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The Urban Food-Water-Energy Nexus Footprint Model: An Early Application

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Contents

1. Background

The 1992 United Nations Conference on Environment and Development made the first call for the creation of sustainability indicators to measure the changes in the social, economic, political, and physical factors of sustainability. Different concepts of carbon (Rees, 1992) and water footprints (Hoekstra, 2011) have emerged as indicators that provide stakeholders with easily understandable information on the environmental effects of their resource consumption. However, footprint models are usually focused on measuring the extent to which a single resource is used which provides limited information on the interdependencies between intertwined resource systems.

Resource systems are frequently integrated and dependent on each other. A particular example of this, which received significant attention in recent years, is the nexus between food, water, and energy (FWE) (Daher & Mohtar, 2012). One example out of many potential interdependencies among FWE resources is the impact of energy cost on irrigated agriculture, which can in turn affect the availability of certain food crops (Komendantova et al., 2020). Such interdependencies within the nexus have not received sufficient attention in research so far, despite their importance for finding pathways towards sustainable resource use.

The Nexus Footprint is an emerging indicator (Maiwald, 2021; Shu et al., 2021; Wahl et al., 2021) that aims to quantify the intersections within the highly interconnected FWE web of a given region. The set of values comprising the Nexus footprint are the values for the direct consumption of food, water, and energy, as well as the water footprint of food, the water footprint of energy, the carbon footprint of food, and the carbon footprint of water. The purpose of the Nexus Footprint model is to provide values allowing stakeholders to identify and visualize trends in urban resource consumption as well as to provide a scientific basis for objective comparison (Wahl et al., 2021).

1.1 Objective of the paper and description of case study areas

The purpose of this discussion paper is to test how a Nexus Footprint could be operationalized empirically. To examine the applicability of this method across different settings, three case study cities (see Table 1) with diverging resource management situations were selected:

1. The first case study examines Pune, India, a large urban hub in the state of Maharashtra. Among other factors, Pune's FWE system is shaped by water access disparities due to wealth inequality which results in resource constraints in the wake of the city's rapid urbanization (Butsch et al., 2017).

2. The second case study examines Amman, the capital city of Jordan, which faces an ongoing water shortage and is considered one of the most water-scarce countries in the world (Ray et al., 2012). Amman's water scarcity is impounded by rapid population growth and is further exacerbated by the effects of climate change. Jordan has a negative virtual water balance (Talozi et al., 2015), meaning that it exports more water than it imports which adds further stress on water sustainability.

3. The final case study city is Vienna, Austria, which exhibits patterns of high water- and carbon-intensive consumption. However, the majority of its electrical energy comes from

renewable sources, there is innate access to high-quality drinking water supply, and relatively high self-sufficiency rates for food products (Leidwein et al., 2013).

Table 1: Case Study City population, average household size, median income, and climate classification information

	Pune (2011)	Jordan (2013)	Vienna (2018)
Population	3,124,458[a]	3,411,400[b]	1,888,776 [c]
Average household size	4[d]	5[e]	2[c]
Median Income (USD per capita per year)	\$1,620[d]	\$2,673[e]	\$38,951[c]
Köppen Climate Classification	Hot semi-arid (BSh) bordering tropical wet and dry (Aw)	Hot semi-arid (BSh)	Oceanic (Cfb)

Data for Pune are from Pune Municipal Corporation (2011)[a] and (Zhu, in preparation)[d]. Data for Amman are from the Jordan Department of Statistics (2021)[b] and *Household Expenditure and Income Survey* (2013)[e]. Data for Vienna are from Statistics Austria (2020)[c]

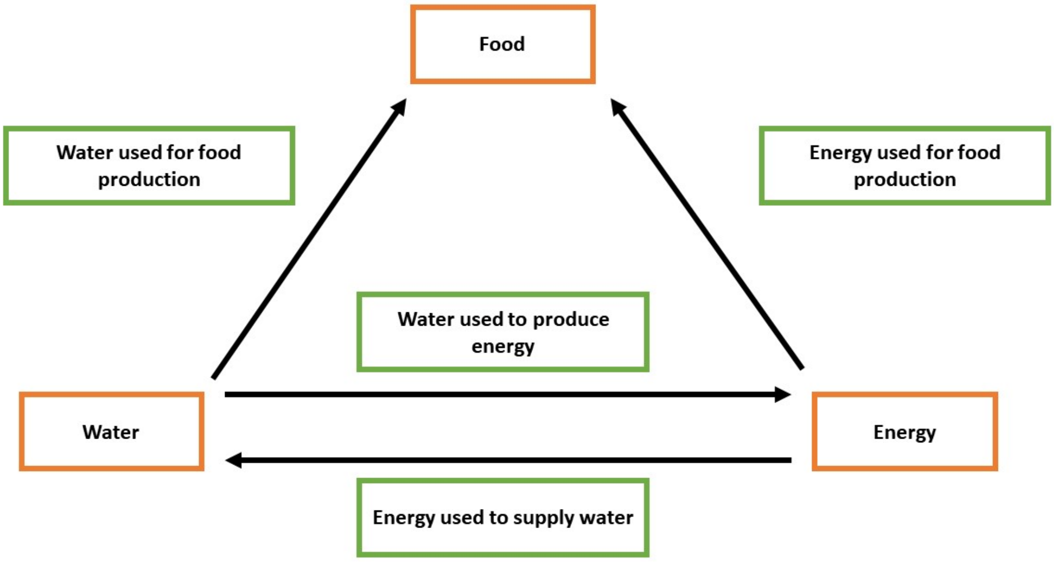
1.2 The Nexus Footprint Concept

The main idea of the Nexus Footprint concept applied in this paper (Maiwald, 2021) is to quantify linkages or interactions between the three resources of the FWE systems (see Figure 1). Basic indicators are derived from this conceptualization as part of a *bottom-up* footprint assessment (see Table 2). The indicators are based on household-level consumption data of various consumer goods and services to provide a representation of *direct* resource consumption per capita and indicate how average lifestyles in the case study areas diverge.

The aim of compiling these indicators is to not only determine consumption levels but to use them as a foundation to quantify interactions within the FWE nexus that involve at least two of the FWE components. For example, the dependence water has on energy relies on including indirect factors such as the energy consumed by water pumping, filtration, etc. (Mekonnen & Hoekstra, 2011). The goal is to illustrate how resource consumption in one domain of the nexus can affect the resources in another, without providing a holistic or comprehensive overview of potentially existing *indirect* interactions and resources uses (Maiwald, 2021).

FWE interrelations can only be uncovered after analyzing both direct and indirect resource consumption. The interrelations in the nexus footprint approach are important for understanding household-level consumption of FWE resources and point towards potentially existing vulnerabilities and unsustainable consumption patterns (Maiwald, 2021). Figure 1 displays the conceptual Nexus Footprint Model. While many types of linkages exist, this early application concentrated on energy and water used for the food consumed, and the energy for the water consumed on a per-capita scale.

Figure 1: Conceptual Nexus Footprint Model depicts interactions between the food-water-energy nexus. *Note that due to insufficient data, the water used to produce the energy consumed was not assessed in this early application.*



2. Methods

2.1 Applying the Nexus Footprint concept

To calculate nexus footprint values, data quantifying the direct consumption of city-level resources was used to determine annual per-capita averages. Average carbon and water emissions intensities from literature were used to quantify interactions among dimensions. Due to a lack of data, the water consumed to generate or transport energy was not included in this application.

