterised by low levels of emergy consumption. In this study hybrid-unit, input-output model was also applied for the first time to the urban scale. Previous studies have estimated total energy consumption by energy and non-energy production processes and proposed recommendations to improve the energy efficiency of supply chains and reduce emissions for national economies such as Portugal (Guevara and Rodrigues, 2016), Canada (Bagheri et al., 2018) and Japan (Ueda, 2022).

The fourth novel aspect of this study is that these problems are associated with negative transformities and artificial aggregation by rows and/or columns (impossible to arrive at matrix product to deal with different dimensions in starting outputs-inputs matrix), and the issue associated with prior knowledge of transformities have been overcome through the integration reflexive (backward and forward linkages matrices), and matrix inversion approaches (Patterson, 2014). This was archived using the first seven-step of the reflexive approach to 'output matrix' U and 'input matrix V' to transform and combine them into the Kernel matrix Z, output-input matrix with positive values along diagonals (+) and negative value (−) along non-diagonals, to insert into matrix inversion equation to produce a positive value of transformities. Here, the first-time underdetermined systems of equations (number of commodities considerably exceeds the number of industries) based on backward and forward linkages were extended, aggregated, and combined into a single matrix (Z). We found the aggregated transformities of production processes and consumption activities at the urban scale by following this procedure. The higher the value of transformity indicates the high emergy inefficiency of the production process or consumption activity (Patterson, 2012).

Moreover, this procedure allowed us to overcome the problems of artificial aggregation by rows and/or columns of an inconsistent system of equations (over-determined or under-determined systems) associated with the matrix inversion approach (Patterson, 2012, 2014) and the inapplicability of reflexive approach to the estimation of transformities from an under-determined system of equations (Patterson, 2014). Lastly, the problem associated with the prior knowledge of transformities for the transformation of quantity × process matrix to a process × process matrix through the market share assumption in physical systems (i.e., energy system) was solved through the application of vector of solar energy inputs into each production process and consumption activity (initial data for matrix inversion). This combined approach solves methodological problems associated with both reflexive and matrix inversion approaches and provides insight into unequal emergy process efficiencies in any socio-ecological system. These aspects constitute the novelty of this work.

We tested this new framework on the case study of Vienna. This case study has been chosen due to its overlapping urban and provincial boundaries. Vienna, the Northeast region of Austria, is the smallest (the area is 414.9 km^2) and the most productive province in the country (Statistik Austria 2020). This region generates about one-quarter of the national GDP, about 96 billion euros (€). Vienna's population is about 1.9 million as of 2018, growing at an annual rate of over 10% (Municipal Department 23 – Economic Afairs, Labour and Statistics, 2018), with the highest urbanisation rate in the country (Statistik Austria 2020). Fig. 1 presents a detailed map of Vienna.

Vienna continues to expand its services-based economy towards knowledge-intensive business services. Most industries in Vienna have shown stable growth in recent decades except for agriculture, manufacturing, and energy industries. The fluctuations in gross value added of agricultural and manufacturing sectors could be partly attributed to the variations in the employment market, resulting in a trade-off between jobs in the manufacturing and service sectors. With production facilities and agricultural fields located outside the Vienna region, the reduced number of jobs could be explained by their low concentration (localisation) in this region despite having their main/head offices inside Vienna. More recently, however, a rise in industrial sectors has substituted the services-based industry, especially after introducing the "smart production policy" in Vienna (Vienna, 2020). This was also illustrated by the location quotient (LQ) values for 2015, a ratio of shares of income (or final energy consumption) in each sector of the regional economy to the income (or final energy consumption) in each sector of the national economy (Munroe, D.K., Biles, J.J., 2005). This ratio indicated a higher concentration of the Vienna province's production facilities and agricultural fields. Tables S–A and S–B's supporting information file "S2"[1] provides the value-added and final energy consumption-based LQ of each industrial sector. The sectoral representation, based on LQ, highlights the rising agricultural and manufacturing activities in the Vienna region.

In July 2014, the Federal Energy Efficiency adopted an implementation strategy for enhancing energy efficiency through the "Smart City Vienna Framework" (Vienna City Administration, 2015). This energy efficiency and renewable energy policies were aligned with the decrease of the final energy demand in Austria as a countermeasure to the economic development and rising urbanisation. Later, the "Energy Framework 2030" promulgated in May 2018 has further strengthened the Smart City Vienna Framework and its implementation plan (Vienna City Administration, 2019). In addition, the "Urban Energy Efficiency Programme 2030" based on this strategy was adopted during the same year (Vienna City Administration, 2019). Implementing multiple strategies has resulted in an increased share of renewables by 6.6% from 2014 to 2018. However, energy efficiency has not improved (i.e., only 0.5% improvement). During the same period, the energy consumption of the manufacturing, agriculture, and transportation sectors increased by 1%, while the energy demand of households and services decreased by 1% (Vienna City Administration, 2015; 2019). This could be attributed to the steady rise of Vienna's industrialisation from 2015 at the expense of services and households and the accompanying changes in the job market. This highlights that several efforts have been made for sustainable urban development and resource sustainability. Nonetheless, analysing the success or potential impact of these efforts in Vienna warrants a comprehensive investigation of the urban socio-economic systems and related metabolism.

The rest of the article is organised as follows: Section 2 explains the methodological framework used in this study. Section 3 discusses the results of this work. Finally, the paper concludes in Section 5 and highlights important implications, limitations, and future recommendations based on this work.

2. Methods and data

This section introduces the overall methodology used to develop a multi-criteria assessment framework used in this study.

2.1. Regional input-output table

As a first step, the regional monetary table was constructed using national monetary use and supply data (AUSTRIA, 2015a). The second step integrated the regional consumption table with the regional monetary use table to build a regional monetary input-output table.

The national monetary use table was regionalised using a supply-side, commodity by industry input-output model, also known as the "Ghosh model", a widely used model (Miller and Blair 2009). A supply-side commodity by industry input-output model follows the original demand-side commodity logic by industry input-output model. The difference between the supply-side and demand-side input-output model lies in the input coefficients used (Miller and Blair 2009). The Ghosh model is based on the direct-output coefficients matrix, calculated by Equation (1) (Liu and Vilain 2004).

$$\beta = U^{-1}Q \quad (1)$$

Where the m × n matrix "β" represents the national share of commodity, *i* sold to industry *j*. This matrix was obtained by dividing the corresponding row of the national monetary use matrix (U) by the

[1] Authors are willing to share their entire dataset in Excel format with those who wish to replicate the results of this research.

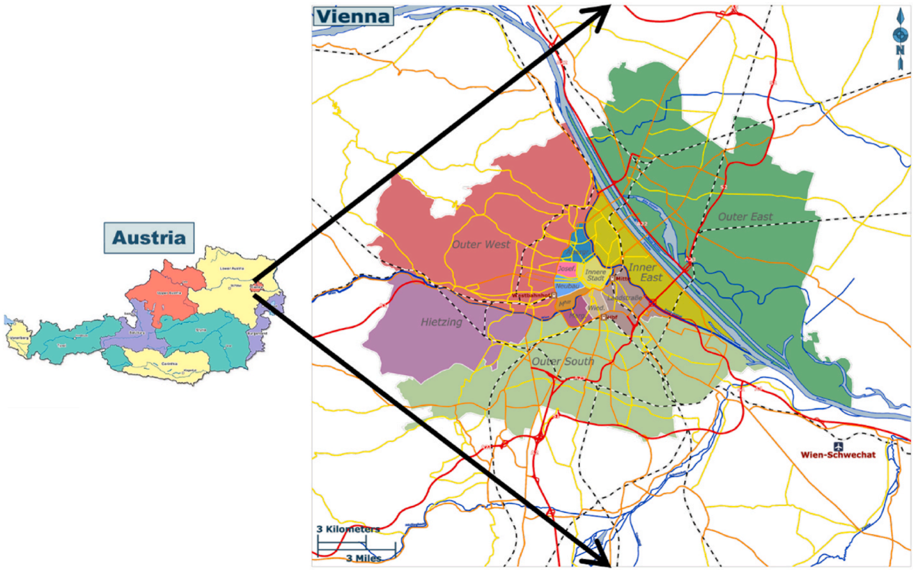

Fig. 1. Map of Vienna based on Wauteurz (2020).

