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Energy–water nexus of formal and informal water systems in Beirut, Lebanon

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Abstract

Many areas in the world with chronic and intermittent water shortages rely on informal water systems for much of their daily water needs with water from tanker trucks, purchased bottled water, rainwater cisterns, or pumped well water. These alternative sources all require varying amounts of energy. Water–energy nexus studies have not yet considered environmental impacts of informal water sources, specifically from an energy intensity and carbon emissions perspective. This study compares energy use and carbon emissions per cubic meter and per capita for both formal and informal water sources for a neighborhood in Beirut Lebanon. Energy use and carbon emissions are calculated for three delivery stages per source including pumping, treatment and distribution. The results show that informal sources have the highest energy use and carbon emissions. From the total water delivered to households, they account for 83% of energy use and 72% of carbon emissions per capita, even though they only provide 23% of total delivered volume per capita. Bottled water and distribution of water by tanker trucks have the highest energy intensity values per cubic meter of all water sources. Moreover, internal building water pumping, which is not typically accounted for, takes up to 14% of total energy use and 23% of total carbon emissions per capita compared to other water sources. To address model uncertainty, we conduct a sensitivity analysis, showing that the base model presented reasonably stable results and identifying the most sensitive parameters for further research. While informal sources help communities overcome water shortages they result with negative impacts. Strategies are proposed to improve the environmental performance of the Lebanese electrical grid, reduce water losses, replace inefficient truck engines and incentivize household to invest in low carbon technologies.

1. Introduction

The interdependence between water and energy provision and use is referred to as the water–energy nexus, recognizing that energy is needed in water systems (Spang and Loge 2015, Hamiche et al 2016) and water is needed for energy and electricity production (Spang et al 2020). This study focuses on energy used in water systems. The energy-for-water field has evolved from understanding the economic costs of energy for water (Hansen 1996, deMonsabert and Liner 1998), to analyzing multiple additional technological and environmental dimensions of how energy is both produced and consumed within water systems (Al-Saidi and Elagib 2017). This study advances the energy-for-water field by expanding the traditional focus from formal piped water infrastructure to include largely ignored informal water supplies (by water delivery trucks, local wells, and bottled water) common in much of the world.
In recent years, energy–water nexus studies have evolved into a range of more refined methods that focus on the importance of regional and local scales (King and Carbajales-Dale 2016) and consider different environmental dimensions of energy use within water systems (Spang et al. 2020). For example, Scott et al. (2011) show the importance of integrating national and regional scales when managing water and energy resources. They explain that when permitting happens at federal and state agencies, local authorities are obstructed from managing their own local resources, resulting in a mismatch between energy and water resource linkages, as well as increased regional waste and pollution. Fang et al. (2015) estimate the energy and greenhouse gas (GHG) emissions intensity of water supply of two utilities in southern California and point out the important contribution of upstream emissions. By using a spatially explicit life cycle assessment (LCA) model, they estimate emissions improvement of local utilities using renewable sources (instead of coal-based electricity). Spang and Loge (2015) provide a high resolution, spatially explicit method to calculate energy-for-water by using granular hourly pumping regional data with geographic and seasonal variations. Mahgoub et al. (2010) apply a LCA approach to Alexandria, Egypt’s urban water system to assess its environmental impact, with proposals to improve the system’s overall performance. Some studies focus on the environmental impacts of specific water sources only. For example, Gleick and Cooley (2009) focus on bottled water and develop an energy footprint required for phases of producing, transporting and using bottled water. Stokes and Horvath (2006, 2009) compare energy use and air emissions of three water supply alternatives in California, including imported water, recycled water, and desalinated water.

Although nexus studies have a wide range of dimensions and objectives, they remain narrowly focused on centralized formal piped water services (Hamiche et al. 2016). However, many areas experience chronic water shortages where piped centralized formal systems cannot supply sufficient water to residents (Liddle et al. 2016, Kooy 2014, Misra 2014, Jepson and Vandewalle 2016). Around four billion people worldwide experience water scarcity at least some parts of the year (Kummu et al. 2016, Mekonnen and Hoekstra 2016), and around 30 to 60% of urban population from the Global South rely on informal water systems to satisfy their water needs (Ahlers et al. 2013). These systems can include different strategies for collecting, pumping, treating, and storing water (Pattanayak et al. 2005, Baquero et al. 2017, Nastiti et al. 2017, Amit and Sasidharan 2019); or using alternative sources such as bottled water, tanker trucks and wells (Moore et al. 2011, Christian-Smith et al. 2013, Nganyanyuka et al. 2014, Jepson and Vandewalle 2016, Walter et al. 2017). Similar to formal water networks, these alternative and informal strategies use energy at different stages including pumping, treating, and distributing water.

The literature on informal water systems has so far focused on case studies from developing countries including South-East Asia (Ranganathan 2014, Kooy 2014, Nastiti et al. 2017, Komarulzaman 2017), Africa (Peloso and Morinville 2014, Liddle et al. 2016, Schwartz et al. 2015), and Latin America (EAI 2011, EAI 2011 Wüthich et al. 2016). More recent scholars have started analyzing informality in higher income countries such as the US (Balazs and Ray 2014, Balazs and Lubell 2014, Jepson and Vandewalle 2016, London et al. 2021). The literature has so far focused on analyzing political drivers of informal water systems (Kooy 2014, Ahlers et al. 2013, Schwartz et al. 2015, Liddle et al. 2016) and its socio-economic implications (Pattanayak et al. 2005, Nganyanyuka et al. 2014, Walter et al. 2017, Nastiti et al. 2017, Komarulzaman 2017, Jepson and Vandewalle 2016). However, few studies focus on environmental impacts of informality by including discussion of water quality impacts of informal sources (El-Fadel et al. 2003, Kjellén and McGranahan 2006, Constantine et al. 2017). Almost no study has looked at the water–energy nexus of informal systems, especially the embedded energy and carbon emissions of informal water sources.

This study addresses this gap by analyzing the embedded energy and GHG emissions of informal water systems relative to a formal system. As a case study, we examine Beirut, Lebanon’s water system and compare the energy nexus and GHG emissions of three informal water sources (tankers, bottled water, and domestic wells) with the formal piped infrastructure for a typical Lebanese neighborhood. Beirut is taken as a representative case study where the learnings may be beneficial for application to other geographic areas that also suffer from a large informal sector (Olinsorge and Yu 2022).

Water is supplied to Beirut through the formal piped infrastructure system from two main areas, shown on figure 1. The main source is a northern water treatment plant in Dbayeh, which receives and treats water from two upstream springs and 17 additional wells, supplying 77% of the city’s water use. The second largest water source (supplying 23% of total city water use) is groundwater from a cluster of 11 wells in the southern Naameh area that is chlorinated for disinfection. Water from these two locations is usually pumped to reservoirs in Beirut for storage before final residential delivery. This study focuses on a typical neighborhood in Beirut (Verdun-Aicha Bakkar) which receives water from two main reservoirs, Tallet el Khayyat (TK) and Bourj Abi Haidar (BAH). The northern treatment plant supplies 77% of the city’s water, and the southern wells supply 23%. However, the formal piped infrastructure is insufficient to meet demand, because it experiences 45% losses from distribution system leaks (Shaban 2020, Bulos and Yam 2021). Thus, 77% of the formal water supply (77% here is coincidental to 77% of household use) comes from northern sources (Dbayeh treatment
plant and 17 additional wells), and 23% comes from the southern wells. This means that of the total household water consumption, the breakdown is 59% is formal water from northern sources (77% of 77%), 18% is formal water from southern wells (23% of 77%), and 23% is from informal sources. Residents pay a flat rate of $200 per year for a ‘promise’ of one cubic meter ($m^3$) of water per household per day. However, they do not receive this promised volume consistently. They generally receive water for a continuous period of around 3 h in the summer and around 7 h in the winter every other day.

To cope with intermittence and the remaining 23% of the needed supply, households and buildings in Beirut use various strategies. Figure 2 shows typical water sources (in blue) and their energy requirements (in orange). For freshwater, people commonly maintain on-site storage in underground and roof reservoirs to capture intermittent piped water from the municipal water supply. The piped water is first sent to underground tanks, which are usually large reservoirs shared by building residents (ranging from 10 $m^3$ to 80 $m^3$). When formal piped water is insufficient, even when stored on site, buildings and households seek other water sources, either pumping water from private wells (sometimes with additional treatment using reverse osmosis—RO) or buying water from tanker trucks from the outskirts of the city. Once building reservoirs are full (from a mix of piped infrastructure, wells, and tanker water), water is then pumped to individual smaller roof reservoirs assigned to each household. For potable needs, people rely mostly on bottled water, mainly because of distrust in the quality of delivered water (Zawahri et al 2011). Bottled water companies usually draw water from the Lebanese mountains where they pump, treat, and fill bottles. The bottles are then transported by delivery trucks directly to households or to local markets.