2.2.1 Carbon and water footprints of average food consumption

The first nexus footprint calculated was the total water footprint used to produce and process food in the average diet for each case study city (W_{FP}). The water footprint of food was expressed as:

$$W_{FP} = \sum_{i=1}^{14} F_i \cdot \omega_i \qquad (1)$$

where F_i represents the average consumption of food (kg) from the combined 14 food categories *i* ∈ $\{1,2,\ldots,14\}$(listed in Table S1) per year, and ω_i represents the global average water footprint (m^3 kg^{-1}) of each F_i, retrieved from Mekonnen & Hoekstra (2011). The 14 food categories (i.e., vegetables, fruit, beef, mutton, etc.) were selected based on data availability and food item standardization across the available data from the three case study cities. The categories include highly consumed food items between each city, excluding alcoholic beverages. The per-capita amount of food consumed by each case study city as well as the data sources for each category are shown in Table S1 of the supplementary information.

The Carbon footprint for food (C_{FP}) was expressed as:

$$C_{FP} = \sum_{i=1}^{14} F_i \cdot C_i \qquad (2)$$

where C_i represents the global average greenhouse gas emissions (kg CO_2e) (Poore & Nemecek, 2018) of each food category which were applied to F_i. These emission factors were reported in carbon dioxide equivalents and thus included non-CO_2 greenhouse gases as well.

2.2.2 Carbon footprint of average residential water consumption

In two of the considered case studies (Pune & Amman), households frequently relied on multiple sources for bulk quantities of water. We therefore consider three of them, where applicable: Publicly supplied network water, well water, and tanker water. This application primarily measured the emissions from the energy used to pump and transport the water to households. The energy used to purify or treat water was not included in the values presented for 'energy used to supply water' due to a lack of data.

Publicly supplied water ($W_{network}$) is the average consumption of water from the public utility which connects households to major water sources through a series of pipes. Well water (W_{well}) represents the average water consumed from the operation of wells tapping into groundwater aquifers, including water from public and private wells. Finally, tanker water (W_{tanker}) is water purchased from the delivery of water in tanker trucks transporting water directly to consumers. Due to comparatively low quantities and lack of reliable data, the consumption of bottled drinking water was excluded from the analysis. The total direct water consumption W_{total} is calculated according to the following equation:

$$W_{total} = W_{network} + W_{tanker} + W_{well} \qquad (3)$$

All forms of water supply require the usage of energy to transport water to households. The carbon footprints of network ($C_{network}$) or well water (C_{well}) were expressed by:

$$C_{network} = W_{network} \cdot E_{network} \cdot \alpha_{network} \cdot \varepsilon \qquad (4)$$

$$C_{well} = W_{well} \cdot E_{well} \cdot \alpha_{well} \cdot \varepsilon \qquad (5)$$

in which W_{well} and $W_{network}$ represent the average residential consumption (m^3) of well water or network water, per capita. $E_{network}$ represents the average electricity (kWh) used to transport water through the public network infrastructure to households. E_{well} represents the electricity (kWh) used to pump water from public and private wells. The $\alpha_{network}$ and α_{well} variables represent the average rate of electricity used to pump network and well water, per cubic meter of water (kWh/m^3). Lastly, ε represents the rate of CO_2 emissions per kWh (CO_2/ kWh) consumed. Only electricity was considered due to the fact that the public network supply is powered by electricity as well as most (98.7%) household pumps (Zhu, in preparation).

Water deliveries through tanker trucks, on the other hand, result in carbon emissions through (i) the use of fuels and (ii) usage of energy at the source of tanker water, e.g., a well or the public network. The latter use of energy is not considered here, as this is difficult to estimate from available data or already included in $C_{Network}$. The carbon emissions of water transported by tanker trucks (C_{tanker}) is therefore expressed as:

$$C_{Tanker} = \frac{\beta \cdot \gamma \cdot W_{tanker}}{T} \tag{6}$$

in which β is the average round-trip distance traveled by tanker trucks transporting water to residential neighborhoods (Sigel et al., 2017; Zozmann, 2020), γ is the carbon dioxide emitted by a middle-duty vehicle per distance travelled (kg CO_2/km) (Seo et al., 2016), T is the average volume of water transported by tanker trucks, and W_{tanker} is the average amount of tanker water consumed per capita (m^3).

2.2.3 Carbon footprint of average residential energy consumption

To calculate the carbon footprint of direct energy consumption, the direct consumption of electricity and other energy sources was calculated. The total carbon footprint of average energy consumption (C_{Energy}) was calculated as the sum of the carbon footprints of resulting from the consumption of energy from five selected sources: Electricity ($C_{Electric}$), LPG (C_{LPG}), Kerosene ($C_{Kerosene}$), District Heating ($C_{District}$), and Natural Gas (C_{NG})

$$C_{Energy} = C_{Electric} + C_{LPG} + C_{Kerosene} + C_{District} + C_{NG} \tag{7}$$

The carbon footprint of the average residential electricity consumption (C_{Elec}) was expressed as:

$$C_{Elec} = \sum_{j=1}^{n} E \cdot \alpha_j \cdot \theta_j \tag{8}$$

where E represents the average electricity used for residential purposes per capita and α_j represents the proportion of electricity generated by each energy source, *j*, (oil, natural gas, coal, etc.). The variable θ_j represents the direct carbon dioxide emissions factor for *j* (Gómez et al., 2006). For α_j, the electricity generation proportions were determined from state or national level data (see Figures 6a, 6b, 6c).

The carbon footprint of the other selected energy sources (LPG, Kerosene, district heating, natural gas) were calculated using similar expressions:

$$C_{LPG} = E_{LPG} \cdot \delta_{LPG} \tag{9}$$

$$C_{Kerosene} = E_{Kerosene} \cdot \delta_{Kerosene} \tag{10}$$

$$C_{District} = E_{District} \cdot \delta_{District} \tag{11}$$

$$C_{NG} = E_{NG} \cdot \delta_{NG} \tag{12}$$

In which E represents the average energy (kWh) used by each energy source (LPG, Kerosene, district heating, natural gas) and δ represents the direct carbon dioxide emissions factor for each energy source (Gómez et al., 2006). District heating and natural gas as energy sources used for heating were only calculated for Vienna. This is due to the fact that in both other case studies, the available data sources suggested no specific energy sources for heating, resulting from the widespread use of electrical air-conditioning systems, which are included in C_{Elec}.

2.3 Data Sources

To examine the nexus footprint of an urban area, commodity data was used to calculate the average resource consumption values. As commodity data was not always readily available at the city-level, national-level household surveys were used to supplement where household data from the case study area was not available. Data sources were also selected by their recentness. As data were generally unavailable for the same years across the three case study cities, footprints are limited in their temporal comparability.

Food consumption quantities were the largest example of utilizing different data sources to calculate a single variable, which was necessary to calculate the water and carbon footprints of food consumption in each case study city. The consumption quantities at the city-level were prioritized, however, some values were substituted by national-level data if the conversion from expenditure was unreliable or if the food category was unavailable at the city level. However, national-level values are unable to accurately depict the consumption patterns that characterize the cities within.