corresponding row of gross commodity output (Q). This matrix denotes a national supply-side commodity by industry model. Then, a national supply commodity by industry model was regionalised to estimate the share commodity inflows to the Vienna region using a simple location quotient (LQ) technique (Liu and Vilain 2004) based on value-added data (earnings generated by the production of goods and services). Finally, the balancing procedure was carried out to adjust the row sum of "β" to be equal to 1 to assign all inflows to individual industrial sectors. If the industry is not present in the region or the LQ < 1, all the commodities sold to this sector are assumed to be sold to the other sectors (Liu and Vilain 2004). For the industry not presented in the Vienna Region, it reflects the following assumption: if an industry such as mining is not present in Vienna Region, the inflows of any commodity that it uses as an input (i.e., natural gas) are assumed to be used by other industries that are both present in the Vienna Region and use the commodity as an input (i.e., natural gas assigned to manufacturing sector because the chemical industry is a sub-sector associated with manufacturing sector).

The national monetary supply was regionalised based on the approach applied to the national use table to build the regional monetary input-output table. The regional monetary supply table was developed using the supply-side model and industry technology as given by Equation (2) (Miller and Blair 2009):

$$D = \frac{S}{Q} \tag{2}$$

Where "D" is the share of each commodity j's total output produced by each industry *i*, Q is the 1 × m vector of commodity gross outputs and "S" is the national supply matrix. The "D" matrix is the core of an industry technology assumption (Guo et al., 2002).

In the second step, we omitted a supply-side input-output model due to poor economic interpretation of economic agents (Mesnard 2004). Hybrid-unit emergy input-output system of the urban economy and environment cannot be constructed if monetary and energy tables describe different technologies (Guevara and Domingos, 2017; United Nations 2018). Moreover, energy use and supply tables appear to be suitable for analysing energy conversion chains (Heun et al., 2018). Therefore, the industrial technology was selected to build a regional monetary input-output table as given by Equation (3):

$$Z = A_i X \tag{3}$$

Where Z is an n × n matrix of intermediate consumption (sales from processing sector i to producer j). The final demand was obtained using the Leontief input-output model as given by Equation (4):

$$F = X - Z \tag{4}$$

Where "F" is an n × 1 vector of final consumption (total sales from processing sector *i* to the consumer *f*). The data contained in "Z", "F", and "X" constitute the regional monetary input-output table.

2.2. Regional energy input-output table

The actual total supply (S) and use data (Q) from the regional energy balances (AUSTRIA 2015b), physical energy flow accounts manual (Physical Energy Flow Accounts - Example Austria - ppt download. Slideplayer.com, 2020), and the structure of national physical energy flow accounts was used to build regional energy use and supply tables (AUSTRIA 2015c). Consequently, the provincial energy use table was integrated with the regional energy supply table using Leontief's "demand-side commodity by industry model".

As data for primary and derived products (electrical energy and heat) was available, the total supply (S) was calculated using Equation (5) for derived or primary products (the primary production of natural inputs was zero):

$$S = U_T + m \tag{5}$$

Where "U_T" represents the primary or secondary production (transformation output) and "m" shows the number of imported energy products. The full use of products (Q) was obtained from Equation (6):

$$Q = Z + F + G + H \tag{6}$$

Where "Z" is the regional sectorial intermediate consumption., "F" is the consumption of households, "G" is the gross capital formation (production of combustible wastes) and "H" represents the exports (Physical Energy Flow Accounts - Example Austria - ppt download. Slideplayer.com, 2020). Since total energy supply should be balanced with the total energy demand, total final energy consumption (Fe) was verified using Equation (7).

$$Fe = Q - Z \tag{7}$$

The regional shares of industrial production and consumption "U_T" were also found using an "a simple location quotient" based on final energy consumption (Miller and Blair 2009; Liu and Vilain 2004). The value-added data was multiplied by the intensity of final energy consumption per million € to compute the final energy consumption of industrial sectors (Vienna City Administration, 2015; Otsuka 2016). The vector of location quotients (regional shares) was used to produce the regionalised versions of matrix "β" and "D". Consequently, "β" and "D" matrices were multiplied by "Q" to build supply and use tables, respectively.

In monetary and energy supply and use tables, the total commodity "Q "and industry "X" outputs must conform to the supply-demand balance (balance for the production units). We used the value-added matrix (W) to check monetary and energy balances. Energy carriers' balances across products and industries must conform to the conservation condition (Heun et al., 2018). In the use and supply table, value-added should be equal to the final demand to comply with the energy conservation rule. Therefore, the value-added matrix (W) was calculated by Equation (8):

$$W = V^T - U \tag{8}$$

Where "V^T" is the transposed supply matrix (commodity by industry), and "U" is the commodity by industry use matrix.

The commodity output proportions matrix (D) was derived from the regional energy supply table using Equation (2).

Since exchanges between commodities were not considered in this study, the D matrix was multiplied by B to obtain the direct-input coefficients matrix "A". Lastly, the final energy consumption was calculated. The monetary and energy input-output tables were necessary since both tables contain the direct and indirect flows exchanged between industrial sectors and the environment.

2.3. Development of emergy input-output model

The next step was to translate monetary and energy flows into standard units of "emergy" to determine the flows exchanged between the industrial sectors and the environment. This was achieved by multiplying those flows by their respective transformities (Li et al., 2010). Transformities for energy and monetary flows were calculated separately due to the nature of flows.

Emergy method accounts for the total environmental support to the process that includes the work of the environment to make a product and for the human economy to process it. The ratio of the available energy previously used up both directly and indirectly in transformations to make energy or monetary product or service to the actual energy content or monetary value of this product or service provides a measure of the environmental cost of the product. This ratio, called transformity expressed in solar equivalent joules (seJ) required to make 1J of a different product or service. The higher transformity represents the higher efficiency and effectiveness of energy transformations in ecological and economic systems. The emergy is derived from available energy (exergy) or the amount of money and transformity; see Equations (9) and (10).

$$\text{emergy (sej)} = \text{transformity (sej/J)} \times \text{available energy (J)} \tag{9}$$

$$\text{emergy(sej)} = \text{transformity (sej/\$)} \times \text{available monetary flow (\$)} \tag{10}$$

Emergy accounts for both the environmental and socio-economic support to the production process. Socio-economic support includes the labour work directly applied to the method and economic services-indirect contribution to the production process such as emergy investment provided from the larger scale of economy. The sum of emergy implied and ecological (i.e., energy) and socio-economic inputs (i.e., money) reflect the total environmental support provided to the urban socioecological system (Asamoah et al., 2017; Liu et al., 2021; Viaglia et al., 2018).

We used matrix algebra to calculate transformities in energy and monetary flow networks. The matrix algebra (MA) is a family of methods for measuring energy quality (transformity) in ecological and economic systems based on solving simultaneous linear equations. These methods estimate transformations (quality equivalent units) in complex ecological and economic network data (energy and monetary input-output tables).