In its modern history (during the 20th century), Beirut experienced different development and reconstruction phases (Nasr and Verdeil 2008). Today the city has an eclectic character which results from the absence of a proper and formal strategic urban plan that regulates its vertical and horizontal expansion (Mohsen et al 2020). The limited governance and urban planning structure of public institutions led to a persistent violation
Figure 2. Water and energy relationship at regional and building level.

of building permit codes (Fawaz 2017, Mohsen et al 2020). As a result, Beirut is a dense city, composed of a wide range of buildings of different styles, that have inconsistent height, and are used for mixed purposes, with commercial shops occupying ground-floor and residential occupying upper floors (Mohsen et al 2020). The selected neighborhood is a representation of this heterogeneous urban typology. It is composed of two communities of different socio-economic levels. (Aicha Bakkar and Verdun). Aicha Bakkar has shorter buildings, with 70% of buildings’ height between 21 to 40 m high and an average buildings’ footprint of 220 m². Verdun has taller buildings, with 70% of buildings’ height between 31 and 50 m and an average buildings’ footprint of 320 m². These differences result from different development periods that each community experienced, which is similar to the different development phases that Beirut experienced as a whole. Aicha Bakkar’s urban development, that started in the 1920s, was unplanned and evolved organically leading to a closely knit typology with smaller building footprints and streets. In contrast, Verdun’s development started 40 years later in the 1960s. Unlike Aicha Bakkar, Verdun is subdivided following a grid-like typology which leads to today’s large homogenous-shaped lots and large buildings footprint (Zaatari 2019). Since both communities belong to the same neighborhood, they are in the same water zone. This means that they receive the same amount of water from the same formal sources, and also experience the same intermittent piped water delivery schedule and pumping requirements. Hence, the communities’ socio-economic differences do not play an important role in the neighborhood’s energy–water nexus needs.

2. Materials and methods

Water delivery can be broken down into five stages, as indicated in table 1. This includes acquisition of water through drilling wells or surface diversions; the manufacturing of piped infrastructure, water treatment plants, trucks and bottles; the operation through different delivery stages; maintenance of piped infrastructure, water treatment plants, trucks and cleaning of wells; and an after-life taking into account dismantling of treatment plant, recycling and reuse of trucks, and water bottles. By focusing on the operation stage (as indicated in gray in table 1) as our system boundary, we narrow the emphasis of our nexus analysis on the pumping, treatment, and distribution of water in Beirut.
| Sources                        | 1. Raw material          | 2. Manufacturing                  | 3. Operation: delivery stages                                                                 | 4. Maintenance                        | 5. After life/recycle          |
|-------------------------------|--------------------------|-----------------------------------|-----------------------------------------------------------------------------------------------|---------------------------------------|------------------------------|
| Formal piped infra-structure  | Drilling well            | Water treatment plant and infrastructure | Pumping groundwater | Water treatment                  | Pumping stations + pumping water from lower to upper reservoirs | Maintenance of plant and infrastructure | Dismantling treatment plant |
| Tankers trucks                | Drilling well            | Manufacturing and shipping of trucks | Pumping groundwater | NA                             | Transporting water through water trucks + pumping water from lower to upper reservoirs | Maintenance of trucks | Reusing and recycling truck and truck parts |
| Bottled water                 | Drilling well            | Processing bottles                | Pumping groundwater | Clean, fill, seal, and label bottles | Transporting water bottles through regional delivery trucks | NA                          | Reusing and recycling plastic bottles |
| Private domestic wells        | Drilling well            | NA                                | Pumping groundwater | Using RO to clean water         | Pumping water from lower to upper reservoirs | Cleaning well                | NA                          |
To analyze water–energy nexus for each water source, one needs to understand the embedded energy within the three delivery stages. The formal piped infrastructure includes pumping groundwater from wells in both the north and south, treating spring water at the Dbayeh water treatment plant in the North, distributing the water to Beirut within the city via four pumping stations (refer to figure 1), and then at a building level, water is pumped from lower to upper reservoirs (refer to figure 2). For tanker trucks, groundwater is pumped at well sites to fill the trucks (without treatment), then water is delivered in bulk by trucks directly to residential buildings, and finally at a building level, water is also pumped from lower to upper reservoirs. Bottled water is pumped from groundwater, treated, bottled, and then transported through regional delivery trucks. The production of the plastic for the bottles is not included in this assessment. For the private wells, groundwater is pumped into underground storage cisterns. In some cases, where residents can afford it, well water is treated with domestic reverse osmosis units (RO), and then water is also pumped internally within the building from lower reservoirs to roof reservoirs where it flows by gravity into individual apartment units. Water losses at the building level are not taken into consideration. Wastewater energy use and emissions are considered to be the same for all water sources.

2.1. Data collection
Data on energy use per volume of water was collected for each source using mixed methods. Quantitative data was collected from the Lebanese water establishment, interviews, and relevant literature and qualitative data was collected via interviews. The formal piped infrastructure energy data were provided by Beirut and Mount Lebanon Water Establishment and volumetric estimates of delivered water were derived from household interviews. For tanker trucks, energy and water data were derived from interviews with tanker truck owners. For bottled water, domestic wells and internal pumping, energy and water data were derived from household interviews. Whenever needed, supplementary information was employed based on feedback from water engineers, from the water establishment and references from similar (international and local) cases, which was especially the case for bottled water. These additional references are elaborated further in the analysis section and the appendix.

Tanker truck and household interviewees were recruited using a convenience sampling process based on ease of accessibility, willingness to participate, and activity in the neighborhood (Etikan et al 2016). Random sampling was impossible given political instability during the data collection period. The sampling process started with one main contact (per tanker truck and per household). At the end of each interview, the interviewees would share contact information for other tanker truck business owners (for tanker trucks interviews), or other social connections in the neighborhood, including their neighbors (for household interviews). The researcher would then contact by phone the new names to make appointments. For the tanker trucks, the process was repeated until the direct contact list was exhausted, where no new tanker truck was answering the phone for new appointments. The process was repeated for the household interviews until the sample size of 105 was reached, which is a sample size similar to other studies of informal water systems (Rosenberg et al 2007, Jepson and Vandewalle 2016). This sample size meets minimum standards for statistical analysis within political and financial constraints (Walter et al 2017).

2.1.1. Formal piped infrastructure
The Lebanese Water Establishment provided aggregated data to estimate energy use for groundwater pumping, water treatment, and distribution. For groundwater pumping, they provided nameplate capacity values for the 17 pumps in the northern region and 11 pumps in the southern region. While the water utility could provide detailed daily operating hours for April 2017 until July 2020, they could only provide an average estimate of daily operation for the pumps in the northern region. For treatment, the water utility provided data on total daily volume treated at the Dbayeh water treatment plant, but could not share energy consumption data. Lacking on-site data, we applied energy intensity values from Plappally and Lienhard (2012). For water distribution, energy consumption was estimated for all 40 pumps at the four main pumping stations based on pump nameplate capacity and daily operating hours for January 2018 to June 2018. The number of pumps at each pump station is: 6 pumps at Naameh station, 4 pumps at Tallet el Khayat station, 22 pumps at Dbayeh station, and 8 pumps at Bourj Abi Haider station. The water establishment also provided information on typical sizes and horse power of pumps used by tanker trucks, bottled water and households (refer to appendix A).

2.1.2. Tanker truck business interviews
Data on tanker truck operations were collected via in-person interviews with truck owners in and around Beirut over two-months from August 2019 to September 2019. Twenty interviews were held with the main manager or owner of tanker truck businesses. Questions were asked in Arabic and all answers were collected as written notes by the researcher. The interviews followed an interview guide composed of different topic areas
including water sourcing information (including average hours of groundwater pumping), truck characteristics and operation (i.e. make/model, age, average volume carried, and average distance traveled of tanker trucks), and socio-economic details (i.e. cost of service, communication with other business owners).

2.1.3. Household interviews
Data on household water consumption were collected by in-person household structured interviews in the Aicha Bakkar and Verdun communities over two months from October 2019 to November 2019. 105 interviews were conducted with at least one adult from each household. Questions were mainly asked in Arabic, but when necessary (especially when using some technical terms), the interviewer asked questions in French or English. Answers were collected using the Survey123 mobile phone application from ESRI ArcGIS. The interviews followed an interview guide of topic areas including groundwater pumping, water treatment and distribution: pump operating hours and pumped volumes for private wells and additional internal building pumps; operating hours of domestic reverse osmosis units; volume and temporal delivery of water deliveries for tanker trucks and bottled water and the scale of deliveries (i.e. water delivered for the whole building or single household), and seasonal variation.

2.2. Data analysis
The analysis started with a base case model. First, we calculate energy and carbon emissions per cubic meter of water of base case model. The unit of analysis is kW hours per cubic meter of water (kW h/m\(^3\)), and kilogram of carbon dioxide per cubic meter of water (kg CO\(_2\)/m\(^3\)). Then, per capita energy use and carbon emissions for the neighborhood are calculated by multiplying energy and carbon intensities results by total delivered volumes per source per person per year. The unit of analysis is total kW h per person per year (kW h/person/year) and total kilogram of carbon dioxide per person per year (kg CO\(_2\)/person/year). Finally, we include a sensitivity analysis that allows assessing the certainty of values obtained in the base case model.

2.2.1. Intensive energy use and carbon emissions per cubic meter of water
As highlighted in table 2 water delivery occurs through three stages of pumping (blue), treating (green), and transporting water (pink). Similar formulas to calculate energy and carbon intensities are used for multiple stages (irrespective of source) as detailed below.