Information gaps for some sources were filled using values from peer-reviewed journals and grey literature reports. In the following, key data sources for each case study are briefly described:

Pune, India

To calculate the water footprint for Pune, India, Household Consumer Expenditure information from the National Sample Survey Office (NSSO) was used to identify consumption quantities of food items. The energy calculations primarily utilized data from the Pune Household Food-Water-Energy Nexus Consumption Survey, a household survey conducted by the Helmholtz Centre for Environmental Research (UFZ) to obtain information on water and energy consumption. The Pune Household Nexus survey is a thus far unpublished household survey (Zhu et al. 2022, *in preparation*) which was conducted in 2020 and includes data from 1,872 households the Pune Metropolitan Area, India. All reported values utilizing data from the survey are preliminary.

Amman, Jordan

For Amman, Jordan, expenditures for food were identified from the 2013 Household Expenditure and Income Survey (HEIS) (OAMDI, 2017). To convert expenditures (Jordan Dinar) to consumption quantities (Kilograms), market prices for food were averaged from the United Nations World Food Programme (World Food Programme, 2021). Substitutions for non-comparable data were made using national-level data from the Jordan Department of Statistics or FAO, depending on the comparability of aggregated food items.

Vienna, Austria

Statistics Austria, Austria's Federal Statistical Office, was the primary source of energy consumption and demographical data for Austria. Due to a lack of household survey data on food consumption, all food consumption values for Vienna were provided by national-level values. These national-level values were sourced from the Food and Agriculture Organization (FAO), a United Nations agency reporting food and agriculture statistics across all UN member nations (Food and Agriculture Association of the United Nations, 2021). FAO data were also used to substitute incomparable values in Pune and Amman.

3. Results

In the following, we present the outcome of this first application of a nexus footprint methodology before proceeding to discuss relevant findings for each case study in Section 4.

3.1 Food

Data on the direct consumption (kg) of the average diet was used to calculate the water and carbon footprints of food consumption (Table 2). The lowest water and carbon footprints for food consumption were found in Pune, India, estimated at 634 m^3 per year per capita and 730 kg CO_2e, respectively. The highest water and carbon footprints for food consumption were found in Vienna, Austria, estimated at 1359 m^3 per year per capita and 2516 kg CO_2e.

Table 2. Food-related Nexus Footprint data

Case Study City	Pune, India	Amman, Jordan	Vienna, Austria
Year	2012	2013	2018
Average food consumption (kg food/capita/year)	455	553	548
Water footprint of food consumption (m^3/capita/year)	634	998	1359
Carbon footprint of food consumption (kg CO_2e /capita/year)	730	1804	2516

Vienna's footprints were higher than values in Amman or Pune due to the higher consumption of animal products. The food items contributing to Vienna's higher footprints were meat (mainly beef, pork) and dairy (mainly milk, and butter). The amount of food consumed on average in each case study city is shown in Table S1 of the supplementary information. However, these values may be lower in reality due to the utilization of global averages for water and carbon emissions factors which are briefly addressed in Section 4.

Figure 2. Annual per capita consumption of food and related footprints

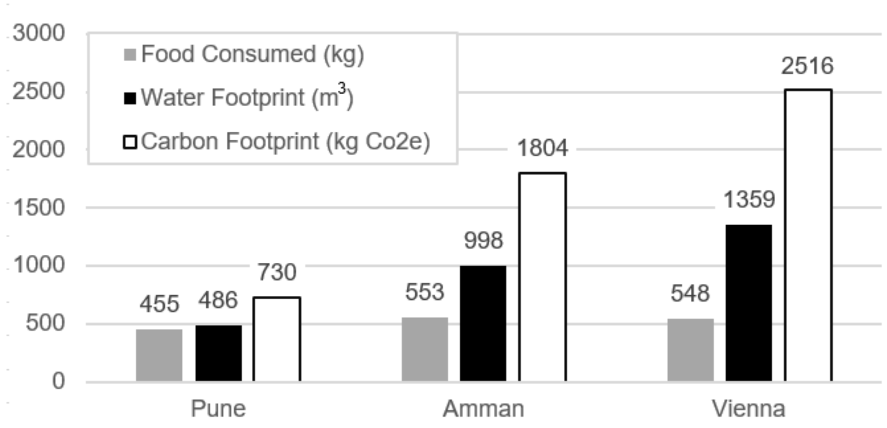


Figure 3. Food consumption quantities (kg) by plant-based food, meat, and dairy for the average diet in each case study city

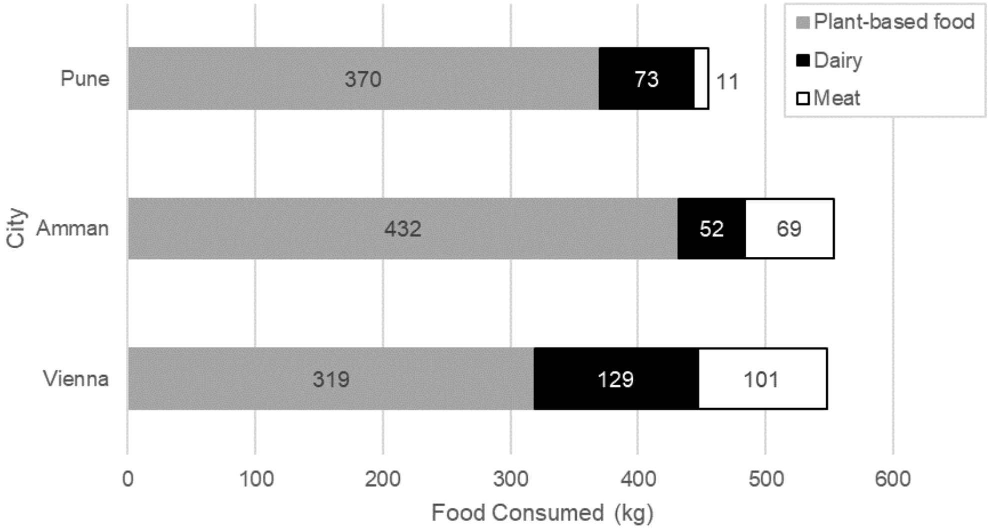


Figure 4. Water Footprints (m^3) by plant-based food, meat, and dairy categories for the average diet in each case study city