The first of this family of methods, called the Quality Equivalent Method (QEM), was developed in Patterson in 1983 in parallel to the Emergy methods introduced by Odum. The quality equivalent units (δ) – are the units that measure the quality of each energy form in the socio-ecological system by applying the specific coefficients determined by solving a series of linear equations. Each linear equation represents the energy (energy conversion chain) or economic processes (distribution of producer outputs throughout the economy). Therefore, QEM fulfils the same function as transformity in the emergy accounting method and can be defined as a transformity of energy and monetary systems. Unlike the QEM emergy method only consider backward linkages and is inapplicable to the forward links.

Consequently, QEM assesses the complete economic and energy transformation process, consisting of upstream and downstream operations. Moreover, QEM does not rely on Emergy algebra methods and instead applies statistical criteria to allocate the emergy inputs to multiple process outputs. This method is assumption-free and removes the requirement to apply decision rules to avoid double counting.

Furthermore, both the emergy and some methods of matrix algebra, namely the matrix inversion approach developed by Costanza, use solar energy as a numeraire, indicating that it's the only primary direct input into ecosystems (Franzese et al., 2009). Lastly, QEM is free of constraints based on the a priori assumption that all processes should have an emergy-based unity efficiency. In natural complex socio-ecological systems, emergy-based process efficiencies are rarely the same because of the existence of residuals of each process. The method allows equal and unequal process emergy efficiencies by solving simultaneous equations.

The main existing challenge in applying those methods is inapplicability to the underdetermined systems (processes less than quantities). The other problems appear in the process of practical implementation of those methods: non-square matrices, joint production (co-products), negative transformities, matrix singularity (non-invertible matrix), equal process efficiencies (emergy inputs of industrial sectors are similar to their emergy outputs), choice of numeraire and non-unique solution vector of transformities and mathematical elegancy (Patterson 2012, 2014). This section developed approaches to tackle most of those problems (except for non-square matrices). The matrix method was integrated with a reflexive method to estimate transformities of industrial sectors from energy and economic systems and overcome methodological problems associated with those two approaches. The matrix method is an extension of energy input-output analysis to estimate emergy flows among industrial sectors (Hannon et al., 1986; Patterson 2012, 2014). Therefore, this method is compatible with any energy and monetary input-output data (Hannon et al., 1986; Patterson 2014). In addition, the reflexive method is helpful in converting an energy or value-added monetary matrix into an emergy-evaluated matrix that guarantees the positive vector of transformities without prior knowledge of transformities.

The matrix inversion method can be significantly improved by using a pre-conditioning procedure. The reflexive method was used to perform pre-conditioning. We took the solar energy inputs into the regional energy use table as a numeraire because it is the only direct primary input into ecosystems based on the emergy analysis (Hannon et al., 1986; Franzese et al., 2009; Patterson 2014). The first seven steps from the reflexive method were used to transform the energy value-added matrix into a matrix that guarantees a positive vector of transformities (Patterson 2014). This procedure aims to formulate the Kernel matrix Z that can be inserted in the matrix inversion equation to produce a guaranteed positive vector of transformities P. The first steps involve an initial guess of transformities (Patterson 2014). We used the vector of solar energy transfomities to avoid double counting and keep the algorithm intact. As the first step, energy and monetary value-added matrices were determined; see Equation (7) (in original article). Then, the emergy-evaluated version of energy and monetary matrices (R) was chosen, Equation (11) (Patterson, 2014).

$$R = W^T \times P \tag{11}$$

where W^T-transposed version of matrix W (process x quantity), P- diagonalised matrix of solar energy transformities (quantity x quantity). The next step involves the construction of the extended 'outputs matrix' S (p x m), where the p-number of the positive elements (outputs) in matrix W. The values of this matrix are obtained through an allocation as a proportion of all inputs (−) of a relevant process to each process output (+). The fourth step is based on constructing the extended 'inputs matrix' T (n x m), where n –the number of negative elements (inputs) in matrix X. The values of this matrix are obtained through an allocation as a proportion of all outputs (+) of a relevant process to each process input (−).

The subsequent step is associated with constructing the aggregated 'outputs matrix' H. H matrix is (n × m) of commodity inputs to produce each of the process n outputs. Matrix H is constructed by summing all the sub-process rows in T with the same output (+). The purpose of this step is to arrange outputs (+) on the diagonals of H while inputs (−) are along the non-diagonals to guarantee a positive transformities vector (P). Later, we built an aggregated 'inputs matrix' G. G is a matrix (m × g) of output processes directly resulting from each g input. Matrix G is constructed by summing all sub-process rows in S with the same input (−). The purpose of this step is to arrange inputs (−) on the diagonals of G while outputs (+) are along the non-diagonals to guarantee a positive transformities vector (P).

The last step borrowed from the reflexive method includes the construction of the Kernel matrix (Z), Equation (12).

$$Z = U - V \tag{12}$$

Where U- aggregated 'outputs matrix' (energy supply matrix) and V aggregated 'inputs matrix' (energy use matrix).

As a result, we obtained a perfect matrix to use with the matrix inversion method. The vector of transformities in this method is determined through the multiplication of primary inputs by total direct and indirect energy or economic requirements of industrial sectors; Equation (13):

$$p = g(U - V)^{-1} \tag{13}$$

Where "U" is the energy supply matrix (m × n), "V" is the energy use matrix (m × n), and "g" is the numeraire vector (1 × n) of solar energy inputs to an industrial sector, and "p" is the transformity vector (1 × m). By substituting for Z^{-1} in Equation (9) above, we obtain the vector of transformities P (1 × n) as given by Equation (14):

$$P = g \times Z^{-1} \tag{14}$$

Where "Z" is the Kernel matrix. This operation was performed since the reflexive method can adjust the matrices "U" and "V" but not change their purpose (backward and forward linkages, respectively). As a final step, the regional monetary and energy input-output tables were multiplied by their respective vectors of transformities (P) and summed up to calculate the total emergy flow, construct the emergy input-output table, and develop a hybrid-unit emergy input-output model.

2.4. Hybrid-unit emergy input-output model

The hybrid-unit emergy input-output model was developed using the multi-factor energy input-output model based on the national economic system (Miller and Blair, 2009; Guevara and Domingos 2017; Bagheri et al., 2018). The significant advantage of this model is the segregation of energy and non-energy production and consumption processes within the national economy. By using the exact model, the input-output tables included five energy producers (production, extraction and capture of energy) (SEEA energy): 'environment', 'electricity, gas, water supply, sewerage, waste, and remediation services, 'agriculture, forestry and fishing', 'mining and quarrying', and 'manufacturing'. The multi-factor energy input-output model was adjusted to the regional level using the industry-based regional accounting (Jackson and Schwarm, 2011) and hybrid-unit regional input-output accounting (United Nations, 2018) frameworks. This is provided in Tables S–B in the supporting information file "S2".

The hybrid-unit emergy IO model could be built by combining the emergy input-output table with the monetary input-output table based on the hybrid-unit input-output approach. By following this approach, economic services provided by the energy industries were incorporated into the analysis (Guevara and Domingos, 2017). Moreover, the framework assisted in identifying an emergy use pattern and in estimating the total environmental support provided to the urban socio-ecological system using the case of the Vienna region. Based on Guevara and Domingos (2017), the elements of the hybrid-unit emergy input-output model are presented in Equation (11):

$$\begin{pmatrix} g \\ x \end{pmatrix} \begin{pmatrix} A_\theta^* & A_\tau^* \\ A_\pi^* & A_\psi^* \end{pmatrix} \quad \begin{pmatrix} h \\ f \end{pmatrix} \tag{15}$$

Where "g" and "x" are respectively the sub-vectors of the total output of energy industries in seJ and non-energy industries in €; "A_θ^*" is the number of emergy inputs purchased directly to produce 1 seJ of output; "A_τ^*" is the number of emergy inputs purchased directly to make 1 € of output; "A_π^*" is the number of monetary inputs purchased directly to produce 1 seJ of output; "A_ψ^*" is the number of monetary inputs purchased directly to make 1 € of output; "h" and "f" are respectively the sub-vectors of final demand for products of energy industries (in seJ), and non-energy industries in €. Solar emjoule (seJ) is the solar equivalent unit used to measure the total environmental cost of a product or service in the emergy accounting method. In the concluding step, the total emergy use vector (g) was calculated using Equation (12):

$$g = \left(L^E + L^E \times A_\tau^* \times A_\pi^*\right) \times h + \left(L^E \times A_\tau^* \times L_\psi\right) \times f \tag{16}$$

Where "L^E" and "L_ψ" are respectively the sum of direct and indirect emergy purchases required to produce a 1 seJ of output and the sum of direct and indirect monetary purchases needed to produce a 1 € of output.