Equations (1) and (2) estimate energy and carbon intensities for pumping and treatment. *Pumping (blue)* includes energy for water extraction (including groundwater), pumping stations for water distribution, and internally pumped water at the building level. Internally pumped water at a building level from lower to upper reservoirs is classified in the distribution stage and it is comprised of a mixture of three sources (formal piped infrastructure, tanker trucks and wells, refer to figure 2). The energy use and carbon emissions intensities of internally pumped water are calculated separately and are not included within the sources. Any energy used for pumping from tanker trucks to buildings is neglected given that trucks generally empty their tanks by gravity to lower building reservoirs.

*Treatment (green)* includes energy to treat raw water sources for water treatment plants, energy for bottled water to clean, fill, seal, and label bottles, and used for domestic reverse osmosis units. Energy for production and disposal of bottles are not taken into consideration.

For these two stages, pumps use electricity from the Lebanese electrical grid with a carbon intensity of 0.774 kg of CO\(_2\)/kW h (IEA 2019).\(^8\) Energy intensity (EI) and carbon intensity (CI) values are calculated according to equations (1) and (2) below:

\[
EI \ (kW \ h/m^3) = \frac{\text{Energy use (kW h)}}{\text{Pumped or treated volume (m}^3\text{)}}. 
\]

\[
CI \ (kg \ of \ CO_2/m^3) = EI \times \text{Emissions factor (kg CO}_2/kW \ h). 
\]

Equations (3) and (4) include estimating energy and carbon intensities for transporting water. *Transportation (pink)* includes fuel needed to transport water via two truck types: tanker trucks transporting bulk water and regional delivery trucks for bottled water. Energy intensity for transportation (EIT) and carbon intensity for transportation (CIT) are calculated using equations (3) and (4):

\[^8\text{Based on discussions with the Water Establishment, the distribution pumps for the formal water system usually use electricity from the grid. However, they do have backup diesel generators that are only used in for emergencies (El Asmar, personal communication, March 21, 2022). For the purpose of our analysis, we assume that all pumps use electricity from the grid.}\]
**Table 2.** Base case model equations per source and delivery stage.

| Sources          | Pumping groundwater | Water treatment | Treatment (pumping and transportation) |
|------------------|---------------------|----------------|----------------------------------------|
| Piped infra-structure | Elp = 442 (kWh)/50.34 (m³) | Elp = 0.56 (kWh/m³) | Elp × 0.774 (kgCO₂/kWh) |
|                   | Clp = Elp × 0.774 (kgCO₂/kWh) | Clp = Elp × 0.774 (kgCO₂/kWh) |               |
| Tankers trucks    | Elp = 408 (kWh)/183 (m³)   | Clp = Elp × 0.774 (kgCO₂/kWh) |               |
| Bottled water     | Elp = 1632 (kWh)/2055 (m³) | Clp = Elp × 0.774 (kgCO₂/kWh) |               |
| Domestic wells    | Elp = 0.010 (kWh)/0.015 (m³) | Clp = Elp × 0.774 (kgCO₂/kWh) |               |

*Pumping water in buildings from lower to upper reservoirs uses a mixture of three sources (refer to figure 2) hence, energy use and carbon emissions intensities are calculated separately.

\[
\text{EIT} \ (\text{kWh/m}^3) = \frac{\text{Fuel economy (Liter of diesel)/100 km}}{\times \text{Energy content of diesel (kWh/Liter of diesel)}} \\
\times \frac{\text{Distance (km)/Truck volume (m}^3\text{)/100}}{} \tag{3}
\]

\[
\text{CIT} \ (\text{kg of CO}_2/\text{m}^3) = \frac{\text{Fuel economy (Liter of Diesel)/100 km}}{\times \text{Emissions factors (kWh/Liter of diesel)}} \\
\times \frac{\text{Distance (km)/Truck volume (m}^3\text{)/100}}{} \tag{4}
\]

The fuel economy value is based on European references for fuel economy of trucks since most trucks in Lebanon come from European markets (MoE/UNDP/GEF 2019). We used average weight of both truck types and compared them with European trucks of similar weights to derive fuel economy values. Energy content of diesel is equal to 10.7 kWh per liter of diesel. Distances are equal to traveled distance from well to neighborhood for each truck type. Volumes are average volume of each truck type, based on interviews and payload weight of trucks. Emission factors are based on the tier 1 method by the IPPC (2006) with CO₂ emissions from a liter of diesel equal to 2.7 kg CO₂ per liter of diesel.

Carbon intensity of Lebanese electrical grid (kg CO₂/kWh h) and emission factors for diesel (kg CO₂/Liter of diesel) represent carbon emissions from combustion only. For the electrical grid this represents carbon emissions from the combustion of fossil fuel for electricity generation, and for trucks it is carbon emissions from combustion of diesel for engines (IEA 2019, IPCC 2006).
The analysis starts with a base case model that uses parameters from the Water Establishment, study interviews and the literature. Range of parameters of each source and delivery stage are included in table 2. Step by step calculations and references for each parameter are in appendix A.

2.2.2. Total supplied volume by source and total energy use and carbon emissions per capita

Total energy use and carbon emissions per person per year are calculated by multiplying energy and carbon intensities per total delivered volumes for all four water sources (piped infrastructure, tanker trucks, bottled water and domestic wells) and additional internally pumped water at a building level. Total delivered volumes per sources are mainly based on interview answers and calculated per source. For each source, the unit of analysis is cubic meter per person per year (m$^3$/person/year).

Since piped infrastructure supply is not metered, estimated final delivered volumes were based on initial average supply values from the water establishment, adjusted with leakage percentages and estimations on summer reduced supply (because of higher intermittence and lower flow). Unit conversion calculations provide total cubic meter of piped infrastructure per person per year. Initial average supply by the water establishment is 180 Liters/person/day (0.18 m$^3$/person/day (Jaafar et al. 2020)). Beirut experiences seasonal fluctuations in water availability and use. Based on household interviews, 50% of the sample population experienced lower flows from August until November. So we considered the dryer period to be four months, and wetter period to be eight months. Production drops in dry months by 40% (based on interview answers and water establishment engineer, El Asmar, personal communication, July 7, 2021). Finally, overall infrastructure loses up to 45% in its distribution phase due to leakages (Shaban 2020, Bulos and Yam 2021).

Water tanker volume is based on household survey answers which provided number and volume of water tanker deliveries purchased per household (or building) per week. It was possible to compute the volume of water delivered by tankers by converting the units from household (or building) per week to person per day (m$^3$/person/day) provide total cubic meter of bottled water per person per year.

The bottled water volume estimate also is based on household survey answers which provided number and volume of bottled water purchased per household per week. Unit conversion calculations (from household per week to person per day) provide total cubic meter of bottled water per person per year.

The volume delivered from domestic wells is calculated by multiplying total hours of operation of pumps per day by the flow rate of the pumps. Unit conversion calculations provide total cubic meter pumped per person per year. The total hours of operation of pumps were derived from interview answers. Not all interviews reported using their wells (32 out of the 105 interviews reported pumping water from their wells). Those who used well pumped on average around 5 min per day at an average flow rate estimated to be around 1.053 m$^3$/hours. It was computed by averaging all flow rates of households based on equation (5):

$$Q = p \times \frac{6116 \times 10^3 \mu}{h \times d}.$$  \hspace{1cm} (5)

Where: $p =$ power (kW), 0.7457 kW. The typical household pump sizes are around 1HP; based on the water establishment (El Asmar, personal communication, February 14, 2020). 6116 $\times$ 103 $\times$ constant for conversion. $\mu =$ pump efficiency (0.70). $h =$ differential head, depth of the wells (m). Depth intake is usually less than the depth of the well. However, since depth intake was not available, it was assumed that the pumps are located at the ground level and that residents were pumping water from the bottom of the pumps which was considered as the pumping height. The interviewees provided the depth of the well, however for the missing depths an average of 70 m was taken into account, which is based to the average of the well depth from the interview answers. $d =$ density (1000 kg/m$^3$).

Internal pumped volume is calculated by multiplying total hours of operation of pumps by the flow rate of the pumps. Unit conversion calculations provide total volume pumped per person per year. The hours of pump operation are based on interview answers, which indicate that on average a building pumps water internally around 20 h per week. Average flow rate from lower to upper reservoirs, which pumps a mixture of three sources (formal piped infrastructure, tanker trucks and wells, refer to figure 2), estimated to be 8 m$^3$/hours. Similar to domestic well volumes, it was computed by averaging all flow rates of households based on equation (5), but with a differential head ($h$) value based on the height of building (pumping water from ground level to roof reservoirs), as opposed to well depth.

2.2.3. Sensitivity analysis to address uncertainty in model estimations

Model uncertainty is explored using a sensitivity analysis. The sensitivity analysis applied a range of values for key parameters in the base case model to estimate a range of possible outcomes for key indicators of interest. To identify the input ranges, we follow a three-step process as highlighted in table 3. Our first choice was to use references from the literature (highlighted in light gray in the table). This allowed us to identify ranges for water treatment of all sources, and water volume and hours of operation for the groundwater pumping of private domestic wells and distribution through pumps of internal building pumping. When this was not possible,
we compared base case model values with adjusted values in two ways. We adjusted fuel economy parameter based on age of trucks in the market (highlighted in medium color dark gray in the table). Hydraulic power of pumps was based on nameplate values and never measured by the water establishment. So we adjusted pumping capacity based on pump size equation (equation (5)) (highlighted in dark gray in the table). Finally, table 3 shows the sensitivity analysis application per source and phase. Where sufficient data did not exist to provide a complete range (i.e., a low and high value around our base case assumption), we included a single high or low value relative to the estimated base case model ‘scenario’. These input range values were then utilized in the model to produce results for a minimum value scenario (all the lowest input parameter values), a base case model scenario (comprised of all the raw data estimates or average values collected from the literature), and maximum value scenario (all the highest input range value.) Step by step calculations and references of the sensitivity analysis range parameters are developed further in appendix A.