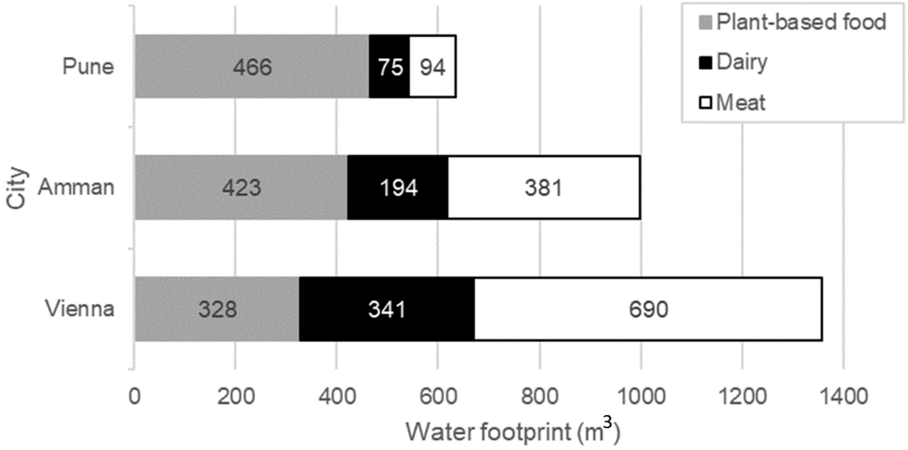
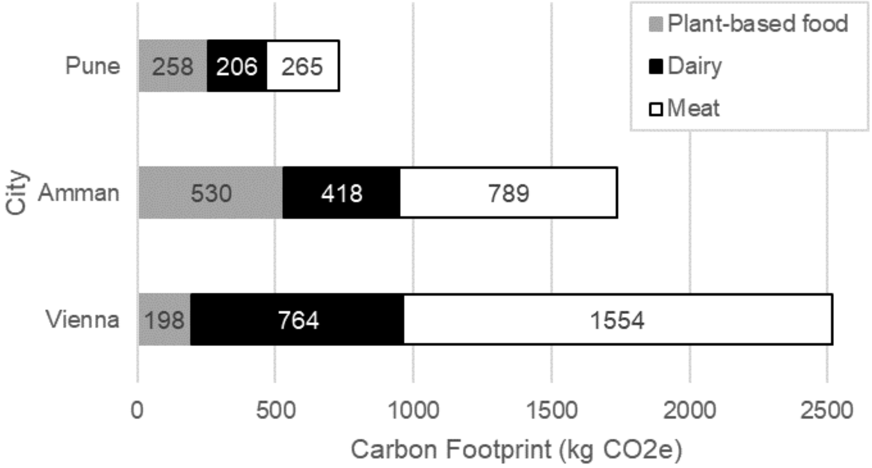


Figure 5. Carbon Footprints (kg CO_2e) by plant-based food, meat, and dairy categories for the average diet in each case study city



3.2 Water

The average residential water consumption per capita per year of the public network water, tanker truck water, and well water was calculated for each case study city. While private households in Pune reported low percentages of utilization of wells (7.7%) and tanker water services (0.02%), these technologies were important to include due to their higher relative carbon emissions. Households in Amman utilized network and tanker truck water only as the drilling and pumping of new wells is illegal in Jordan (Molle et al., 2017). In Vienna, tanker trucks are not utilized as the public network water is highly accessible. While about 3% of the public water supply is pumped from groundwater during maintenance or emergency use, electricity is generated from the water's natural gravity flow resulting in a net gain of electricity (Vienna Water, n.d.).

The data in Table 3 shows that tanker water as a secondary water source is much more important in Amman, likely due to the insufficient pipe network as well as the more generally water scarcity and the stresses on the public water system from rapid urbanization. It is also clear that on average, households consume significantly more water in Vienna. Network water consumption values for Amman were extracted from HEIS water billing data (Klassert et al., 2018). As water consumption within the first tariff block is free (except for a metering fee), values of 20 and 38 were used to substitute water quantities in the HEIS dataset.

Table 3. Average consumption of network, tanker, and well water sources per capita

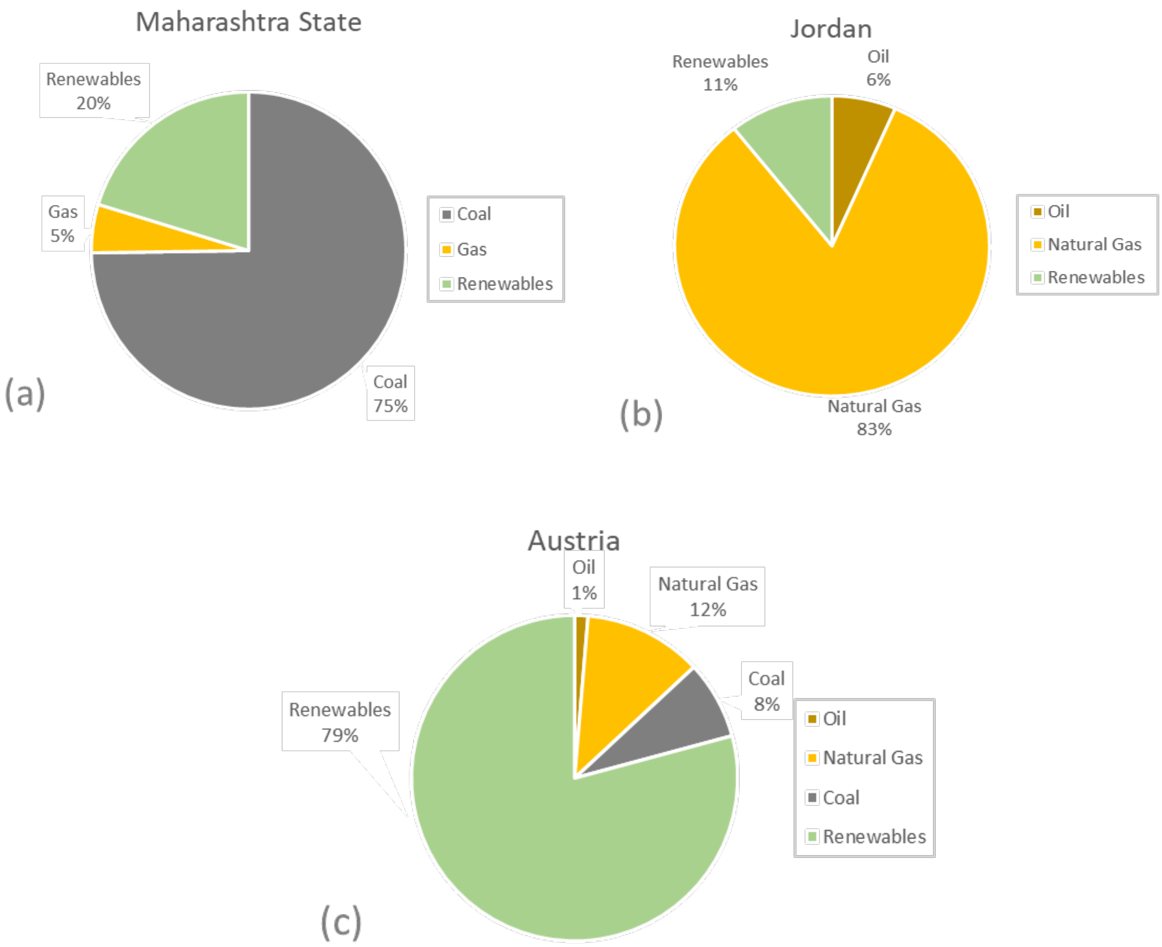
	Pune, India		Amman, Jordan		Vienna, Austria	
	Value	Year	Value	Year	Value	Year
Network water consumption ($m^{3/}$capita/year)	36	2020	37	2013	51	2012
Tanker water consumption ($m^{3/}$capita/year)	0.01	2020	0.91	2010	0	NA
Well water consumption ($m^{3/}$capita/year)	0.06	2020	NA	NA	NA	NA
Total water consumption per capita ($m^{3/}$capita/year)	36.07		37.91		51	

3.3 Energy

Carbon footprints were calculated for the average per-capita consumption of five highly consumed energy sources: Electricity, Kerosene, LPG, District heating, and Natural gas.