The vector (g) is the emergy consumed by each industrial sector and the environment. Therefore, by adding the values along the column, total emergy use by each industrial sector and the environment can be calculated to characterise the total emergy exchanged between the urban economy and the environment. By this method, the total environmental support provided to the urban-socio-ecological system could be estimated.

2.5. Data collection and sources

Due to the absence of regional and city-level data, we obtained the data from national supply and use tables contained in the national accounts (AUSTRIA, 2015a). For intermediate monetary consumption and final monetary demand categories, we used Austria's national monetary supply and use data for the year 2015, a complete representation of the national economy. The monetary supply and use table consisted of 65 industries following NACE 2008 classification and 65 products following the CPA classification (AUSTRIA, 2015a). Then, a national monetary supply and use commodity by industry model was downscaled based on value-added data (earnings generated by the production of goods and services) (Vienna City Administration, 2015) to estimate the share commodity inflows to the Vienna region using a simple location quotient (LQ) technique (Liu and Vilain 2004). Here, we aggregated industrial sectors in Austrian supply and use tables to match aggregated gross value-added data by the NACE industry (Statistik AUSTRIA, 2015e). As a result, we obtained monetary supply and use tables, which differentiate between 16 sectors and 64 products.

For energy input-output data, we downscaled physical energy flow accounts (PEFA) (AUSTRIA 2015c). The total regional energy supply and use by-product (total commodity output in TJ) were obtained from the Vienna energy balances (AUSTRIA, 2015b). 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. We then used a simple location quotient (LQ) technique (Liu and Vilain 2004; Otsuka 2016) to downscale the national proportions to obtain regional shares of commodities sold to various industries. The downscaling procedure for national energy supply data involved standard procedure, whether Ghosh or Leontief's "commodity by industry model" is chosen (Shao and Miller, 1990). Then, multiplication of regional proportions derived from energy supply and use tables the by total energy supply (or use) from Vienna energy balances (AUSTRIA 2015b) yielded Vienna's regional energy supply and use tables (Miller and Blair 2009).

Renewable energy sources and some energy products used in households were taken from Vienna's regional energy balances (AUSTRIA, 2015b) as it already contains data on the total consumption of households, energy exports, and stocks. To match the data obtained from energy balances with the information on product classification reported in PEFA (39 energy products), we needed to aggerate data by summing the product categories from EB. We took the following natural energy inputs categories and aggregated some of them: hydropower; wind power; solar energy (solar heat, photovoltaic); biogenic primary energy carriers (production of fuelwood, wood waste, black liquor, liquid biofuels and biogases); ambient heat, geothermal energy, reaction heat was taken from the downscaled national physical flow accounts, namely the vector of the final energy demand of households. We also borrowed from the same source energy product categories: gasoline, coal and peat; coke oven gas, blast furnace gas (including converter gas); coke, coal tar, hard coal (patent fuel) briquettes and brown coal briquettes; liquid (NGL); naphtha; fuel oil; refinery gas and liquefied petroleum gas; other oil products (excluding naphtha) and refinery feedstocks; fuelwood, wood pellets and briquettes, wood waste, charcoal, other solid biofuels; bioethanol, biodiesel, and other liquid biofuels; landfill gas, sewage sludge gas, and other biogas; district heat; biogenic waste; non-renewable waste (industrial waste and municipal waste non-renewable). As some energy products were not available on a regional scale (i.e., fossil non-renewable natural energy inputs) and were absent from national physical energy supply and use tables (i.e., nuclear fuel), the number of products was reduced to 25. We, therefore, obtained national physical energy supply and use tables containing 25 energy products and 16 industries, exactly matching the number of sectors included in monetary counterparts.

3. Results and discussion

This section will discuss the results of this analysis using the Vienna region as a case study.

3.1. Input-output table for Vienna region

The monetary and energy input-output tables provided support in identifying urban resource flows and assessing the efficiency of urban metabolism. With the help of regional input-output tables, monetary transactions between each pair of components assisted in identifying the weak and strong sectoral connections. Table 1 presents the summary of Vienna's provincial monetary input-output table as of 2015. The complete sectoral details are provided in Tables S–C in the supporting information file "S2".

Based on the regional input-output table (Table 1 and Tables S–C), "mining and quarrying" and "agriculture, forestry, and fishing" are the weakest sectors in the urban economy. Those two sectors and "manufacturing" have shown dependence on imported products. The highest importer was the "manufacturing" sector with 33% of products imported from outside of Vienna region. In addition, all industries, except for "information and communication", "electricity, gas, water supply, sewerage, waste, and remediation services", "professional, scientific, technical, administrative, and support service activities", "financial and insurance activities", could be characterized by negative net incomes (i. e. income-expenditure). The "manufacturing" and "human health and social work activities" sectors had the lowest net incomes i.e., −10237.62 and −1684.4 million €, respectively. These negative values are due to the large import shares in the total outputs of those sectors. Table 2 presents the summary of the energy input-output table for Vienna, as of 2015. The complete sectoral transactions are provided in Tables S–D in the supporting information file "S2".

As shown, "agriculture, forestry, and fishing", "manufacturing" and "electricity, gas, water supply, sewerage, waste, and remediation services" are characterised by the largest share of renewable energy. The "mining and quarrying" sector did not use any renewable energy inputs

Table 1
Summary of the monetary input-output table for the Vienna region, as of 2015.

Sector	Intermediate Consumption	Value Added	Imports	Final Demand	Total output
Agriculture, forestry, and fishing	556.30	168.06	25.00	318.42	749.35
Mining and quarrying	103.00	35.04	22.00	66.65	160.04
Manufacturing	9001.95	7452.29	5848.84	16086.46	22303.08
Electricity, gas, water supply, sewerage, waste, and remediation services	2250.30	432.50	1945.00	1266.65	4627.80
Construction	3472.20	333.04	3372.00	4207.18	7177.24
Wholesale and retail trade, repair of motor vehicles	4527.69	453.71	10185.00	11757.16	15166.40
Transportation and storage	2897.17	1051.04	4406.00	4708.04	8354.21
Accommodation and food service activities	1266.73	514.69	2681.00	3850.59	4462.41
Information and communication	1191.39	952.82	6543.00	5722.57	8687.21
Financial and insurance activities	1506.74	1054.40	5149.00	4896.74	7710.13
Real estate activities	1363.19	462.18	7410.00	7791.29	9235.37
Professional, scientific, technical, administrative, and support service activities	3506.88	2146.35	11657.00	11242.41	17310.23
Public administration and defence, social security	1044.37	434.14	4687.00	5866.11	6165.51
Education	350.14	149.78	5091.00	5413.55	5590.92
Human health and social work activities	1228.96	583.35	5569.00	7253.40	7381.31
Arts, entertainment, and recreation, repair of household goods and other services	700.18	207.04	3335.00	3909.03	4242.23

Where intermediate consumption, value added (income), imports, final demand (expenditure) and total output is in Million Euro (€). The sum of intermediate consumption, imports and value added is equal to the sum of intermediate consumption and final demand for each sector, representing the total economic output of each industrial sector.

