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Water Consumption and Environmental Impact of Multifamily Residential Buildings: A Life Cycle Assessment Study

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Abstract: Water use in buildings accounts for a large share in global freshwater consumption where research on the impacts of life cycle water use receive little or no attention. Moreover, there is very limited knowledge regarding such impacts that focus on the life cycle emissions from water consumption in building environments in the world's most water-stressed countries. Hence, this study attempted to quantify the environmental impacts of operational water use in a multi-family residential building through a life cycle assessment (LCA). A small part of a Middle Eastern country, Doha (Qatar), has been selected for the primary assessment, while water-use impact in Miami (Florida) was chosen as a second case study, as both locations fall into similar climate zone according to ASHRAE Climate Zone Map. The LCA score indicated much higher impacts in the Doha case study compared to Miami. The variation in the result is mainly attributed to the raw water treatment stage in Doha, which involves energy-intensive thermal desalination. Again, relative comparison of the annual water and electricity use impacts for the modeled building was performed at the final stage for both locations. Water use was attributable for 18% of the environmental impacts in Miami, while this value increased to 35% in Doha. This initial assembled LCA result will be beneficial to both water authorities and building research communities in establishing more sustainable water use policies for specific regions/countries that will ultimately benefit the overall building environment.

Keywords: life cycle assessment (LCA); operational water use; environmental assessment; residential buildings; urban water cycle

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1. Introduction and Background

Buildings are considered one of the highest consumers of freshwater. At the same time, the use of water in buildings creates a wide range of environmental impacts. As freshwater availability has become a focus of attention, most of the research in this field has emphasized ways to secure a fresh water supply and reduce water consumption in buildings, while the impacts of building's water use and their relative significance have rarely received attention in either the building or water research studies [1].

1.1. Water in Residential Buildings

The requirement for water in residential buildings is increasing rapidly with the increase in the global population. Simultaneously, pressures associated with more variable rainfall and changing annual rainfall averages are applying additional water pressures in certain regions. On a global scale, domestic water use accounts for 11% of the total water consumption [2]. Domestic (or residential) water use includes water consumed for activities both inside and outside the house, such as water used in washing, cleaning, showering, kitchen tasks, outdoor landscaping, and other activities. Water used in these activities varies according to culture, region, weather, and lifestyle, while the basic water required to meet domestic needs is the same for all, irrespective of all these factors [3].

By 2050, the expected world population growth, to around 9.1 billion, will significantly impact the domestic water consumption [4]. At the same time, per capita consumption by country is highly varied, with some countries significantly greater than others, despite having less renewable water sources such as UAE and Qatar. Among, them Qatar, a small sovereign Arab state, is experiencing accelerated population growth over the last few decades, especially after its declaration as a host country for the football world cup in 2022. Population growth due to massive socioeconomic development, coupled with changes in lifestyle, has dramatically increased the domestic water requirements in Qatar. According to water statistics, household water use has increased fourfold in just fourteen years (2002–2016), and the amount of water supplied to households was recorded as 322.21 million m^3 in 2016 (Figure 1) [5]. This statistic indicates that Qatar's proportion of municipal supply to the households is 40%, which, while not accounting for industrial uses, is still high compared to many other countries.

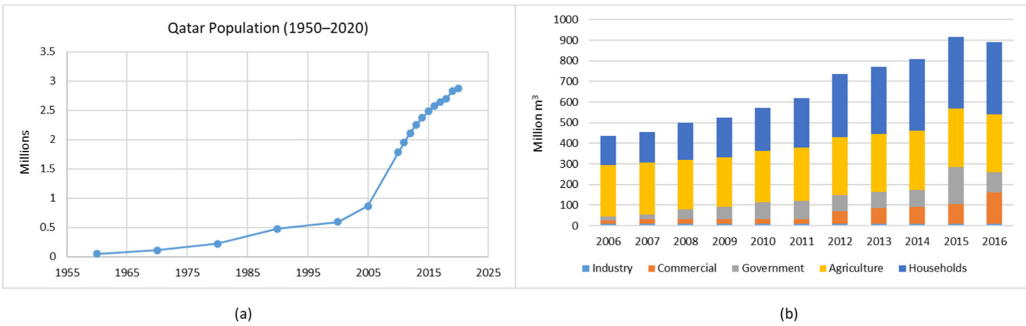


Figure 1. Increase in population (**a**) and increase in water use by economic sectors (**b**) in the State of Qatar. The major water end-use is associated with domestic use. Data excludes water loss in the network and the majority of water used in heavy industry and is compiled from various ministries overseeing utilities within Qatar [5].