Electricity generation sources for Vienna and Amman came from national-level IEA data which revealed that 79% of Austria's electricity came from renewable sources (mostly hydroelectric). The remaining sources were mostly natural gas, coal, and biofuels. Jordan's electricity generation sources change considerably every year due to usage of different fossil fuels, however, for 2018, the majority was sourced from natural gas and oil with 11% from renewable sources. Pune's electricity generation source data came from the Maharashtra State Power Generation Company, a state-level source which revealed a 75% proportion of electricity generated from the burning of coal which emits the most carbon dioxide out of the energy sources used in the three case studies (94,600 kg of CO_2 per TJ). The various electricity generation sources are displayed in Figure 6 for each case study city.

Figure 6. (a) Electricity Generation Sources in Maharashtra State (2017) *(b)* Electricity Generation Sources in Jordan (2018) *(c)* Electricity Generation Sources in Austria (2015)



Energy used for heating can contribute a significant amount of carbon emissions. Outside of electricity, households in Amman and Pune rely mostly on LPG and Kerosene to fulfill heating purposes (primarily for cooking and water heating). In Vienna, however, different heating sources apart from electricity such as natural gas and district heating are used for cooking, water heating, and space heating purposes.

District Heating provides heat to homes by producing heat at a centralized plant and delivering the heated water to homes via a network of insulated pipes for space and water heating purposes. However, only a third of Viennese homes are part of the district heating network (Wien Energie, 2012b).

Table 4 includes the average per-capita carbon footprint of the two largest sources of heating energy in Vienna, natural gas and district heating. The provided carbon footprints for electricity in Table 4 include the CO_2 emissions generated by electricity consumed for purposes beyond solely heating.

Table 4. Carbon footprints of electricity, kerosene, LPG, district heating, and natural gas

	Pune, India		Amman, Jordan		Vienna, Austria	
	Value	Year	Value	Year	Value	Year
Carbon footprint of average residential electricity consumption (kg CO_2/capita/year)	111[a]	2019	146[b]	2015	94[b]	2015
Carbon footprint of average residential kerosene consumption (kg CO_2/capita/year)	23	2019	23	2019	62	2015
Carbon footprint of average residential LPG consumption (kg CO_2/capita/year)	121	2019	136	2018	0	2015
Carbon footprint of average residential district heating consumption (kg CO_2/capita/year)	NA		NA		222	2017/ 2018
Carbon footprint of average residential natural gas consumption (kg CO_2/capita/year)	NA		NA		680	2017/ 2018
Total carbon footprint of average residential energy consumption for selected sources per capita (kg CO_2/capita/year)	255		305		1058	

[a] Indicates national-level data

[b] Electricity generation sources and proportions were calculated from data provided on the state-level

A majority (68%) of the heating energy generated by district heating programs in Vienna come from surplus electricity and high-efficiency biomass CHP (Wien Energie, 2012a). Due to electricity being accounted for separately, the default emissions factor (Gómez et al., 2006) for municipal waste was applied to only the remaining 32% of the energy consumed to calculate the carbon footprint of district heating as Vienna's district heating systems are municipal waste incinerators.

Individuals in Pune have a low per capita consumption of electricity (416 kWh/capita/year) but a comparatively high carbon footprint due to its reliance on coal to generate electricity (Figure 6a). In Vienna, however, the highest carbon footprints are seen in district heating and natural gas. While the carbon footprint for district heating held the highest values, the district heating system is able to convert municipal waste into usable energy which provides a key benefit in waste management.

3.3.1 Energy Used for Water Transport

Table 5 displays the carbon dioxide emissions of water from selected sources (public water supply, tanker trucks, and wells) which provided a diverse set of results. Vienna had almost net-zero CO_2 emissions from its water supply as 97% water is transported down the Lower Austrian-Styrian Alps without the need for pumps. In fact, the water is used to generate hydroelectricity during transport.

Table 5. Carbon emissions from selected energy sources

	Pune, India		Amman, Jordan		Vienna, Austria	
	Value	Year	Value	Year	Value	Year
Carbon footprint for network water consumption (kg CO_2/capita/year)	3.4	2020	30	2013/2014	0	2017
Carbon footprint used for tanker water consumption (kg CO_2/capita/year)	0.0086	2020	0.99	2010	0	NA
Carbon footprint for well water consumption and private pumping (kg CO_2/capita/year)[b]	6.7	2020	NA	NA	NA	NA
Total carbon footprint for selected residential water sources (kg CO_2/capita/year)	10.51		31		0	

[b] Data used to calculate well water consumption were derived from energy used by individuals to pump water from private wells and augment the network water

Amman had the highest carbon footprint from water consumption due to the energy-intensive aquifer pumping conveyance system used to transport public network water. Amman’s remaining emissions came from tanker water trucks which sell directly to consumers and are utilized by 14% of households in Jordan (Potter & Darmame, 2010).

Pune’s carbon footprint was largest for well water consumption which includes the pumping energy used to extract water from wells as well as the pumping used to extract network water at a higher pressure.

4. Towards a differentiated urban nexus footprint

While the nexus footprint indicators discussed above characterize resources consumption patterns with average values, such an approach might conceal relevant existing differences within a diverse urban population. It can, therefore, be useful and feasible for bottom-up approaches to further differentiate within the population of a case study area. To do so comprehensively was beyond the scope of this first assessment. However, to demonstrate that differentiation of footprints may be useful for understanding consumption patterns, this section investigates whether specific disparities in resources consumption can be identified for future analyses.

A straightforward means of differentiating bottom-up footprint analyses is to assess the impact of income on resource consumption. Potential disparities in water utilization across income classes were examined for Pune (Table 6) and Amman which had household survey data that allowed such an analysis. Income groups were separated into low, middle, and high groups by quartiles. Income was determined by dividing the household net wages and salary by the number of earners within the household. The HEIS survey was used to calculate income data for Amman and the preliminary Pune Household Nexus Survey was used to calculate income data for Pune.

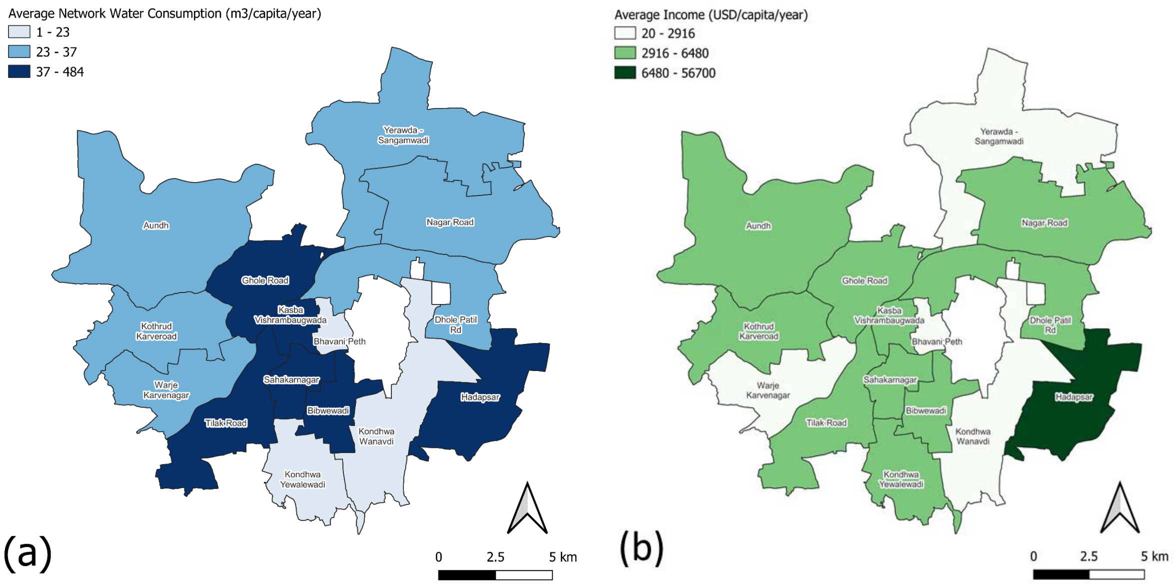
For Table 6, income groups were classified with low-income groups having net wages below the 50th percentile, middle-income groups having net wages between the 50th and 75th percentiles, and high-income groups having net wages above the 75th percentile.