Table 2
Summary of the energy input-output table for Vienna region, as of 2015[a].

Sector	Intermediate Consumption	Renewable Energy	Imports	Value Added	Total Output
Agriculture, forestry, and fishing	47.83	1150.31	130.30	24.61	1353.05
Mining and quarrying	79.56	0.00	210.20	132.80	422.56
Manufacturing	6743.86	3161.05	22433.32	496.37	32834.60
Electricity, gas, water supply, sewerage, waste, and remediation services	4710.05	7351.51	15232.57	16355.89	43650.02
Construction	1124.32	0.03	4584.16	0.00	5708.51
Wholesale and retail trade, repair of motor vehicles	3640.92	4.86	7822.04	0.00	11467.82
Transportation and storage	5197.72	6.69	20808.08	0.00	26012.49
Accommodation and food service activities	1973.23	5.30	2735.38	0.00	4713.91
Information and communication	451.81	1.27	692.17	0.00	1145.25
Financial and insurance activities	268.70	0.84	479.65	0.00	749.19
Real estate activities	507.01	0.20	501.85	0.00	1009.06
Professional, scientific, technical, administrative, and support service activities	1237.54	6.55	3534.13	0.00	4778.22
Public administration and defence, social security	4410.87	9.43	4594.68	0.00	9014.98
Education	1009.32	8.79	1036.23	0.00	2054.34
Human health and social work activities	2746.61	0.28	2275.06	0.00	5021.95
Arts, entertainment, and recreation, repair of household goods and other services	1201.66	19.80	1731.69	0.00	2953.15

Where renewable energy, intermediate use, value added, final demand and output is in Terajoules (TJ). The sum of intermediate consumption, renewable energy, imports and value added for each sector represents the total energy output of each industrial sector.

in its production process. The 'construction", "real estate activities", and "human health and social work activities" consumed the least renewable energy to sustain their production activities: 0.03 TJ, 0.20 and 0.28TJ, respectively.

These results highlight the importance of renewable energy in production activities. The renewable and non-renewable energy inputs are captured directly by upstream industries to produce primary energy products (i.e., biofuels). On the other hand, downstream sectors are dominated (services and households) by non-renewable natural energy products. Considering the high total energy consumption of these compartments (i.e., transportation and storage) and energy demand (households), sustainable consumption strategies should be adopted.

As a matter of imports, the "construction" and "transportation and storage" sectors rely on the highest share of imported energy products, 80% and 79% (out of total output), respectively. On the contrary, "human health and social work activities" and "real estate activities" use mostly local energy inputs: 55% and 50%, respectively. Overall, the sectors located on the upstream part of the energy conversion chain have a larger consumption than the downstream sectors. Notably, the "electricity, gas, water supply, sewerage, waste, and remediation services" and "manufacturing" sectors have the largest outputs: 43650.02 TJ and 32834.60TJ, respectively. Moreover, the energy sector is responsible for a significant part of the final demand (households, capital formation and exports): 16355.89TJ. Since this sector is a product of the aggregation of two industries: "electricity, gas, steam and air conditioning supply" and "water supply; sewerage, waste management, remediation activities", the overall output and final demand appear to be considerable.

Finally, Table 2 shows that downstream sectors do not deliver any energy to the final consumers (final demand). That means that the first priority of the regional development strategy should be to decrease the final energy consumption and increase investment in the "manufacturing" sector.

3.2. *Transformities of monetary and energy flows*

The positive vector of transformities for energy and monetary flows between industrial sectors of the urban economy and the environment was derived. Table 3 presents the transformities from energy and economic network data, respectively, for the Vienna region.

As given, transformities of industrial sectors based on "economic network data" were on average 78 times higher compared to the transformities based on "energy network data". This result shows that transformities based on "energy network data are more efficient in processing emergy flows to maintain 1 unit of structure (organisation). The economic services are provided by the industries as an investment to

Table 3
Transformities from energy and economic network data.

Sector	Energy network data (sej/J)	Economic network data (sej/€)
Agriculture, forestry, and fishing	8.57E+08	5.39E+10
Mining and quarrying	8.57E+08	2.17E+11
Manufacturing	6.44E+08	3.26E+10
Electricity, gas, water supply, sewerage, waste, and remediation services	8.57E+08	6.26E+11
Construction	2.66E+09	1.15E+10
Wholesale and retail trade, repair of motor vehicles	7.73E+08	1.54E+10
Transportation and storage	2.51E+09	2.37E+10
Accommodation and food service activities	2.66E+09	2.74E+10
Information and communication	2.15E+09	3.53E+09
Financial and insurance activities	2.39E+09	6.59E+09
Real estate activities	1.20E+09	3.12E+10
Professional, scientific, technical, administrative, and support service activities	7.14E+08	8.56E+09
Public administration and defence, social security	2.66E+09	2.91E+10
Education	1.16E+09	2.49E+10
Human health and social work activities	2.38E+09	1.56E+10
Arts, entertainment, and recreation, repair of household goods and other services	7.32E+08	2.14E+10
Renewable energy	8.03E+08	0.00E+00

other industries tend to increase the total emergy support to the process (industry). More detailed inspection shows that the transformities obtained from economic network data for "electricity, gas, water supply, sewerage, waste, and remediation services", "mining and quarrying", "agriculture, forestry, and fishing", and "manufacturing" are 730, 253, 63 and 51 times higher, respectively. This means that while these sectors receive the highest investment among industrial sectors of Vienna's economy to produce their products (i.e., investments into livestock sales barns), their actual sales to the other industries are rather small (intermediate consumption of these four sectors in Table 1). This could be related to the dependency of "agriculture, forestry, and fishing", "mining and quarrying", "electricity, gas, water supply, sewerage, waste, and remediation services", and "manufacturing" sectors on imported products and relatively small own production of these sectors compared to the demand on their products. The Smart City Wien Development strategy till 2050 included the adjustment of those industries in its program through respective subgoals: energy consumption (renewable imports and efficiency), urban farming, urban mining (from non-renewable to recycled products), and productive city (eco-industrial park).

On the other hand, the most efficient industries were "information and communication" and "financial and insurance activities" with the divergence of only 2 and 3, respectively. This result means that transformities based on "economic network data" are 2 and 3 times lower compared to the transformities based on "energy network data" for "information and communication" and "financial and insurance activities", respectively. This result also implies that these two services (tertiary sectors) were still underdeveloped in 2015. The high transformity values based on "energy network data" associated with these two sectors are related to their considerable direct energy consumption and their position in the middle of the energy conversion chain (Zhang et al., 2014b). Therefore, the other priority should be to increase energy utilisation efficiency and decrease the direct energy consumption of those sectors.

The transformities based on "energy network data" of "construction", "accommodation and food service activities", and "public administration and defence, social security" were the highest and were about 4 times that of the "manufacturing" sector (6.44E+08 seJ/J). The "public administration and defence, social security" is at the end of the industrial supply chain, indicating that its transformity based on energy flows should be low. The transformities of "construction" and "accommodation and food service activities" are higher than the energy and basic industrial sectors. Therefore, the energy consumption of these sectors should be reduced, and the technology should be upgraded to improve energy utilisation efficiency. The transformities based on "economic network data" of "electricity, gas, water supply, sewerage, waste, and remediation services", "mining and quarrying", "agriculture, forestry, and fishing", and "manufacturing" sectors were the highest: 6.26E+11 seJ/€, 2.17E+11 seJ/€, 5.39E+10 seJ/€, and 3.26E+10 seJ/€, and these transformities were 95, 33, 8 and 5 times that of the sector with the lowest magnitude, namely "financial and insurance activities". These sectors are positioned at the beginning of an industrial supply chain, indicating that their transformities based on economic flows should be the lowest. Therefore, these sectors should decrease their dependence on machinery by promoting labour force, substituting expensive machinery and raw materials (i.e., crude oil, steel) with the cost-effective solutions (i.e., solar energy, fuelwood) and increasing the reuse and recycling of materials (i.e., use of animal waste to produce biogas and renewable diesel to satisfy "energy "and "transportation" demands, respectively).