1.2. Life Cycle Assessment of Residential Building's Water Use

Built environment is well known for its environmental impacts, generating around 39% of the global carbon dioxide (CO_2) emissions [6,7]. Although water and energy are considered the primary elements in any residential unit, mostly the emissions from energy use have been considered in building research to date, while water-use impacts are rarely reported. In the early 1970s, the oil embargo and environmental movement were the main reasons behind the massive increase in research on energy utilization and associated impacts in the building sector [8]. Water, however, also has significant environmental impacts which can be realized from the fact that the water sector in the United States produces nearly 5% of the country's total greenhouse gas (GHG) emissions, mainly through utilization of energy in different steps in its initial treatment, conveyance, and post-use treatment [9]. The limited studies that have considered buildings' operational water use have shown it to have significant impacts similar to or greater than that associated with water treatment and supply [1,10,11]. Hence, water scarcity and recent advancements in sustainable water use in the residential building sector have distinctly highlighted the necessity of the overall impact assessment for water use in buildings, especially for the highly water-stressed countries.

Life cycle assessment (LCA) is a systematic tool for the evaluation of environmental impacts associated with any product or process throughout its lifespan [12]. The comprehensive nature of this tool makes it suitable for use in the building sector, and hence it has been used to assess buildings since 1990 [13]. To date, research focusing on the LCA of buildings have mainly covered the impacts from construction materials, construction processes, and energy use during the construction and operational stage [14]. Numerous studies have been undertaken for separate water use stages, either focusing on water supply and distribution using different treatment technologies or water use in buildings or only treatment of wastewater [15,16]. However, the application of LCA to assess water use in buildings including all the life cycle water stages (initial water treatment and transport, water use in buildings, and finally transportation to the wastewater facility and wastewater treatment) is quite rare, which has made it a key research area to deal with [1]. The summary of the LCA studies focusing different sector of water cycle for building's are listed in Table 1. This summary of the LCA studies clearly indicates the opportunity and necessity of research that combines all the life cycle water-use stages for buildings to find the overall impact.

Table 1. List of LCA studies focused on different sector of water cycle for buildings.

Studies	Year of Publication	Study Location	Specific Focus	Main Findings
[17]	2006	Karlsruhe, Germany	Groundwater treatment	Steel-based treatment infrastructure was found responsible for significant emissions.
[18]	2016	Northern Colombia	Surface water treatments	Pumping power had the highest contribution to the global warming potential (GWP) category, and coagulation and disinfectant agents also had large impacts.
[19]	2013	Algeria	Surface water treatment	Pre-treatment chemicals were major contributors to GHG emissions.
[20]	2012	Czech Republic	Surface and groundwater treatment	Surface water plants had fourfold greater impacts on the GWP, fossil depletion, and acidification potential categories. Among the different chemicals, coagulation agents and aluminum sulfate were found to be critical for the total impact.
[21–24]	2004–2005	Spain	Treatment by desalination	Environmental impact of reverse osmosis (RO) was found to be significantly lower than that of the multi-stage flush distillation (MSF) or multi effect distillation (MED) processes as well as less emission when using renewable energies such as wind or solar.
[25]	2008	Southern Spain	Brackish groundwater and seawater	Global and local environmental impacts associated with RO could be significantly reduced by using brackish groundwater as the source rather than seawater.
[26]	2014	Perth, Western Australia	Reverse osmosis treatment	Renewable energy-based plants successfully reduced nearly 90% of GHG emissions compared to the fossil fuel-based plant. The use of electricity in conventional plants was responsible for more than 90% of the GHG emissions, while chemical use in renewable plants was identified as having a major contribution (60%).
[27]	2015	Toledo, Ohio	Water use in buildings (toilet flushing)	Rainwater harvesting was both economically and environmentally desirable compared to conventional toilet flushing.
[1]	2006	USA	Water use in buildings	Water heating consumed the most energy; thereby, in the building's water cycle, water-use within buildings had the highest impact.