Table 6. Public water supply utilization by income groups in Amman, Jordan, and Pune, India

	Network Water Consumption (m^3/capita/year)		
	Low Income	Middle Income	High Income
Pune	32.07	40.84	37.33
Amman	36.71	34.18	35.73

After separating household survey data by income groups (Table 6), Pune and Amman had very different utilization of network water. Wealthier individuals in Pune on average utilized more water from the public supply than the low-income population, while in Amman there was little variation across income groups. In Pune, the wealthier classes may be consuming more public water because they are located in areas where the public network is most stable and accessible.

Figure 7. (a) Spatial distribution of average network water consumption (m^3/capita/year) (Zhu, in preparation) in Pune, India, by administrative wards. *(b)* Spatial distribution of income (USD/capita/year) (Zhu, in preparation) in Pune, India, by administrative wards.



Figures 7a and 7b therefore compare the spatial distribution of network water consumption and income in Pune. The maps were created using preliminary data from the Pune Household Nexus survey and QGIS 3.20.2 software to analyze network water use, spatially. Both maps were generated by graduating data into three categories by quantiles. The spatial analysis was only conducted for Pune as the Pune Household Nexus survey provided location data which was not publicly available for Amman or Vienna. Table 6 showed that higher and middle-income groups in Pune tend to use more network water than lower-income groups, however, the spatial analysis showed more variance and complexity between the two variables. In future analyses, spatial statistical models may further investigate this relationship.

Differences in the consumption of other water sources including tanker trucks, private wells, and public wells, were also calculated across Pune's income groups (Table 7). The most significant results revealed higher consumption of water from private wells in middle and high-income groups, which suggests that those with higher financial means have the possibility to invest in alternatives to the intermittent public network water supply. Note that these values are calculated by dividing consumption by the total population to generate a per-capita value. While only a small percentage of the population consumes water from wells and tanker trucks, these water sources are important due to their relatively high emissions intensity per cubic meter of water.

Table 7. Water consumption by individuals in Pune, India, by tanker truck, private well, and public well water sources across income groups

	Low-Income	Middle Income	High Income
Tanker Truck (m^3/capita/year)	0.013	0.012	0.018
Private Well (m^3/capita/year)	0.011	0.068	0.087
Public Well (m^3/capita/year)	0.022	0.031	0.025

Data sourced from the preliminary findings of the Pune Household Nexus Survey (Zhu, in preparation)

5. Discussion

This study demonstrated that FWE nexus resources consumption and interdependencies can be characterized through a simple set of indicators, using mostly publicly available data, supplemented by household surveys where available. This rather “inexpensive” indicator can serve as a useful complement to in-depth studies of water or carbon footprints, as it provides a basis for understanding how individual resource systems interact. As a “bridging” indicator, the nexus footprint could work towards overcoming siloed sustainability policy development.

This can be exemplified by some of the results we retrieved in this first assessment. A nexus footprint may highlight potential synergies: In Pune and Amman, the intermittent and partly insufficient public water supply systems lead to the use of carbon-intensive alternatives among households as was shown in the use of well water pumping and tanker truck deliveries. By improving household access to water, carbon emissions can be avoided because as carbon-intensive alternatives become irrelevant.

The comparability between case studies in such different contexts as studied in this paper is limited. A good example of these limitations is the consumption of heating energy in Vienna, which leads to a substantial carbon footprint when compared to the other two areas, where climatic conditions reduce the need for heating. Applying this framework in diverse contexts, however, demonstrated its usefulness irrespective of the regional focus.

To some degree, our results show the impact that lifestyle differences have on resource use: In Vienna, average diets are heavy in animal products, especially meat, and result in vast amounts of carbon emissions compared to the more plant-based diets in Amman and Pune. The average Viennese diet also fails to meet nutritional guidelines with overconsumption of animal products and underconsumption of fruit and vegetables (Vanham, 2013).

On the other hand, it became apparent that the comparatively high use of electricity in Vienna has lower climatic implications than the coal-powered, comparatively low consumption levels in Pune. Further differentiating resource consumption data by income or other demographic factors can reveal vulnerable populations and provide a more comprehensive picture than a mere city-wide average. Our analysis showed that even a relatively simple additional analysis can quantify and reveal disparities in the accessibility of essential resources due to income or location within a supply system with strong spatial inequalities.

This early operationalization of the FWE nexus model has several limitations and is meant to serve as an exploration of the model's potential capabilities. While this bottom-up approach provides valuable information, the largest limitation is that, on its own, it cannot provide a system-wide picture of sustainability. Analyses such as this one should be complemented by top-down, input-output, material flow analyses to produce a more comprehensive understanding of resource interactions.

The data quality could have been vastly improved through the publication of further household-level data in Vienna and more regional energy consumption data across all three case studies. Both the carbon and water footprint calculations relied on global averages for carbon emissions factors which severely impacted accuracy. Jordan imports up to 95% of its food (Vasquez & Khraishy, 2015) and would likely have much higher greenhouse gas emissions for food than India or Vienna which have higher agricultural capabilities and rely far less on food imports. Global averages for carbon emissions factors were used to approximate values and illustrate the concept of the nexus footprint. However, future studies could improve upon this design by using more accurate and region-specific emissions factors.

Assumptions were also made for the carbon footprint of electricity which used national level electricity generation data for Amman and Vienna in place of state or city specific data. Another major limitation was the lack of both recent and consistent data. Several calculations were required to rely on data from different years or older data without more recent data points to use.

6. Conclusion

Our analysis is a first attempt to use a bottom-up nexus footprint metric to point towards relevant interconnections in the FWE nexus of an urban area. This approach can be a starting point for other FWE researchers interested in nexus interaction at the individual level rather than larger-scale city or district levels. Stakeholders from case study cities can review how resources in their city interact with one another or how their consumption patterns affect these nexus interactions.

This early application of the urban nexus footprints model showed that the nexus model is a useful sustainability indicator as it is capable of providing a focused perspective on resource interdependencies within the food, water, and energy resource nexus. The indicator is especially helpful in identifying mismanaged resources and disparities in resource access. However, the nexus footprints indicator is still in the early stages of its development. Further testing of its capabilities with different techniques, spatial levels, and regions needs to be conducted. After developing a large enough base of evidence, a method can then be refined and standardized for widespread application.