Finally, the results show that the matrix inversion method overcame the problems of initial guess or estimation of transformities that could lead to a different solution vector as the solar energy vector is known prior to the analysis.

3.3. Results of Hybrid-unit emergy input-output analysis of Vienna region

Table 4 summarises the results obtained from the hybrid-unit emergy input-output model for Vienna for the year 2015. The complete sectoral transactions are provided in Tables S–E in the supporting information file "S2". The "energy" industries include industries involved in energy extraction and production. The energy extraction category includes "agriculture, forestry, and fishing" and "mining and quarrying". According to the SEEA-Energy energy production category incorporates "electricity, gas, steam and air conditioning supply" and a few sub-processes in the "manufacture" sector (i.e., Manufacture of coke and refined petroleum products). We used highly aggregated data on "electricity, gas, water supply, sewerage, waste, and remediation services" and "manufacturing" sectors since detailed information on sub-sector and sub-processes involved in energy production was not available. Other industries were considered non-energy industries (Guevara and Domingos, 2017).

In this study, the "Renewable energy sector" was considered a separate category of energy industries.

Table 4
Total emergy use for Vienna region.

Sector	Emergy use (seJ)
Renewable energy	2.08E+19
Electricity, gas, water supply, sewerage, waste, and remediation services	1.03E+19
Agriculture, forestry, and fishing	1.03E+18
Mining and quarrying	6.82E+16
Manufacturing	6.37E+18
Construction	4.07E+18
Wholesale and retail trade, repair of motor vehicles	5.92E+18
Transportation and storage	1.36E+19
Accommodation and food service activities	7.80E+18
Information and communication	1.32E+18
Financial and insurance activities	1.06E+18
Real estate activities	1.24E+18
Professional, scientific, technical, administrative, and support service activities	2.01E+18
Public administration and defence, social security	1.95E+19
Education	2.05E+18
Human health and social work activities	1.13E+19
Arts, entertainment, and recreation, repair of household goods and other services	1.76E+18
Total emergy use	1.10E+20

Emergy use of each sector allows us to understand the magnitude of emergy support to each industry of Vienna's economy. The "renewable energy" sector uses the most emergy among sectors, while the consumption of "mining and quarrying" was the lowest among sectors: 2.08E+19 seJ and 6.82E+16 seJ, respectively.

The lowest value of emergy consumption by the "mining and quarrying" sector highlights that the Vienna government is focused on improving renewable energy production (i.e., capturing of energy from biofuels by the agriculture sector) and circular economy strategies (i.e., use of buildings and vehicles inside Vienna as sources of processed raw materials such as copper and aluminium).

The sector "Agriculture, forestry, and fishing" uses only slightly more emergy (1.03E+18 seJ) compared to the "mining and quarrying" sector. Vienna's Region is ranked the last by the yearly volume of agricultural production despite being the most populated region in Austria (Statistik Austria 2020), indicating that the "agriculture, forestry and fishing" sector is in a similar situation in terms of investments as "mining and quarrying" sector. Considering the importance of the "agriculture" sector in renewable energy production (i.e., bringing raw materials into the system), allocating more investments into this sector could assist the government in meeting economic and environmental targets. "Electricity, gas, water supply, sewerage, waste, and remediation services" is the second-highest user among upstream sectors. In fact, large power plants with an output exceeding 20 MW are in Vienna Region.

The "Renewable energy" sector is supported by a large emergy consumption, confirming the importance of renewable energy in the context of Vienna's regional economy. Currently, organic agriculture occupies only 17% of the Vienna region's agricultural land (Green and Open Spaces STEP, 2025). By 2030 this land for organic agriculture is planned to be expanded using city areas to promote the neighbourhood and community gardens for organic food production (Green and Open Spaces STEP, 2025). Thus, the use of renewable energy sources (i. e., solar energy) and their importance in social production and life is expected to increase in the future. Hence, it is recommended to improve the share of renewable energies in sectors' consumption.

The "construction" sector uses less emergy, amounting to 4.07E+18 seJ. The moderate use suggests that this sector is still in the developing phase. The energy-intensive process such as "manufacture of coke and refined petroleum products" are located outside of the region. Therefore, the "manufacturing" sector uses emergy at a moderate level compared to other upstream industries. This result is similar to "construction".

"Public administration and defence, compulsory social security", "transportation and storage" and "human health and social work activities" are characterized by the highest emergy consumption among industries: 1.95E+19 seJ, 1.13E+19 seJ, and 1.13E+19 seJ, respectively. Compared to other sectors, the highest value of those sectors confirms a strong policy commitment to provide high-quality social services oriented towards smart cities and urban sustainability in line with Vienna's development strategy (Urban Development Plan STEP, 2025). Since this sector is responsible for the provision of social services, more extensive development plans, require more investment into "public administration" to develop this sector to meet the demand for transportation infrastructure (80% of trips with eco-friendly means of transport such as bicycle by 2025) and social infrastructure (i.e., Vienna Hospital Concept 2030) (Economy and Innovation Vienna, 2030). "Wholesale and retail trade, repair of motor vehicles" consumed 6 times more emergy compared to the "agriculture, forestry and fishing". This difference stems from lower agricultural investments since the magnitude of the indirect consumption increases with progression along the supply chain. The wholesaling process (i.e., distribution of electricity, natural gas, farm, and pharmaceutical products, etc.) is more money-intensive compared to exchanges among upstream sectors (i.e., agriculture and manufacturing) due to benefits obtained from the expanded consumer market (long distribution channels of goods through numerous retail stores, tertiary consumers, or other manufacturing wholesalers) before reaching the end-consumer (i.e., households).