Table 1. *Cont.*

Studies	Year of Publication	Study Location	Specific Focus	Main Findings
[10]	2005	USA	Water use in buildings	The LCA score for water heating utilizing natural gas resulted 30% lower than the LCA score for heating using electricity, while water-efficient appliances and fixtures were found to have 22% lower LCA scores than the conventional ones.
[28]	2003	Finland and USA	Water use in buildings	Water use had the significant impact (15% of total eutrophication) in the eutrophication category.
[29]	2017	India	Wastewater treatment	Electricity use in treatments had the highest impact out of all the nine impact assessment categories considered.
[30]	2007	Portugal	Wastewater treatment	High energy use in activated sludge treatment had the largest impact on the GWP category compared to other treatment processes such as constructed wetlands and slow-rate infiltration.

1.3. Purpose of the Study

Although several studies are being performed in water research area, however, comprehensive impact analysis of water use in buildings through LCA are rarely reported. Those that have typically are associated with buildings located in the United States, Europe, or Australia, while there are no studies concentrated in top water-stressed countries where desalination plays a key role in water supply. Moreover, no literature has compared the impact of residential water use for identical buildings in two different continents/regions. The Gulf Cooperation Council countries of the Middle East provide an interesting comparison, as extreme water scarcity result in more energy intensive water supply systems, while high GDPs and local customs both contribute to some of the highest per capita water uses globally. Qatar is one such example, with more than 99% of municipal supply dependent on desalinated water and one of the highest per capita water consumptions globally at over 500 L/p.d. Hence, the objective of this paper is to evaluate comprehensive environmental impacts of water use in residential buildings and further analyzing the differences in water-use impact for different locations, including all the water use stages with a comparison between Qatar, as a representative Middle East country, and the United States.

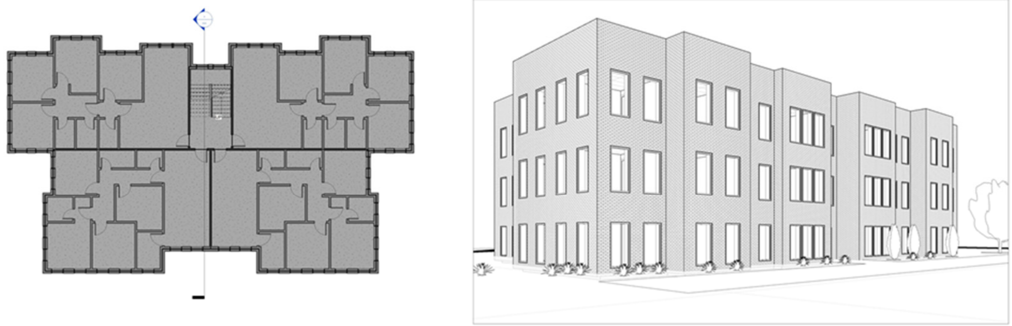
In this paper, we have examined water-use impacts for a modelled residential unit in Doha, Qatar and compared it with an identical unit located in a similar climate zone (Miami, Florida) according to the ASHRAE Climate Zone Map. The LCA results provided relative contribution of each water use stage for both locations in order to focus on the major contributing stages that demand more attention and research. As water security has a high priority in Qatar along with protection of the environment, this study will provide a baseline for the water authorities and building policymakers to develop more efficient and sustainable future region-specific residential water use strategies. Along with this, it has also the potential of providing indication for different building rating systems for further modification to protect the overall environment within the country and other Gulf Cooperation Council countries.

2. Methods and Procedures

The following sections describe the methods used in this work. Two main steps were followed: first, a residential building was modelled; second, an LCA model was developed to examine the impacts of water use in buildings (Figures S1 and S2).

2.1. The Case Study Building

Building Information Modeling (BIM) was used to model a representative case study residential building as shown in Figure 2. BIM is a promising 3D process that virtually constructs a building model including all the design and operational phase issues [31]. The case study building was then placed in two locations that share similar weather patterns based on the ASHRAE codes. A total of 8 climate zones have been defined by ANSI/ASHRAE/IESNA (Standard 90.1-2007). Although the actual water use patterns in these two selected places are different, this study has been conducted based on the baseline annual water requirement value that is the same irrespective of human nature and surrounding conditions in these two cases. Next, the Autodesk Green Building Studio (GBS) was employed to determine baseline annual energy and water requirements for each building.