3. Results

The results are divided into three sections. We start presenting intensive energy use and carbon emissions per cubic meter of water per source for different delivery stages. We then show total energy use and carbon emissions per total delivered volumes per person per year for the case study area. We finish by presenting sensitivity analysis results.

3.1. Energy and carbon intensities per cubic meter by delivery stage and source

The results for energy and carbon intensities are presented for each water delivery stage in tables 4 and 5 respectively. The tables include model values, minimum and maximum value scenarios. We present base case model values from most to least intensive. Range values are in tables 4 and 5 for reference, and presented in more detail in section 3.3.

For wholesale water acquisition, groundwater pumping, tanker trucks showed the highest energy intensity 2.2 kW h/m³, followed by bottled water 0.79 kW h/m³, private domestic wells 0.69 kW h/m³, and the formal piped infrastructure 0.009 kW h/m³. For the treatment, the energy use intensity is highest for bottles with 0.915 kW h/m³, followed by the formal piped infrastructure 0.56 kW h/m³ and then private domestic wells 0.52 kW h/m³. For the distribution, the energy use intensity is also highest for bottles with 0.3 kW h/m³, followed by tanker trucks 0.73 kW h/m³, the formal piped infrastructure 0.137 kW h/m³, and internal pumping 0.089 kW h/m³.

In sum, the total energy intensity for the informal sources was higher than the energy intensity for the formal the piped infrastructure. For the informal sources, bottled water had the highest energy intensity values 62.04 kW h/m³, followed by tanker trucks (9.57 kW h/m³), private domestic wells (1.22 kW h/m³), and internal building pumping, which was comparatively insignificant (0.09 kW h/m³). The formal piped infrastructure total energy use was 0.71 kW h/m³.

For carbon intensity results, tanker trucks also had the highest carbon emissions for the groundwater pumping stage 1.72 kg CO₂/m³, followed by bottled water 0.615 kg CO₂/m³, private domestic wells 0.538 kg CO₂/m³, and formal piped infrastructure 0.007 kg CO₂/m³. For treatment, the carbon intensity is highest for bottles with 0.708 kg CO₂/m³, followed by formal piped infrastructure with 0.433 kg CO₂/m³ and private domestic wells with 0.402 kg CO₂/m³. For distribution, the carbon intensity is also highest for bottled water 15 kg CO₂/m³, followed by the tankers 1.82 kg CO₂/m³, the formal piped infrastructure 0.106 kg CO₂/m³ and internal pumping with both equal to 0.069 kg CO₂/m³.

Similar to the energy intensity results, the total carbon intensity of informal sources was higher than the formal piped infrastructure. Bottled water had the highest carbon intensity (16.32 kg CO₂/m³), followed by tanker trucks (3.55 kg CO₂/m³), private domestic wells (0.94 kg CO₂/m³), and internal pumping releases insignificant amounts of CO₂ with 0.07 kg CO₂/m³. The formal piped infrastructure has a total carbon emission intensity of 0.55 kg CO₂/m³.

3.2. Total energy use and carbon emissions per capita

Total delivered volume and total energy use and carbon emissions per person per year are presented in table 6. We present base case model values from most to least intensive. Range of values and percentages of variability are placed in table 6 for reference and are presented in more detail in section 3.3.

The formal piped infrastructure delivers 77% of the overall volume to the neighborhood (roughly 35.6 m³/person/year), followed by 12% from domestic wells which provide (5.4 m³/person/year), 10% from tanker trucks (4.7 m³/person/year), and lastly, 2% from bottled water (0.8 m³/person/year). Since internal pumping is not a water source, its volume is not included in the total water volume.

In terms of total annual energy use per person, bottled water has the highest total energy use with 49 kW h/person/year, followed by tanker trucks with 45 kW h/person/year, formal piped infrastructure with
### Table 3. Application of sensitivity analysis per source and phase.

| Energy intensity          | Pumping groundwater                                      | Water treatment | Distribution                                      |
|---------------------------|----------------------------------------------------------|-----------------|---------------------------------------------------|
| Formal piped infrastructure | • Adjusted hydraulic power size based on pump size formula → Compared base model and adjusted calculation as range | → Energy use range based on literature | • Adjusted hydraulic power size based on pump size formula → Compared base model and adjusted calculation as range |
| Tankers trucks            | • Adjusted hydraulic power size based on pump size formula → Compared base model and adjusted calculation as range | —               | • Adjusted fuel economy based on truck age in the market → Compared base model and adjusted calculation as range |
| Bottled water             | • Adjusted hydraulic power size based on pump size formula → Compared base model and adjusted calculation as range | → Energy use range based on literature | • Adjusted fuel economy based on truck age in the market → Compared base model and adjusted calculation as range |
| Private domestic wells    | • Adjusted hours of operation based on literature → Compared base model and adjusted calculation as range | → Energy use range based on literature | — |
| + Internal building pumping | —                                                        | —               | • Adjusted water volume based on literature → Compared base model and adjusted calculation as range |


25 kW h/person/year, internal pumping 21 kW h/person/year (14%), and lastly private domestic wells with 7 kW h/person/year. Since bottled water and tanker trucks have the highest energy intensity values (62 kW h/m³ and 9.5 kW h/m³ respectively, table 4), it makes sense that they contribute most to total annual energy use for water per person. Formal piped infrastructure has the highest delivered volume, which becomes a high proportion of annual per capita energy use, even though it has one of lowest energy intensity values of all water sources at 0.71 kW h/m³ (table 4). Internal building pumping still has sizable extensive energy use, because of the high volume internally pumped (even with the lowest energy intensity 0.09 kW h/m³, table 4). Finally, private wells have the lowest annual per capita energy use, given its low energy intensity value (1.2 kW h/m³, table 4) and small share of volumetric water use.

For total annual carbon emissions per person, the formal piped infrastructure system has the highest proportion of emissions with 19 kg of CO₂/person/year, followed by tanker trucks with 17 kg of CO₂/person/year, internal pumping with 16 kg of CO₂/person/year, bottled water with 13 kg of CO₂/person/year, and private domestic wells with the lowest percentage with 5 kg of CO₂/person/year. The higher carbon emissions from the formal piped infrastructure are from the much higher volume of water consumed from this source and the inefficiency of the Lebanese electrical grid, as detailed later in the discussion section. Tanker trucks have the second highest carbon emissions mainly related to the inefficiency of the trucks themselves as well as hauling water by vehicle as compared to piped networks (even with relatively a low supply of 4.7 m³/person/year, table 6). Internal pumping has relatively high carbon emissions, because of the high volume pumped internally (even with the lowest carbon intensity values of 0.069 kg of CO₂/m³, table 5). Bottled water has a relatively low total carbon emissions because of its low delivered volume (even with the highest carbon intensity value of 16.3 kg of CO₂/m³, table 5). As for private domestic wells, their total emissions have the lowest percentage, because they have a low carbon intensity value (0.9 kg CO₂/m³, table 5).

3.3. Energy and carbon intensities per cubic meter sensitivity analysis

For the sensitivity analysis, we ranked energy intensity and carbon emissions values from low to high sensitivity. If variability from model values and updated values varied less than 33%, than we considered parameters to have a low sensitivity, if variability was between 33% and 66% we considered parameters to have a middle level sensitivity, and finally, if variability was above 66%, we considered parameters highly sensitive. The sensitivity analysis shows that private domestic wells have the most variable data with a difference of −82% and +43%, followed by the formal piped infrastructure with +57%, tanker trucks with −47% (only for its total carbon emission) (refer to table 6). These variations stem mainly from differences in groundwater pumping linked to well depth (refer to tables 5 and 4), reflecting reduced energy use with shallower wells. For our calculations, we considered average wells depths based on water establishment data and survey results. In addition, for private domestic wells, higher variation also stems from differences in treatment, which we based on scenarios developed by Garfi et al (2016). Data accuracy is further discussed in the data limitation section.