Since the investment of downstream industries into the upstream components (extractive and productive industries) drives the development and technological advancement of the upstream industries, two strategies can be considered. The first strategy regards supply-side interventions (i.e., to reduce non-renewable energy production by the traditional agriculture, enhancing sinks, fossil fuel offsetting, and increase the share of renewable energy production by the "agriculture" sector to promote and support the downstream sectors characterised by low emergy consumption such as financial and insurance activities) (Scherer and Verburg, 2017). To operate heavy farming machinery, process foods, refrigerate goods during transportation, create packaging materials, and manufacture and transport agrochemicals such as fertilisers and pesticides, a large amount of natural gas obtained from the Vienna Basin is necessary (Mayer and Schatz, 2020). Switching to natural fertilisers such as animal manure and adopting manure management practices to capture biogas via anaerobic digestion for energy might be a good solution for reducing non-renewable energy consumption (Scherer and Verburg, 2017). In addition, solar-powered water pumps for irrigation, solar dryers such as solar drying systems based on an evacuated tube collector (ETC), solar greenhouses based on concentrated PV thermal technology for their heating and cooling, and ventilation for agricultural enterprises such as pig farms to keep in check the temperature and air quality (Hussain and Lee, 2015). As of sink, the productivity of small areas associated with traditional agriculture in the Vienna Region should be improved through investments to save the natural area for the generation of environmental support to Vienna's economy and to reduce additional energy requirements stemming from agricultural yield losses associated with climate change and to provide an additional land area for renewable energy production (Scherer and Verburg, 2017). Supply-side interventions are mainly concerned with the improvement of productivity and deliver ability of producers, while demand-side interventions are concerned with consumers' consumption and receiver ability (Creutzig et al., 2016; Wang, 2020; Wieland et al., 2019). The agriculture and mining sectors are the most underdeveloped sectors in the region (Zhang et al., 2014b), with the least consumption originating from other sectors (both direct energy and indirect monetary consumption), thereby failing to satisfy the demands of "financial and insurance activities" and "real estate activities "for energy consumption, which in turn are unable to invest in the agricultural and mining production. Therefore, it is important to promote local direct renewable energy consumption and to increase the share of imported agricultural and mining products in the consumption of "financial and insurance activities" and "real estate activities "(Scherer and Verburg, 2017). This can be archived through the conversion of solar radiation into electricity for lighting purposes using photovoltaic cells and solar thermal energy to heat real estate properties such as condominiums. Vienna Government is mostly focused on subsidising the decarbonisation measures in the housing sector (final energy consumption of households) by the deployment of PV in the multi-apartment building sector is supported by subsidies through Photovoltaic Systems Program (Gollner et al., 2020; Komendantova et al., 2018; Neumann et al., 2021). These measures need to be extended for these two tertiary sectors to switch to renewable energy consumption for light and heating purposes (Komendantova et al., 2018). In addition, it is advisable to decrease the direct energy use by these two tertiary sectors. In addition, it is advisable to reduce the direct energy use from energy producers (energy and manufacturing sectors) by these two tertiary sectors. Decreasing energy production of secondary energy products (heat and electricity) by the energy sector used to manufacture plastics and paper products would reduce direct energy consumed by two targeted tertiary sectors. For this purpose, demand response by the end-users, short-term adjustments of users' consumption to renewable energy generation via a change in behaviour and use of technology such as a shift of energy consumption in time (using a building as energy storage), contributes to the decrease of electricity consumption and energy use efficiency by the tertiary sector, saving monetary resources (revenues from electricity cost reduction) for their development (Kirkerud et al., 2021; Wohlfarth et al., 2018). Kirkerud et al. (2021) found that territories with a high share of hydropower use benefit economically from applying demand response to electric space heating and water heating. Vienna Region also falls within this category (Vienna City Administration, 2015; "Austria: Power production share by source, 2021," 2022). Therefore, it may be a promising option for improving electricity management, leading to a decrease in direct energy consumption of non-residential buildings and the improvement of the investment capacity of two critical tertiary industries. The same measure also needs to be implemented in other service industries since saving their funds contributes to the investments in critical energy industries ("agriculture, forestry, and fishing" and "mining and quarrying") and tertiary sectors (financial and insurance activities" and "real estate activities "). Thus, the supply-side and demand-side interventions should be applied to improve the development of the Vienna metabolic system in terms of monetary generation and energy consumption by tertiary industries and energy production and monetary consumption by energy industries.

Furthermore, these results mean that the total emergy use of the Vienna region (1.10E+20) should be increased to accommodate the needs of the urban socio-ecological system. The higher total emergy use reflects the higher "real wealth" in the system (Campbell et al., 2014). According to the 4th principle of thermodynamics (Maximum Empower Principle), any system increases total emergy flow during its self-organization process to maximise its emergy flows exchange, production, and emergy use efficiency in the system to survive in the long-term perspective (Odum, 1983, 2007; Lahlou and Truffet, 2020). The regions are committed to grow GDP (economic growth) while decreasing their direct energy consumption, i.e., to minimize environmental impacts while sustaining urban welfare (human health and well-being) (Campbell et al., 2014; Donati et al., 2020). For survival and sustainability in the long-term perspective, the harmonious relationship between socio-economic and ecological sub-systems of the urban ecological system needs to be considered for the mutual benefits of humans and nature (socio-economic and ecological benefits). For this purpose, it is essential to increase monetary support (i.e., investments) to the sectors characterised by low emergy consumption ("agriculture, forestry, and fishing" and "mining and quarrying"). Thus, using a strategy that results in the more considerable total environment support provided to Vienna's socio-ecological system seems reasonable.

3.4. Research implications, limitations, and future scope

The hybrid-unit emergy input-output model can be applied to any region worldwide, subject to the availability of national monetary accounts and regional energy balances to construct the model. Statistical offices can use these data to improve the input-output databases with a more detailed description of emergy flows and economic transactions in cities and regions.

Researchers into urban metabolism and regional (local) administrators will benefit significantly from the application of those accounts to their works. The model will assist managers and policymakers worldwide in developing sustainable resource management policies targeting the improvement of vulnerable sectors in line with "integrated wealth assessment" and "circular economy" principles.

We encountered some practical problems during the estimation procedure. The outputs-inputs matrix Z constructed from economic network data does not have a zero 'eigenvalue' due to the regionalisation method employed instead of the survey or partial survey methods. For this reason, it is not possible to use Eigenvalue–eigenvector or Singular Value Decomposition (SVD) method to obtain transformities using regional monetary network data.

The other limitation was the unavailability of region-specific economic data to construct a regionalised version of the national monetary input-output table. Therefore, we regionalised the national tables using the industry earnings and location quotient approach to obtain the approximate version of the regional monetary input-output table. Three issues could lead to overestimating intermediate consumption and final demand from the regionalisation (downscaling) procedure. Firstly, production technology is assumed to be uniform among regions within a single country, resulting in regional production share associated with a specific industry, excluding imports, equal to the national one (Miller and Blair, 2009). However, suppose the technology used in the production process differs (coal-fired versus gas-fired power plant for electricity production). In that case, the share production is assumed to be the same as on the national level (i.e., coal-fired in all Austrian regions, even though no coal is used in Vienna). This suggests that industries with LQ = 1 might have a lower share of production than 1. For instance, the productivity of the energy industry can easily be underestimated since, nationally, hydropower plants are dominant, but in Vienna, nearly half of power plants operate using natural gas (40%) (Vienna City Administration, 2015; "Austria: Power production share by source, 2021," 2022). Assuming hydropower is the only source of power generation for electricity plants in Austria underestimated productivity of natural gas power plants located in Vienna leads to the underestimation of share of production of this industry in underestimating the share of production of this industry in the Vienna region. This non-uniformity in production recipes for electricity across regions in Austria is not incorporated into the LQ estimation procedure (Miller and Blair, 2009).

The other issue is that it is assumed that either net exporter or importer of the same products, leading to the overestimation either of imports (LQ < 1) or exports (LQ > 1) included in the location quotient of a specific industry. In our case, the share of imported goods and services used by "manufacturing" sector" might be underestimated since exports for this sector have not been incorporated in the estimation of location quotient (LQ < 1). The same applies to "transportation and storage" sector, for underestimation of exports of liquid biofuels such as biodiesel. Finally, there is an issue with the share of regional production (A^r) not exceeding the national one (A^n), as it is not clear if the percentage of the national output exceeds a national average. Some studies even emphasised that the share of regional production often transcends regional administrative boundaries. Industries usually represent economic clusters, agglomeration of industries that can have administration offices in the city, but its production activities associated with the Vienna region lie outside the administrative boundary (Pominova et al., 2021). The sector that falls under this requirement is the Manufacturing sector, for which a limit of 100% may be underestimated.

It's also important to note that we downscaled production (make matrix) and consumption (use matrix data). (Liu and Vilain, 2004; Miller and Blair, 2009). This approach has been applied only once to estimate the number of commodities sold to each industry in a commodity-by-industry format. In simple terms, they derived the supply-side version of the monetary use table (consumption of commodities by industries). On the other hand, we applied this approach to downscale national monetary supply, national energy supply, and use tables. The application of LQ to downscale both production and consumption data introduces the risk of underestimating the productivity of industries in the Vienna Region.