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Supplementary Information

Table S1 displays the source of the quantity of each food item used to calculate the food water footprint for each case study city. Pune, India primarily relied on city-level data from the NSSO Survey (National Sample Survey Office, 2013). Amman, Jordan used city-level food item expenditure data from the HEIS Survey (OAMDI, 2017). Vienna almost entirely relied on nation-level FAO data (Food and Agriculture Association of the United Nations, 2021). FAO data was also used to supplement quantities in Pune and Amman when it was required for standardization purposes of food products across the case studies. Data from JDOS (Jordan Department of Statistics, 2021) and Statistics Austria (Statistics Austria, 2020) were used for the same purposes.

Table S1. Food quantities and data sources used to calculate water and carbon footprints for each case study city

	Pune		Amman		Vienna	
	Food (kg)	Data Source	Food (kg)	Data Source	Food (kg)	Data Source
Vegetables	89.1	FAO[a]	137.4	HEIS	87.7	FAO[a]
Fruit	59.9	NSSO	65.9	HEIS	100.8	FAO[a]
Cereals	182.9	FAO[a]	119.9	JDOS[a]	114.4	FAO[a]
Pulses	12.6	NSSO	7.3	JDOS[a]	0.7	FAO[a]
Oil	3.0	NSSO	22.1	HEIS	0.0	FAO[a]
Sugar	21.2	FAO[a]	77.1	HEIS	14.0	FAO[a]
Nuts	1.6	FAO[a]	2.3	JDOS[a]	1.0	FAO[a]
Beef	2.8	NSSO	6.8	HEIS	16.7	FAO[a]
Mutton	3.0	NSSO	5.3	HEIS	1.1	FAO[a]
Pig	1.6	NSSO	0.0	FAO[a]	49.0	FAO[a]
Chicken	2.2	NSSO	41.8	HEIS	18.5	FAO[a]
Eggs	1.6	NSSO	15.1	HEIS	15.3	FAO[a]
Milk	73.3	NSSO	20.8	HEIS	82.2	Statistics Austria
Butter	0.1	FAO[a]	31.2	JDOS[a]	46.3	FAO[a]
Total (kg)	454.7		553.1		547.7	

[a]National-level data rather than city-level

Table S2. Data sources utilized to calculate FWE Nexus indicators

	Pune, India	Amman, Jordan	Vienna, Austria
Average network water consumption per capita (m^3)	(Zhu, in preparation)	(OAMDI, 2017)	(*Water and Wastewater Services in the Danube Region*, 2015)
Average tanker water consumption per capita (m^3)	(Zhu, in preparation)	(Klassert et al., 2015; Gerlach & Franceys, 2009; Potter & Darmame, 2010)	NA
Average well water consumption per capita (m^3)	(Zhu, in preparation)	NA	NA
Water footprint of food production (m^3)	(National Sample Survey Office, 2013); (Food and Agriculture Association of the United Nations, 2021)**;** Mekonnen & Hoekstra, 2011	(OAMDI, 2017); (Food and Agriculture Association of the United Nations, 2021); JDOS; World Food Programme; Mekonnen & Hoekstra, 2011	(Food and Agriculture Association of the United Nations, 2021); Mekonnen & Hoekstra, 2011
Average residential electricity consumption per capita	(Zhu, in preparation)	Dar-Mousa & Markhamreh, 2019; Almuhtady et al, 2019; IEA	(Vienna City Administration, 2017)
Average residential kerosene consumption per capita per year	(Zhu, in preparation)	(*Ministry of Energy and Mineral Resources Annual Report*, 2017)	(Statistics Austria, 2020)
Average residential LPG consumption per capita per year	(Zhu, in preparation)	(Al-Ghandoor, 2013)	(Statistics Austria, 2020)

Carbon emissions of average electricity consumption (kg of CO_2)	(Maharashtra State Power Generation Co. Ltd., 2017)	(International Energy Agency, 2021)	(International Energy Agency, 2021)
Carbon footprint of average residential natural gas consumption (kg CO_2/capita/year)	NA	NA	(Statistics Austria, 2020)
Carbon emissions of average residential energy consumption for selected sources per capita (kg CO_2)	(*Carbon Inventory of Pune City*, 2012)	(Alkurd et al., 2018)	(Vienna City Administration, 2017)
Carbon emissions for network water consumption (kg CO_2/capita/year)	(Zhu, in preparation) (Kumar et al., 2017)	(Komendantova et al., 2020) (Jordan Ministry of Water and Irrigation, 2016a)	(Vienna Water, n.d.)
Carbon emissions used for tanker water consumption (kg CO_2/capita/year)	(Zhu, in preparation); (Zozmann, 2020)	(Potter & Darmame, 2010) (Gerlach & Franceys, 2009) (Seo et al., 2016)	NA
NA: No data available			

References

Al-Ghandoor, A. (2013). Evaluation of energy use in Jordan using energy and exergy analyses. *Energy and Buildings*, *59*, 1–10. https://doi.org/10.1016/j.enbuild.2012.12.035

Alkurd, R., Takruri, H. R., & Amr, A. M. (2018). Trends of Energy and Macronutrients Intakes in Jordan as Obtained by Household Expenditure and Income Surveys. *Journal of Agricultural Science*, *11*(1), p191. https://doi.org/10.5539/jas.v11n1p191

Butsch, C., Kumar, S., Wagner, P. D., Kroll, M., Kantakumar, L. N., Bharucha, E., Schneider, K., & Kraas, F. (2017). Growing 'Smart'? Urbanization Processes in the Pune Urban Agglomeration. *Sustainability*, *9*(12), 2335. https://doi.org/10.3390/su9122335

Carbon Inventory of Pune City. (2012). The Energy and Resources Institute. https://www.pmc.gov.in/sites/default/files/miscellaneous/Carbon_Inventory_of_Pune_City_2012.pdf

Daher, B., & Mohtar, R. (2012). *Water, energy, and food: The Ultimate Nexus*. https://doi.org/10.1081/E-EAFE2-120048376

Food and Agriculture Association of the United Nations. (2021). *Food Balances*. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data/FBS

Gerlach, E., & Franceys, R. (2009). Regulating water services for the poor: The case of Amman. *Geoforum*, *40*(3), 431–441. https://doi.org/10.1016/j.geoforum.2008.11.002

Gómez, D., Watterson, J., Americano, B., Ha, C., Marland, G., Matsika, E., Nenge Namayanga, L., Osman-Elasha, B., Kalenga Saka, J., & Treanton, K. (2006). *IPCC Guidelines for National Greenhouse Gas Inventories*. *2*. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

Hoekstra, A. Y. (2011). *The water footprint assessment manual: Setting the global standard*. Earthscan.