Table 4. Energy intensity per cubic meter of water per delivery stage (kW h/m³). Base model, minimum and maximum value scenarios.

| Energy intensity kW h/m³ | Pumping groundwater | Water treatment | Distribution | Total energy intensity |
|-------------------------|---------------------|-----------------|--------------|-----------------------|
|                         | Min  | Model | Max   | Min  | Model | Max   | Min  | Model | Max   | Min  | Model | Max   | Min  | Model | Max   |
| Formal piped infrastructure | 0.009 | 0.090 | 0.406 | 0.560 | 0.716 | —     | 0.137 | 0.303 | 0.55  | 0.71  | 1.11  |
| Tankers trucks           | 0.083 | 2.230 | —     | —     | —     | 7.340 | 8.183 | 7.42  | 9.57  | 10.41 |
| Bottled water            | 0.072 | 0.695 | —     | 0.260 | 0.520 | 1.04  | —     | —     | —     | 0.33  | 1.22  | 1.74  |
| Private domestic wells    | 0.072 | 0.695 | —     | 0.260 | 0.520 | 1.04  | —     | —     | —     | 0.33  | 1.22  | 1.74  |
+ Internal building pumping | —    | —     | —     | 0.072 | 0.089 | —     | 0.07  | 0.09  | 0.09  |

Table 5. Carbon intensity per cubic meter of water per delivery stage and sources (kg of CO₂/m³). Base model, minimum and maximum value scenarios.

| Carbon intensity per cubic meter of water (kg of CO₂/m³) | Pumping groundwater | Water treatment | Distribution | Total carbon intensity |
|---------------------------------------------------------|---------------------|-----------------|--------------|-----------------------|
|                                                        | Min    | Model | Max    | Min    | Model | Max    | Min    | Model | Max    | Min    | Model | Max    |
| Formal piped infrastructure                             | 0.007  | 0.069 | 0.314  | 0.433  | 0.554 | —     | 0.106  | 0.235 | 0.43  | 0.55  | 0.86  |
| Tankers trucks                                          | 0.064  | 1.726 | —      | —      | —     | —     | 1.825  | 2.03  | 1.89  | 3.55  | 3.76  |
| Bottled water                                           | 0.015  | 1.276 | 0.080  | 0.708  | 1.393 | —     | 15.00  | 16.74 | 15.62 | 16.32 | 19.41 |
| Private domestic wells                                   | 0.035  | 0.538 | —      | 0.201  | 0.402 | 0.805 | —      | 0.26  | 0.94  | 1.34  |
+ Internal building pumping                               | —      | —     | —      | 0.035  | 0.069 | —     | 0.06  | 0.07  | 0.07  |
Table 6. Total energy use and carbon emissions per person per year.

| Volume of water delivered per person per year m³/person/year | Total energy use per person per year kW h/person/year | Total carbon emissions per person per year kg of CO₂/person/year |
|---------------------------------------------------------------|-----------------------------------------------------|---------------------------------------------------------------|
|                                                               | Min       | Model     | Max       | Min       | Model     | Max       |
| Formal piped infrastructure                                   | 35.6      | 77%       | 20 (−22%) | 25        |          | 40 (+57%) |
|                                                              | 22%       |           |           | 15 (−22%) | 19        | 31 (+57%) |
| Tankers trucks                                                | 4.7       | 10%       | 35 (−22%) | 45        |          | 49 (+9%)  |
|                                                              | 22%       |           |           | 9 (−47%)  | 17        | 18 (+6%)  |
| Bottled water                                                 | 0.8       | 2%        | 49 (−1%)  | 49        |          | 56 (+14%) |
|                                                              | 43%       |           |           | 12 (−4%)  | 13        | 15 (+19%) |
| Private domestic wells                                        | 5.4       | 12%       | 2 (−73%)  | 7         | 9 (+43%)  | 13 (−73%) |
|                                                              | 73%       |           |           | 1 (−73%)  | 5         | 7 (+53%)  |
| + Internal building pumping                                   | 238       | —         | 17 (−20%) | 21        | 21 (0%)   | 16 (0%)   |
| Total                                                         | 46 (excluding internal pumping)                     | —         | 121       | 147       | 175       | 51        |
|                                                              |           |           |           | 71        | 87        |           |
4. Discussion

While energy–water nexus analyses have evolved to incorporate different technical, environmental and geographical dimensions, they have remained narrowly focused on centralized formal piped water services (Hamiche et al 2016). This study is the first to analyze energy consumption for water provision for both formal piped water sources and informal sources from bottled water, tanker trucks and private domestic wells. Using a neighborhood in Beirut as a case study, we compared energy use and carbon emissions per cubic meter and per capita for both formal and informal water sources. Energy use and carbon emissions are calculated for three delivery stages per source including pumping, treatment and distribution. Our main findings show the following: (1) informal water sources altogether have the highest energy use and carbon emissions. They account for 83% of total energy use and 72% of total carbon emissions per person per year, even though they only provide 23% of total delivered volume per person per year. (2) Bottled water and distribution of water by tanker trucks have the highest energy intensity values per cubic meter of all water sources. (3) Internal water pumping and formal piped water infrastructure system result relatively with high energy use and carbon emissions per person per year.

4.1. Energy and carbon intensities per cubic meter by delivery stage and source

Informal water sources have the highest energy and carbon intensity values per cubic meter, with bottled water having the highest per cubic value based on its highest component values for treatment and distribution. The higher energy intensity value for treatment is a result of the bottled water going through a more robust filtration with higher associated energy use. To calculate energy use, the base model uses average energy intensity values for typical treatment methods of ozonation, UV radiation, ultrafiltration, and reverse osmosis (with a TDS of 500 ppm), based on Gleick and Cooley (2009). The sensitivity analysis shows that water treatment for potable use can be highly variable as it can be as low as 0.01 kW h/m³ or as high as 1.8 kW h/m³, and in some cases can reach up 3 kW h/m³, as in southern California (Gleick and Cooley 2009). Hence, accurate metered data is further needed to validate these results. Moreover, our study did not take into consideration the production and disposal of the plastic bottles. If we include these additional energy requirements in future analysis, bottled water estimates will probably result with even higher energy and carbon intensity values.

As expected, our case study shows that transporting water through trucks (bottled water through regional trucks and bulk water through tanker trucks) has the highest energy and carbon intensity per cubic meter compared to other delivery stages. The results meet our expectation with trucks having higher emissions than pumping stations. Our interviews with tanker trucks showed trucks were made between 1970s and 2020s (with 40% made between 1970 and 1999 and 60% made between 2000 and 2020). Hence, the calculations were based on average fuel economy for trucks (model value) and took into consideration a 15% decrease in fuel economy efficiency based on the truck age (sensitivity analysis), which resulted with even higher levels of energy use and carbon emissions. In addition, tankers have additional harmful hidden emissions such as the nitrous oxides (NOx) and other impacts from black carbon (BC) and particulate matter (PM) not included here. The main problem is that tankers usually operate inside a city, releasing these harmful emissions to populated areas. Further studies could include impacts of informal water supplies from NOx, BC, and PM on residents. Tankers also have greater volume restrictions compared to formal piped infrastructure as they can only transport a limited volume with each trip. Thus, even though they help overcome local water shortages, they are not a complete substitute for the formal piped infrastructure.

The formal piped infrastructure system has low energy intensity per cubic meter, which meets our expectations of having the piped infrastructure to be more efficient than informal water sources. Our model base scenario shows that overall the Lebanese formal piped infrastructure energy intensity is around 0.71 kW h/m³ and ranges between 0.63 and 1.16 kW h/m³ (refer to table 4). Model base result is close to other Mediterranean examples such as Aveiro, Portugal that has an energy intensity of 0.79 kW h/m³ or Tarragona, Spain with 0.85 kW h/m³ (Lee et al 2017). However, if we compare with world averages, we find that our energy intensity ranges are slightly lower. The average energy intensity of formal piped infrastructure across 20 examples from Africa, Asia, Europe, and North America, is around 1.46 kW h/m³ (Lee et al 2017), showing that our results are on average 39% lower. This indicates that the higher value of our range (1.11 kW h/m³ refer to table 4) might be more representative of the actual energy intensity of the Lebanese formal piped infrastructure.

4.2. Total energy use and carbon emission per capita

When added together, the informal water sources (tanker trucks, bottled water, and private domestic wells) represent 83% of total energy for water use and 72% of total carbon emissions per person per year, even though informal sources are only 23% of the total water supplied per person per year. While we expected tanker trucks and bottled water to have high total energy use and carbon emissions (because of their high energy intensity values), we were surprised with the results from internal building pumping. Even though internal pumping
has very low intensity per cubic values, it still contributes to 14% of per capita energy use and 23% of per capita carbon emissions, mainly a result of the high pumped volumes from lower to upper reservoirs. Internal pumping is not usually accounted for in energy-for-water studies because it is not part of the formal infrastructure network. However, this study shows that in areas of chronic water shortages, residents maximize their on-site storage using lower and upper reservoirs and need to pump their water internally at the building scale. Our interview answers indicate that residents pump water internally around 20 h per week at a building level.

The formal piped infrastructure expends 17% of per capita energy for water use, which is relatively low—ranking third after bottled water and tanker trucks. This is mainly because of its low energy intensity value, as discussed earlier. However, contrary to our expectations, it has the highest per capita carbon emissions (28%, refer to table 6). This high carbon emissions estimate can be linked to its high proportion of delivered water (77%), but also to the inefficient and carbon intensive Lebanese electrical grid. The Lebanese grid has a carbon intensity 60% higher than world averages, with a value of 0.774 kg of CO₂/kW h as compared to the average world grid carbon intensity of roughly 0.485 CO₂/kW h (IEA 2019). Thus, this high carbon intensity value for the Lebanese grid results in higher per capita carbon emissions for the piped water infrastructure.

4.3. Recommendations and implications

Since informal water sources have higher energy use and carbon emissions values than the formal water system in our case study, most recommendations focus on the informal water system. Nevertheless, it is important to address the high carbon emissions for the piped infrastructure, mostly related to the inefficient Lebanese electrical grid. One way forward would be to move away from overreliance on fossil fuel-based power generation and to start investing in renewable energy to lower the carbon intensity of the electrical grid which will enable the transition to a green and smart economy and mitigate climate change effects (Usman et al 2020, EEA 2021).