The location quotients should reflect production characteristics for the supply table (share of value-added, employment) and consumption characteristics (i.e., percentage of monetary of final energy demand) for the use table. The value-added of final demand data should be sufficient when both tables conform to the balance of production units (W^T=Fe). Application of the original version of the location quotient is associated with industrial input-output tables. Therefore, Liu and Vilain (2004) especially stressed that the use of energy inputs (products) evaluated in monetary terms could be overestimated (i.e., close to the national counterparts) due to the difference in usage of energy inputs between regions and nations. Therefore, the overestimation of monetary use by electricity, gas, water supply, sewerage, waste, and remediation services (D + E) results in an overestimation of this sector's emergy consumption. Lastly, the supply-driven commodity-by-industry input-output model assumes that any primary input from the environment or production factor (labour, value-added) drives changes in the total value of production (sectoral gross inputs) (Miller and Blair, 2009; Wieland et al., 2019). This implies the responsibility of industry energy extraction industries (direct users of natural resources such as crude oil, natural gas or their monetary equivalents) and other energy industries located at the beginning of the supply chain (Wieland et al., 2019). Our results suggest that the sectors with higher value of renewable energy inputs, imports and value-added among energy industries can have unrealistically large emergy consumption: Manufacturing (C), Electricity, gas, water supply, sewerage, waste, and remediation services (D + E). When the results are interpreted, these uncertainties associated with regionalisation should be taken with caution.

In addition, we encountered the sectorial aggregation problem in regional energy balances. The "service" sectors were aggregated into a single industry, and only the total intermediate consumption was available. We applied the location quotient to regionalise the national energy use table in this case. Lastly, the final results obtained from the hybrid-unit emergy input-output model can be overestimated for some industries since this model is more suitable for evaluating downstream consumption regionalised from national consumption and imports are excluded (limited to the regional boundary). These industries are "electricity, gas, steam and air conditioning supply" and "forestry". Since this model still has been only applied once to the national level, testing on different regional datasets is required to ascertain whether or not the consumption of these two sectors deviates from this application.

The approach used in this paper does not allow disaggregating the use of emergy in different resource categories for detailed analysis of ecosystem services supporting the sector in the Vienna Region because this approach is only applicable to the industry-by-industry input-output system (Guevara and Rodrigues, 2016). The hybrid-unit emergy input-output model is used to estimate the emergy consumption of each sector in the urban economy. The disaggregation using the location quotient approach to differentiate different sub-sectors (sub-processes) associated with each industry (production process) in terms of supply and use is also not possible. The minor detail of regional value-added and employment (AUSTRIA, 2015e). The regional value-added in the national statistical database is highly aggregated, containing only 16 industries. Regional data on final energy consumption by energy product is available for 11 sub-sectors associated with the "manufacturing" sector, five sub-sectors related to "transport and storage", "mining and quarrying", "construction", and 'tertiary sector' (AUSTRIA 2015d). The most detailed data do not include any data on renewable energy input and energy residuals, sub-sector associated with the other 14 sectors following NACE classification, excluding "manufacturing" and" transportation and storage". Therefore, the future directions could explore different models, such as the approximate multi-factor energy input-output model used to disaggregate the energy sector by sub-processes (Guevara and Rodrigues, 2016). The other option is to use Vienna's household budget survey, which is compiled on a quinquennial basis and covers biennial data (i.e., 2014–2015). However, the monetary household consumption data can be used only when budget survey data is reallocated from the standardised UN Classification of Individual Consumption by Purpose (COICOP) to CPA 2008 classification through a concordance matrix (Smetschka et al., 2019). The same procedure should be performed for the Austrian household budget survey, which is also complied with using the COICOP classification (Smetschka et al., 2019). Then, the location quotient for each sector can be estimated and applied to downscale national monetary use data. Future studies should explore different options for disaggregation of monetary (and energy) supply data to allow a more detailed analysis of the ecosystem services used to support each of the sectors of Vienna's economy.

The model can be handy in other hybrid-unit input-output applications such as detailed and complete energy, material consumption and GHG emissions accounting based on a 'full life-cycle perspective'. In addition, this approach can be complemented with environmentally extended input-output analysis (EE-IOA) to obtain more reliable findings on sectors responsible for high consumption and emissions within city boundaries.

Future studies can refine our monetary and energy data by using an aggregated final demand vector from national research institutes. For example, for Vienna, the data can be obtained from the Austrian Institute of Economic Research (WIFO) and the Austrian Institute of Technology (AIT). Moreover, future research should estimate more realistic values of transformities from energy network data by using the reflexive method combined with Eigenvalue–eigenvector or Singular Value Decomposition (SVD) methods. Those methods use statistical criteria (least squares solution) that remove the need for the specification of numeraire (i.e., solar energy). Future studies can also combine this approach with ecological network analysis to determine if the urban metabolic system is emergy-efficient using a system's resource efficiency index or to analyse the utility of relationships between the sectors to identify and assess the problems leading to the inefficient or unsustainable resource consumption processes. Those directions can provide a basis for understanding and improving the development of the urban metabolic system in terms of circular metabolism.

4. Conclusion

The results of this study show that the "Renewable energy" sector in Vienna's Region is supported by a large emergy consumption, confirming the importance of renewable energy in the context of Vienna's regional economy. Among the tertiary sectors, "public administration and defence, social security", "transportation and storage", and "human health and social work activities" are characterised by high emergy support, confirming a strong policy commitment to provide high-quality social services oriented towards smart cities and urban sustainability in line with the Vienna's development strategy (Urban Development Plan STEP, 2025). The lowest emergy use of the "mining and quarrying" sector shows that Vienna's government does not prioritise this sector and is focused on improving circular economy strategies and renewable energy production. Moreover, the demand for products of the "agriculture, forestry, and fishing" sector in this region is the lowest, leading to the lowest consumption. The most insufficient production of this sector among the Austrian regions relates to the high concentration of social services in the Vienna Region and large areas occupied by forest ecosystems. This sector is in the early stage of developing its distribution channels. In contrast, "electricity, gas, water supply, sewerage, waste, and remediation services" and "wholesale and retail trade, repair of motor vehicles" sectors are opposite. The investments in "agriculture, forestry, and fishing" sector should be prioritised due to the role of this sector in renewable energy production and its position in the supply chain: acceptance of renewable energy from the source and its transfer in the production and supply of agricultural products (i.e., farm products) to all other sectors.

Future strategies should consider applying supply-side and demand-side interventions to continue improving the share of renewable energies while promoting and supporting sectors with low emergy consumption (i.e., organic agriculture). Future research should focus on integrating our model with ecological network analysis to study the system-level emergy metabolism and relationships between system's internal processes. Despite meeting the Sustainable Cities Goal seems challenging, the multi-criteria framework constitutes a tool to assess the resource efficiency aspects of cities.

The integration between emergy accounting and the hybrid-unit energy input-output model proved to help overcome shortcomings of single criteria approaches when investigating internal problems and associated external upstream environmental burden (environmental consumption). Particularly, this framework allowed to incorporate economic services provided by energy industries to each other and non-energy industries (tertiary sector), isolating and accounting separately for emergy consumption of energy and tertiary sectors in Vienna's urban metabolic system. Finally, using a detailed representation of the energy and economic transactions according to the energy conversion process and levels of energy use in the economy provided by the framework allowed us to accurately identify emergy consumption by each energy and non-energy production sector. The proposed multi-criteria and system-based approach for studying urban system provide an avenue for exploring the interplay of environment, economy, and monetary and physical resources in any urban socio-ecological system worldwide and, ultimately, could support local managers and policymakers in charge of developing environmental policies based on the "integrated wealth assessment" and "circular economy" principles.

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

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