International Energy Agency. (2021). *IEA – International Energy Agency*. IEA. https://www.iea.org

Jordan Department of Statistics. (2021). *Interactive Database*. http://jorinfo.dos.gov.jo/Databank/pxweb/en/

Jordan Ministry of Water and Irrigation. (2016a). *National Water Strategy 2016—2025*. http://extwprlegs1.fao.org/docs/pdf/jor156264E.pdf

Klassert, C., Sigel, K., Gawel, E., & Klauer, B. (2015). Modeling Residential Water Consumption in Amman: The Role of Intermittency, Storage, and Pricing for Piped and Tanker Water. *Water*, *7*(7), 3643–3670. https://doi.org/10.3390/w7073643

Klassert, C., Sigel, K., Klauer, B., & Gawel, E. (2018). Increasing Block Tariffs in an Arid Developing Country: A Discrete/Continuous Choice Model of Residential Water Demand in Jordan. *Water*, *10*(3), 248. https://doi.org/10.3390/w10030248

Komendantova, N., Marashdeh, L., Ekenberg, L., Danielson, M., Dettner, F., Hilpert, S., Wingenbach, C., Hassouneh, K., & Al-Salaymeh, A. (2020). Water–Energy Nexus: Addressing Stakeholder Preferences in Jordan. *Sustainability*, *12*(15), 6168. https://doi.org/10.3390/su12156168

Kumar, P., Matto, M., & Sharda, C. (2017). *Mainstreaming Energy Efficiency in Unrabn Water and Wastewater Management in the Wake of Climate Change*. Centre for Science and Environment. https://cdn.cseindia.org/attachments/0.73120800_1505297784_Policy-Paper-Mainstreaming-Energy-Efficiency-in-Urban-Water.pdf

Leidwein, A., Kolar, V., Mechtler, K., Baumgarten, A., Berthold, H., Strauss, G., Steinwider, J., Maria Krachler, M., Weigl, M., Eitzinger, J., Formayer, H., Schlatzer, M., Rohrer, G., Längauer, M., Steinhäusler, F., Pichelstorfer, L., Vas, J., Teixeira, A. da S., Tribl, C., … Ortner, K. (2013). Food security risks for Austria caused by climate change. 664.Maharashtra State Power Generation Co. Ltd. (2017, November 17). *Installed Capacity*. https://www.mahagenco.in/index.php/generation

Maiwald, L. (2021). The contribution of a mixed-methods approach on urban resource nexus governance [Master thesis, Utrecht University]. https://dspace.library.uu.nl/handle/1874/405345

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, *15*(5), 1577–1600. https://doi.org/10.5194/hess-15-1577-2011

Ministry of Energy and Mineral Resources Annual Report. (2017). Ministry of Energy and Mineral Resources. http://images.mofcom.gov.cn/jo/201807/20180729161644462.pdf

Molle, F., Al Karablieh, E., Al Naber, M., Closas, A., & Salman, A. (2017). *Groundwater Governance in Jordan The case of Azraq Basin*. https://ageconsearch.umn.edu/record/273350/files/H048395.pdf

National Sample Survey Office. (2013). *India—Household Consumer Expenditure, NSS 68th Round Sch1.0 Type 2: July 2011—June 2012, Type—2—Overview*. Ministry of Statistics & Programme Implementation. http://microdata.gov.in/nada43/index.php/catalog/126/study-description

OAMDI. (2017). *Harmonized Household Income and Expenditure Surveys (HHIES)* (Version 2.0 of Licensed Data Files). HEIS 2013 - Department of Statistics (DOS), The Hashemite Kingdom of Jordan. Egypt: Economic Research Forum (ERF). http://erf.org.eg/data-portal/

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*(6392), 987–992. https://doi.org/10.1126/science.aaq0216

Potter, R. B., & Darmame, K. (2010). Contemporary social variations in household water use, management strategies and awareness under conditions of 'water stress': The case of Greater Amman, Jordan. *Habitat International*, *34*(1), 115–124. https://doi.org/10.1016/j.habitatint.2009.08.001

Pune Municipal Corporation. (2011). *Data of Census 2011 of Pune Municipal Corporation*. Pune Municipal Corporation. https://www.pmc.gov.in/sites/default/files/census-population-data-2011.pdf

Ray, P. A., Kirshen, P. H., Rosenberg, D. E., & Hagan, R. E. (2012). *An Overview of the Water Situation in Amman, Jordan*. 1980–1989. https://doi.org/10.1061/41114(371)207

Rees, W. E. (1992). Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environment and Urbanization*, *4*(2), 121–130. https://doi.org/10.1177/095624789200400212

Seo, J., Park, J., Oh, Y., & Park, S. (2016). Estimation of Total Transport CO2 Emissions Generated by Medium- and Heavy-Duty Vehicles (MHDVs) in a Sector of Korea. *Energies*, *9*, 638. https://doi.org/10.3390/en9080638

Shu, Q., Scott, M., Todman, L., & McGrane, S. J. (2021). Development of a prototype composite index for resilience and security of water-energy-food (WEF) systems in industrialised nations. *Environmental and Sustainability Indicators*, *11*, 100124. https://doi.org/10.1016/j.indic.2021.100124

Sigel, K., Klassert, C., Talozi, S., Klauer, B., Gawel, E., & Zozmann, H. (2017). *Socioeconomic Surveys on Private Tanker Water Markets in Jordan: Objectives, Design and Methodology*. https://www.ssoar.info/ssoar/handle/document/52823

Statistics Austria. (2020). *Statistics*. STATISTIK AUSTRIA. https://www.statistik.at/web_en/statistics/index.html

Vanham, D. (2013). The water footprint of Austria for different diets. *Water Science and Technology*, *67*(4), 824–830. https://doi.org/10.2166/wst.2012.623

Vasquez, O., & Khraishy, M. (2015). *Market Overview and Guide to Jordanian Market Requirements*. 22.

Vienna City Administration. (2017). *Energy! Ahead Energy Report of the City of Vienna*. Municipal Department 20 – Energy Planning. https://www.wien.gv.at/stadtentwicklung/energie/pdf/energiebericht2017-en.pdf

Vienna Water. (n.d.). *The Journey of Vienna’s Drinking Water*. City of Vienna. Retrieved July 23, 2021, from https://www.wien.gv.at/english/environment/watersupply/supply/way.html

Wahl, D., Ness, B., & Wamsler, C. (2021). Implementing the urban food–water–energy nexus through urban laboratories: A systematic literature review. *Sustainability Science*, *16*(2), 663–676. https://doi.org/10.1007/s11625-020-00893-9

Water and Wastewater Services in the Danube Region (No. 97227). (2015). IAWD Danube Water Program. https://openknowledge.worldbank.org/bitstream/handle/10986/22137/Water0and0wast00state0of0the0sector.pdf?sequence=1&isAllowed=y

Wien Energie. (2012a). *District Heating & Cooling in Vienna*. https://www.districtenergyaward.org/wp-content/uploads/2012/10/Vienna_Austria-District_Energy_Climate_Award.pdf

Wien Energie. (2012b, December 30). *THE ROAD TO RENEWABLE ENERGY*. https://www.wienenergie.at/wp-content/uploads/2020/06/wienenergie_jb_2011_engl_91568.pdf

World Food Programme. (2021). *Jordan—Food Prices*. Humanitarian Data Exchange. https://data.humdata.org/dataset/wfp-food-prices-for-jordan

Zhu, Y. (in preparation). *Pune Household Food-Water-Energy Nexus Consumption Survey* [Household Survey]. Helmholtz-Zentrum für Umweltforschung.

Zozmann, H. (2020). Tanker water market survey in Pune, India. Helmholtz Centre for Environmental Research.