Informal water sources are often needed to help communities access water and overcome water shortages. However, there are important economic and environmental trade-offs with these alternative water sources. Generally, informal water sources are 3 to 40 times more expensive (Wutich et al 2016), use more energy, and emit more carbon than formal piped water networks. Thus, to transition to a more resilient and sustainable system, we need strategies that reduce these negative impacts of informal sources or reduce the need for them. Knowing that the Lebanese water system suffers from 45% leakage (Shaban 2020, Bulos and Yam 2021), solutions should focus on improving the formal piped infrastructure to reduce losses, which could thereby reduce demand for informal sources (and lower the energy and carbon emissions from delivered water). This strategy is currently being developed by the Lebanese water utility as an indirect method to reduce reliance on informal tanker truck deliveries (Hoayek, personal communication, September 8, 2019). However, upgrading the formal piped infrastructure system is easier said than done in a region that suffers from poorly managed public institutions (El Fadel et al 2003, Alameddine et al 2018). Hence, pursuing a hybrid strategy that goes beyond a unilateral focus on improving the formal system by also seeking to attenuate the impact of the informal water sources, might be more realistic.

Informal sources have developed in different ways and at different scales, so a range of strategies is likely necessary to address their challenges. On a city scale, bottled water and bulk water are usually transported by delivery and tanker trucks that tend to have high energy use and GHG emissions. Policies could be developed to phase out the use of old and polluting trucks with inefficient engines and push truck owners to upgrade to more efficient engines and/or engines that rely on cleaner energy sources, e.g., natural gas, hydrogen, and electricity.

At the building level, Lebanese households rely on on-site storage and private wells, with higher total energy use and carbon emissions to pump water from ground-level to roof reservoirs. This internal pumping within buildings is controlled by the residents in a decentralized fashion. Strategies could incentivize residents across socio-economic levels to move toward more efficient pumping systems, such as using solar-powered pumps. In Lebanon, a successful example of a similar technology incentive was the widespread adoption of solar water heaters (SWH) by households of different socio-economic levels. This was only possible through a financial incentive program that provided households with loans at low interest rates to procure and install subsidized SWH from approved providers (LCEC 2019). The financing mechanism was based on a collaboration between the Lebanese Central Bank, Lebanese local commercial banks and the Lebanese Ministry of Energy and Water (LCEC 2019). This type of decentralized solutions provides flexibility in infrastructure (Brown et al 2009, Farrelly and Brown 2014, Bichai et al 2015) and improve community cohesion through participation that drives community involvement and empowerment (Kyessi 2005, Russell 2014).

In our case study, the selected neighborhood was composed of two communities of different socio-economic levels. However, both communities are within the same water zone. Hence they have the same water intermittence schedule from the piped infrastructure and similar pumping needs. This means that they have similar energy–water nexus requirements. Moreover, in Lebanon, water shortages are generally widespread
and communities of different socio-economic levels resort to similar informal water sources to satisfy their daily water needs. However, in other examples around the world, informal water systems tend to be more present among vulnerable and disadvantaged communities (Ranganathan 2014, Peloso and Morinville 2014, Jepson and Vandevalle 2016, Balazs and Lubell 2014, Balazs and Ray 2014, London et al 2021). There are some studies that focus on the affordability of informal water sources of different income groups (Nastiti et al 2017, Pattanayak et al 2005, Amit and Sasidharan 2019, Christina-Smith et al 2013, Walter et al 2017). Moving forward, more research is needed to analyze how socio-economic disparities impact the energy nexus of informal water sources.

4.4. Data limitations
Data availability was limited for different reasons for different water sources. For the piped infrastructure, we could not obtain actual energy intensity values for groundwater pumping and distribution, hence we used nameplate pump capacities that did not include efficiency factors of the pumps. Moreover, pump station data were limited to a six-month period, from January to June 2018. Hence, we could not account for seasonal changes. Finally, for water treatment in the formal sector, we could not obtain energy data from the water treatment plant, so we used energy intensity values based on estimates from Plappally and Lienhard (2012).

To obtain energy and water data on informal water sources, we developed surveys to collect data directly from the providers as well as residential consumers. We gathered data directly from 20 tankers and 100 household interviews, but we were not able to validate this raw data with national statistics on household water use and water tanker use because these data do not exist. We could not obtain any energy and volume data on pumping groundwater for tankers and bottled water companies. Thus, we based our groundwater pumping assumptions for tanker trucks on the groundwater pumping values from the formal piped system. We could not obtain data on water treatment for bottled water companies in Lebanon, so we based our calculations on Gleick and Cooley (2009), one of the rare studies that focuses on the energy impacts of bottled water. We are aware that the study differs in scope and context therefore we followed typical treatment techniques applied in bottled water plants and used the energy use values proposed by Gleick and Cooley (2009). Moreover, we could not obtain data on water treatment in Lebanese households. Knowing that households in Lebanon rely mainly on reverse osmosis to treat water and that most equipment are usually important from European markets (MoE/UNDP/GEF 2019), we based our calculations on the three scenarios developed by Garfi et al (2016) that referred to local manufacturers in Barcelona. Further studies are needed to validate pumping groundwater values and drinking water treatment values.

We addressed these limitations through a sensitivity analysis. This analysis followed a three-step process. First we used a range of parameters found in the literature. We then adjusted fuel economy values considering the age of trucks in the market. Hydraulic power of pumps was based on nameplate values and never measured by the water establishment. So we adjusted pumping capacity based on pump size equation (equation (5)). The analysis showed that our base model presented reasonable values. It also identified parameters for investigation in future studies. More specifically, the analysis showed that the parameters used to calculate energy use for pumping groundwater and water treatment are highly sensitive and produce some variability in model results. Thus, future research should validate the obtained ranges. The analysis also showed low variability for transportation and internal pumping. This allows us to confirm that transporting water through trucks is highly inefficient and that internal building pumping has significant total energy use and carbon emissions.

5. Conclusion
People in areas that experience water shortages often rely on multiple sources, including formal piped water infrastructure and informal sources such as tanker trucks, bottled water, and domestic wells. These informal sources are essential in securing community access to water when formal piped infrastructure fails to deliver a sufficient and reliable water supply. While a wide range of studies exist on energy use in the water sector, the water–energy nexus literature has generally neglected the energy use and carbon emissions from informal water sources. Given that 30% to 60% of communities in developing countries rely on these informal sources (Ahlers et al 2013), it is necessary to develop a framework that includes informal water sources in water–energy nexus assessments. This study develops such a framework and compares the energy use and carbon emissions (both per cubic meter and per capita) for formal and informal water sources for a typical neighborhood in Beirut, Lebanon.

Overall findings show that informal water sources have the highest energy use and carbon emissions per cubic meter and per capita. They also account for 83% of total energy use and 72% of total carbon emissions of per person per year, even though they only provide 23% of total delivered volume per person per year. This shows that even when communities only partially rely on informal sources, the environmental impacts of these informal sources can be quite significant. The assessment of transporting water through trucks...
(bottled water through regional trucks and bulk water through tanker trucks) proved to be especially important since they have the highest energy and carbon intensity values per cubic meter, and also have the added impacts of NOx black carbon and particulate matter emissions. Further, they are much more limited in the total volume of water they can deliver relative to a larger, formal piped distribution network. This study also sheds light on another hidden energy use and carbon emitting urban water activity—internal water pumping within buildings. Such activities are not typically included in energy–water nexus studies. Finally, even though formal piped infrastructure has the lowest energy and carbon intensity values per cubic meter, it has the highest per capita carbon emissions of water consumption due to the high carbon intensity of the Lebanese electric grid.

While we recognize the role of informal water sources in compensating for inadequate supply from formal water supplies, it remains essential to improve the formal infrastructure systems when possible. In the case of Beirut, reducing system leakages (currently estimated at 45%) is crucial for reducing demand for water from informal sources, and reducing their negative environmental impacts. In the meantime, regional decision-makers should also pursue strategies to directly mitigate energy use and carbon emissions impacts of informal systems by incentivizing the replacement of carbon intensive trucks and by developing financial mechanisms that will incentive households to invest in more efficient pumps for internal water pumping. Finally, for the formal piped infrastructure, moving away from overreliance on fossil fuel-based power generation and investing in renewable energy to lower the carbon intensity of the electrical grid will enable climate change mitigation and transition toward a green and smart economy.

This study is first to compare the energy–water nexus of formal and informal water sources and to highlight the high energy use and carbon intensity values of informal sources. Data availability was a limiting factor in our analysis and we developed a sensitivity analysis to address this uncertainty. Nonetheless, moving forward, it would be important to compare the results (especially for pumping groundwater and water treatment) with other case studies for regions that also rely on informal water sources. Expanding this analysis across regions will help better estimates of the economic and environmental impacts of informal water sources.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Appendix A. Values and assumptions per source and delivery stages

A.1. Formal piped infrastructure

Formal piped infrastructure has three delivery stages: pumping groundwater, water treatment and distribution through pumping stations (refer to table 1). Assumption and values of delivery stages are developed further below.

A.1.1. Pumping groundwater

Calculations are based on the nameplate of hydraulic power and daily values of pumping capacity and operation hours of southern and northern wells with their weighted average. Northern wells supply 77% of total volume compared to 23% for southern wells (Beirut and Mount Lebanon Water Establishment):

- Nameplate hydraulic power: 68 kW.
- Nameplate pumping capacity: 50,340 m³/day.
- Operating hours: 6.5 h/day.
- Daily electrical consumption: 442 kW h/day.

\[
EI = \frac{442 \text{ (kW h)}}{50,340 \text{ (m}^3\text{)}} = 0.009 \text{ (kW h/m}^3\text{)}
\]

\[
CI = \frac{442 \text{ (kW h)}}{50,340 \text{ (m}^3\text{)}} \times 0.774 \text{ (kg CO}_2\text{/kW h)} = 0.007 \text{ (kg of CO}_2\text{/m}^3\text{)}
\]
Sensitivity analysis: Based on equation (5), to pump a volume of 50 340 m³/day (equal to 34 958 l/min) we need a pump of 694 kW.

We consider that height is 85 m—based on depth of wells based on water establishment data.

Pump efficiency to be equal to 70%.

\[
\text{EI (kW h/m}^3\text{)} = 4511 \text{ (kW h)/50} \text{.340 (m}^3\text{)} = 0.090 \text{ (kW h/m}^3\text{)}
\]

\[
\text{CI (kg of CO}_2\text{/m}^3\text{)} = 4511 \text{ (kW h)/50.340 (m}^3\text{)} \times 0.774 \text{ (kg CO}_2\text{/kW h)} = 0.069 \text{ (kg of CO}_2\text{/m}^3\text{)}
\]

\[
\text{EI (kW h/m}^3\text{)} = \frac{24 627 \text{ (kW h)/81} \text{.190 (m}^3\text{)}}{24 627 \text{ (kW h)/81} \text{.190 (m}^3\text{)} \times 0.774 \text{ (kg CO}_2\text{/kW h)} = 0.235 \text{ (kg of CO}_2\text{/m}^3\text{)}
\]

A.1.2. Water treatment

Dbayeh water treatment plant has four treatment steps of screening, flocculation, filtration (rapid sand filtration), and chlorination (Margane and Houben 2010). We assume a total energy intensity for potable water treatment (including sedimentation, coagulation, gravity filtration, and surface water chlorination/dechlorination) of 0.5605 kW h/m³ (Plappally and Lienhard 2012).

With a total treated volume of 200 000 m³ per day (Beirut and Mount Lebanon Water Establishment) we calculated the electrical consumption as: energy use per cubic meter (kW h/m³) \times total treated volume (m³) = 112 102 kW h.

\[
\text{EI (kW h/m}^3\text{)} = 0.56 \text{ (kW h/m}^3\text{)}
\]

\[
\text{CI (kg of CO}_2\text{/m}^3\text{)} = 0.56 \text{ (kW h/m}^3\text{)} \times 0.774 \text{ (kg CO}_2\text{/kW h)} = 0.433 \text{ (kg of CO}_2\text{/m}^3\text{)}
\]

Sensitivity analysis: Based on Plappally and Lienhard (2012) energy intensity can vary between 0.406 and 0.716 kW h/m³. So energy intensity can vary on average 30% (increase and decrease).

\[
\text{EI (kW h/m}^3\text{)} = 0.406 \text{ or 0.716 (kW h/m}^3\text{)}
\]

\[
\text{CI (kg of CO}_2\text{/m}^3\text{)} = 0.406 \text{ or 0.716 (kW h/m}^3\text{)} \times 0.774 \text{ (kg CO}_2\text{/kW h)} = 0.314 \text{ or 0.554 of (kg of CO}_2\text{/m}^3\text{)}
\]

A.1.3. Distribution

Calculations based on the nameplate hydraulic power and daily values of pumping volumes and of operating hours of four pumping stations with their weighted averages (Beirut and Mount Lebanon Water Establishment):

- Nameplate hydraulic power: 505 kW.
- Nameplate pumping capacity: 81 190 m³/day.
- Operating hours: 22 h/day.
- Daily electrical consumption: 11 275 kW h/day.

\[
\text{EI (kW h/m}^3\text{)} = \frac{11 110 \text{ (kW h)/81} \text{.190 (m}^3\text{)}}{11 110 \text{ (kW h)/81} \text{.190 (m}^3\text{)} \times 0.774 \text{ (kg CO}_2\text{/kW h)} = 0.106 \text{ (kg of CO}_2\text{/m}^3\text{)}
\]

Sensitivity analysis: Based on equation (5), to pump a volume of 81 190 m³/day (equal to 56 382 l/min) we need a pump of 1119 kW.

We consider that height is 85 m—based on water establishment data.

Pump efficiency to be equal to 75%.

\[
\text{EI (kW h/m}^3\text{)} = \frac{24 627 \text{ (kW h)/81} \text{.190 (m}^3\text{)}}{24 627 \text{ (kW h)/81} \text{.190 (m}^3\text{)} \times 0.774 \text{ (kg CO}_2\text{/kW h)} = 0.235 \text{ (kg of CO}_2\text{/m}^3\text{)}
\]

A.2. Tanker trucks

Tanker trucks have two delivery stages: pumping groundwater, distribution through water trucks (refer to table 1). Assumption and values of delivery stages are developed further below.
A.2.1. Pumping groundwater

Pumping groundwater is based on the following:

- Average hydraulic power: 67 kW (Beirut and Mount Lebanon Water Establishment). The groundwater pump sizes for the tanker trucks were not available. Thus, we assumed that tanker trucks use the same pump sizes for groundwater pumping as the formal piped infrastructure. This assumption was later confirmed as reasonable by a water establishment engineer (El Asmar, personal communication, July 1, 2020).
- Pumping capacity: 183 m$^3$/day, based on the tanker trucks survey.
- Average operating hours: 6 h/day, based on the tanker trucks survey.
- Average electrical consumption: 396 kW h.

\[ EI = \frac{408 \text{ (kWh)}}{183 \text{ (m$^3$)}} = 2.23 \text{ (kWh/m$^3$)} \]

\[ CI = \frac{408 \text{ (kWh)}}{183 \text{ (m$^3$)}} \times 0.774 \text{ (kg CO}_2\text{/kWh)} = 1.73 \text{ (kg of CO}_2\text{/m$^3$)} \]

Sensitivity analysis: Based on equation (5), to pump a volume of 3220 m$^3$/day (equal to 2236 l/min) we need a pump of 44 kW. We consider that height is 85 m—based on water establishment data. Pump efficiency to be equal to 75%.

\[ EI = \frac{15 \text{ (kWh)}}{193 \text{ (m$^3$)}} = 0.083 \text{ (kWh/m$^3$)} \]

\[ CI = \frac{15 \text{ (kWh)}}{193 \text{ (m$^3$)}} \times 0.774 \text{ (kg CO}_2\text{/kWh)} = 0.064 \text{ (kg of CO}_2\text{/m$^3$)} \]

A.2.2. Distribution

Transportation of water is based on the following:

- Fuel economy: 33.1 L of diesel/100 km. The tanker interviews show that the average size of trucks is around 20 tons. We assumed that tanker trucks are equivalent to long haul trucks with an average payload weight of 19.3 tons (almost equal to 20 tons) with fuel economy baseline of 33.1 L of diesel/100 km including a 41.9% engine brake thermal efficiency, (Rodríguez et al 2018, Delgado et al 2017).
- Emissions factor: 2.66 kg CO$_2$/L of diesel.
- Energy content of gasoline: 38.6 MJ per liter of diesel = 10.7 kW h per liter of diesel.
- Traveled distance: 40 km. Based on the residential interviews we assume that, for 1 delivery order, tanker trucks travel a distance of 40 km (equivalent to a roundtrip from the location of the wells in Beirut’s suburbs to case study area including traffic). We omitted any stop per delivery trip and consider that trucks transport water from the wells directly to the case study area.
- Truck volume: 19 m$^3$. Since 1 ton of water is equal to 1 m$^3$, we considered that the volume of water transported is equivalent to the trucks’ payload weight with 19 m$^3$ for the tanker trucks.

\[ EIT = \frac{33.1 \text{ (L of diesel)/100km)} \times 10.7 \text{ (kWh h/ (L of diesel) \times 40(km)/19.3 (m$^3$))}}{100} = 7.34 \text{ (kWh/m$^3$)} \]

\[ CIT = \frac{33.1 \text{ (L of diesel)/100km)} \times 2.66 \text{ (kWh h/Liter of diesel) \times 40 (km)/19.3 (m$^3$)} /100 = 1.82 \text{ (kg of CO}_2\text{/m$^3$)} \]

Sensitivity analysis: Fuel economy varies with truck age: based on our survey 40% of trucks are made between 1970 and 1999 and 60% made between 2000 and 2020. Fuel economy efficiency decreases by 15% for trucks from 1970–1999 and by 8% for trucks from 2000–2010 (EAI 2011). Fuel economy is decreased by 12% (weighted average of above %) and equal to 36.9 L of fuel/100 km.

\[ EIT = \frac{36.9 \text{ (L of diesel)/100 km)} \times 10.7 \text{ (kWh h/ (L of diesel) \times 40 (km)/19.3 (m$^3$))}}{100} = 8.183 \text{ (kWh/m$^3$)} \]

\[ CIT = \frac{36.9 \text{ (L of diesel)/100 km)} \times 2.66 \text{ (kWh h/Liter of diesel) \times 40 (km)/19.3 (m$^3$)} /100 = 2.034 \text{ (kg of CO}_2\text{/m$^3$)} \]
A.3. Bottled water

Bottles have three delivery stages: pumping groundwater, treatment through cleaning, filling, sealing and labeling bottles, and distribution through regional delivery trucks (refer to table 1). Assumption and values of delivery stages are developed further below.

A.3.1. Pumping groundwater

Pumping groundwater is based on the following:

- Average hydraulic power: 67 kW, same as the water tanker pump size data (Beirut and Mount Lebanon Water Establishment).
- Average operating hours of pumps: 24 h/day, (El Asmar, personal communication, January 05, 2020).
- Pumping capacity: 2055 m³/day (Daou and Mikhael 2016).
- Average electrical consumption: 1604 kW h.

\[
EI (\text{kW h/m}^3) = \frac{1632 (\text{kW h})}{2055 (\text{m}^3)} = 0.794 (\text{kW h/m}^3)
\]

\[
CI (\text{kg of CO}_2/\text{m}^3) = \frac{1632 (\text{kW h})}{2055 (\text{m}^3)} \times 0.774 (\text{kg CO}_2/\text{kW h}) = 0.615 (\text{kg of CO}_2/\text{m}^3)
\]

Sensitivity analysis: Based on equation (5), to pump a volume of 10 238 m³/day (equal to 7110 l/min) we need a pump of 141 kW.

We consider that height is 85 m—based on water establishment data. Pump efficiency to be equal to 70%.

\[
EI (\text{kW h/m}^3) = \frac{3388 (\text{kW h})}{2055 (\text{m}^3)} = 1.649 (\text{kW h/m}^3)
\]

\[
CI (\text{kg of CO}_2/\text{m}^3) = \frac{3388 (\text{kW h})}{2055 (\text{m}^3)} \times 0.774 (\text{kg CO}_2/\text{kW h}) = 1.276 (\text{kg of CO}_2/\text{m}^3)
\]

A.3.2. Water treatment

Gleick and Cooley (2009) is one of the only studies in water–energy nexus literature that focuses on bottled water and looks at the energy footprint for various phases of water production, transportation, and use. Spring water is sometimes treated through processes such as ultrafiltration, ozonation, ultraviolet radiation, and reverse osmosis. For bottled water, total energy intensity was estimated at 0.915 kW h/m³ (Gleick and Cooley 2009).

\[
EI (\text{kW h/m}^3) = 0.915 (\text{kW h/m}^3)
\]

\[
CI (\text{kg of CO}_2/\text{m}^3) = 0.915 (\text{kW h/m}^3) \times 0.774 (\text{kg CO}_2/\text{kW h}) = 0.708 (\text{kg of CO}_2/\text{m}^3)
\]

Sensitivity analysis: Based on Gleick and Cooley (2009) energy intensity to treat bottled water can vary from 0.01 to 1.8 kW h/m³. So energy intensity can vary on average 93% (increase and decrease).

\[
EI (\text{kW h/m}^3) = 0.010 or 1.800 (\text{kW h/m}^3)
\]

\[
CI (\text{kg of CO}_2/\text{m}^3) = 0.010 or 1.800 (\text{kW h/m}^3) \times 0.774 (\text{kg CO}_2/\text{kW h}) = 0.008 or 1.393 (\text{kg of CO}_2/\text{m}^3)
\]

A.3.3. Distribution

Transportation of water is based on the following:

- Fuel economy: 36.4 L of diesel/100 km. We assumed that regular delivery trucks are equivalent to regional delivery trucks with an average payload weight of 12.9 tons with a baseline fuel economy of 37.4 liters of diesel/100 km including a 44.8% engine brake thermal efficiency, (Rodríguez et al 2018, Delgado et al 2017).
- Emissions factor: 2.66 kg CO2/L of diesel.
- Energy content of gasoline: 38.6 MJ per liter diesel = 10.7 kW h per liter of diesel.
- Traveled distance: 200 km. Based on the residential interviews we assume that, for 1 delivery order, delivery trucks travel a distance of 200 km (equivalent to the average roundtrip distance from two major springs in Mount Lebanon—Sohat and Sannine—to the case study area including traffic). We also omitted any stop per delivery trip and consider that trucks transport water from the sources directly to the case study area.
• Truck volume: 12 m³. Since 1 ton of water is equal to 1 m³, we considered that the volume of water transported is equivalent to the trucks’ payload weight with 12 m³. We excluded the weight of plastics.

$\text{EIT (kW h/m³)} = 36.4 \text{(Liter of diesel)/100 km) } \times 10.7 \text{ (kW h/(Liter of diesel) } \times 200 \text{(km)}/12.9 \text{ (m³)}/100 = 60.33 \text{ (kW h/m³)}$

$\text{CIT (kg of CO₂/m³)} = 36.4 \text{ (Liter of diesel)/100 km) } \times 2.66 \text{ (kW h/Liter of diesel) } \times 200 \text{ (km)}/19.3 \text{ (m³)}/100 = 15.00 \text{ (kg of CO₂/m³)}$

**Sensitivity analysis:** Similar to tanker truck data, we assume that regional trucks age is on average older. Similarly, fuel economy decreases by 12% and is equal to 40.6 L of fuel/100 km.

$\text{EIT (kW h/m³)} = 40.6 \text{ (Liter of diesel)/100 km) } \times 10.7 \text{ (kW h/(Liter of diesel) } \times 200 \text{ (km)}/12.9 \text{ (m³)}/100 = 67.35 \text{ (kW h/m³)}$

$\text{CIT (kg of CO₂/m³)} = 40.6 \text{ (Liter of diesel)/100 km) } \times 2.66 \text{ (kW h/Liter of diesel) } \times 200 \text{ (km)}/19.3 \text{ (m³)}/100 = 16.74 \text{ (kg of CO₂/m³)}$

### A.4. Private domestic wells

Private domestic wells have two delivery stages: pumping groundwater, water treatment through reverse osmosis. Assumption and values of delivery stages are developed further below.

#### A.4.1. Pumping groundwater

Groundwater pumping calculations are based on the following:

- Average hydraulic power: 1HP (0.745 kW), typical domestic pump size, (El Asmar, personal communication, February 14, 2020).
- Average hours of operation: 47 min/building/day (based on the household survey). Which is equal to 0.014 h/day.
- Average electrical consumption of household pumps: 0.011 kW/h.

$\text{EI (kW h/m³)} = 0.010 \text{ (kW h)/0.015 (m³)} = 0.695 \text{ (kW h/m³)}$

$\text{CI (kg of CO₂/m³)} = 0.010 \text{ (kW h)/0.015 (m³)} \times 0.774 \text{ (kg CO₂/kW h)} = 0.538 \text{ (kg of CO₂/m³)}$

**Sensitivity analysis:** Private wells in Beirut operate 4.4 h/day only during summer season, (Acra et al, 1997). Based on our survey, Beirut experiences 4 dry summer month. Hence, taking into consideration summer weighted average, hours of operation is 1.5 h/day. Pumped volume is around 46.8 m³ only during summer season (Acra et al, 1997). Hence, taking into consideration summer weighted average, mean flow is 15.6 m³/day.

$\text{EI (kW h/m³)} = 1.12 \text{ (kW h)/15.6 (m³)} = 0.07 \text{ (kW h/m³)}$

$\text{CI (kg of CO₂/m³)} = 1.12 \text{ (kW h)/15.6 (m³)} \times 0.774 \text{ (kg CO₂/kW h)} = 0.06 \text{ (kg of CO₂/m³)}$

#### A.4.2. RO treatment

RO treatment values are based on Garfi et al (2016). They look at the environmental impacts caused by drinking water consumption in Barcelona using a LCA methodology. They develop multiple scenarios one of which takes into consideration domestic reverse osmosis units installed on tap water (that is usually delivered from conventional drinking water treatment plants). The study looked at the energy requirements of various domestic reverse osmosis units based on two local manufacturers. Assuming that most of the Lebanese products are usually important from European markets (MoE/UNDP/GEF 2019), we used the average of the values provided by Garfi et al (2016) of 0.5 (kW h/m³).

$\text{EI (kW h/m³)} = 0.52 \text{ (kW h/m³)}$

$\text{CI (kg of CO₂/m³)} = 0.52 \text{ (kW h/m³)} \times 0.774 \text{ (kg CO₂/kW h)} = 0.402 \text{ (kg of CO₂/m³)}$
Sensitivity analysis: Energy intensity for domestic treatment can vary from 0.26 up to 1.04 kW h/m³ (Garfi et al. 2016). So energy intensity can vary on average 43% (increase and decrease).

A.5. Internal building pumping

Assumption and values for internal pumping:

- Average hydraulic power: 1HP (0.745 kW), typical domestic pump size, (El Asmar, personal communication, February 14, 2020).
- Average hours of operation: 0.078 h/day, based on the household survey.
- Average pumped volume: 0.652 m³/day, based on the household survey.
- Average electrical consumption of household pumps: 0.058 kW h/day.

Sensitivity analysis: Based on results from domestic well pumping, we will assume that hours of operation are equal to 1.5 h/day.

Based on results from domestic well pumping, we will assume that pumped volume is equal to 15.6 m³/day.

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