(a) (b)

Figure 2. Building model using Building Information Modelling (BIM). The figure in (**a**) is the floor plan showing the detailed floor plan view of the modelled building and the figure in (**b**) represents the final 3D view of the complete building.

2.1.1. Building Characteristics

The case study building was designed as a multi-family residential building (number of residents: 30) up to the third floor. The floor area of the model building was 1189 m^2. The design of the building followed all suitable codes and regulations in both locations.

In this study, Doha, Qatar was the base location, and Miami, Florida was selected as a second case study location to analyze the differences in water-use impact for different locations. Selection of these two locations were based on international guidelines, which confirms that both locations share the same climate zone (Climate Zone 1: very hot-humid and dry) according to ASHRAE 90.1-2010 Climate Zone [32]. The structural design (number of floors, rooms, etc.) of the case study building was identical in both locations. Based on four climatic values (heating-degree days (HDD) below 18 °C, cooling-degree days (CDD) above 10 °C, monthly mean temperature, and monthly precipitation), the climate zone defined by ASHRAE dictates the appropriate energy requirement of buildings in that location. Climate Zone 1 has been defined as having very hot weather and meets the specific thermal criteria, 5000 < CDD 10 °C $\leq$ 6000 in SI units. The construction parameters for both buildings were also the same as both followed the requirements of Climate Zone 1. Although the construction materials of building vary greatly from place to place, it does not affect the energy requirement in buildings as long as the U value is the same where the U-value of a material can be defined as how effective the specific material as an insulator. Table 2 summarizes the values for each construction parameter. Additional information regarding the building details and assumptions can be found in SI, Tables S1 and S2.

Table 2. Construction details for case study building.

Characteristics	Area, m^2	Characteristics	Area, m^2
Roofs: R20 over roof deck (U value *: 0.04)	1340	Air walls: Air surface (U value: 15.32)	32
Ceilings: Interior drop ceiling tile (U value: 0.46)	0.929	Non-sliding doors: R2 default door (U value: 0.42)	223
Exterior walls: (R5.7) 8 in concrete (U value: 0.15)	845	North facing-58 windows (U value: 4.99)	97
Interior walls: Uninsulated interior wall (U value: 0.41)	1661	Non-north facing-108 windows (U value: 4.99)	181

U value *: U value unit W/(m^2 K).

2.1.2. Water and Energy Requirements

Further analysis of the building model using GBS provided the annual energy and water consumption by category for both representative buildings. Energy calculations followed the requirements of ASHRAE 90.1-2010, and water use calculations were based on the American Water Works Association (AWWA) Research Foundation 2000 Residential/Commercial and Institutional End Uses of Water report and the 2000 Uniform Plumbing Code of the International Association of Plumbing and Mechanical Officials (IAPMO), for both locations [32–34]. The water consumption of each building was the same based on the building codes, which assumes that the baseline water requirements are identical irrespective of location or human behavior. For the water calculations, residents spent 58% of the day inside the modelled building. Energy utilization was almost similar in each location except in three categories, energy use for space cooling, fans, and water heating, because of slight variations in outdoor conditions. Energy use in Doha for space cooling and fans was 25.4% and 9.18% higher than in the Miami case, while energy utilization for water heating was 11.4% higher in Miami. A Summary of the annual energy and water requirements for both locations is listed in Table 3.

Table 3. Annual energy requirements for case study building from Green Building Studio (GBS).

Category	Doha, Qatar (kWh/yr)	Miami, Florida (kWh/yr)
Fans	18,166	16,638
Misc. equipment	46,240	46,290
Space heating	706	455
Pumps & Aux.	1468	1483
Space cooling	85,323	68,034
Lights	32,294	32,287
Hot water	28,711	32,010
Total	212,908	197,196

2.2. Water Use Stages

Domestic water undergoes several transitions before reaching households for direct use, and again after use when it is discharged from the buildings. To analyze the comprehensive water-use impacts, LCA considered all the water use stages. The following sections describe the water use stages in detail along with the LCA framework used for assessment. Five water use stages were identified to analyze the complete water use scenario for residential buildings: water treatment, water transportation, water use by households, wastewater transport, and wastewater treatment. Figure 3 shows a simplified diagram of the different water use stages and specific water use stage diagram for both locations.

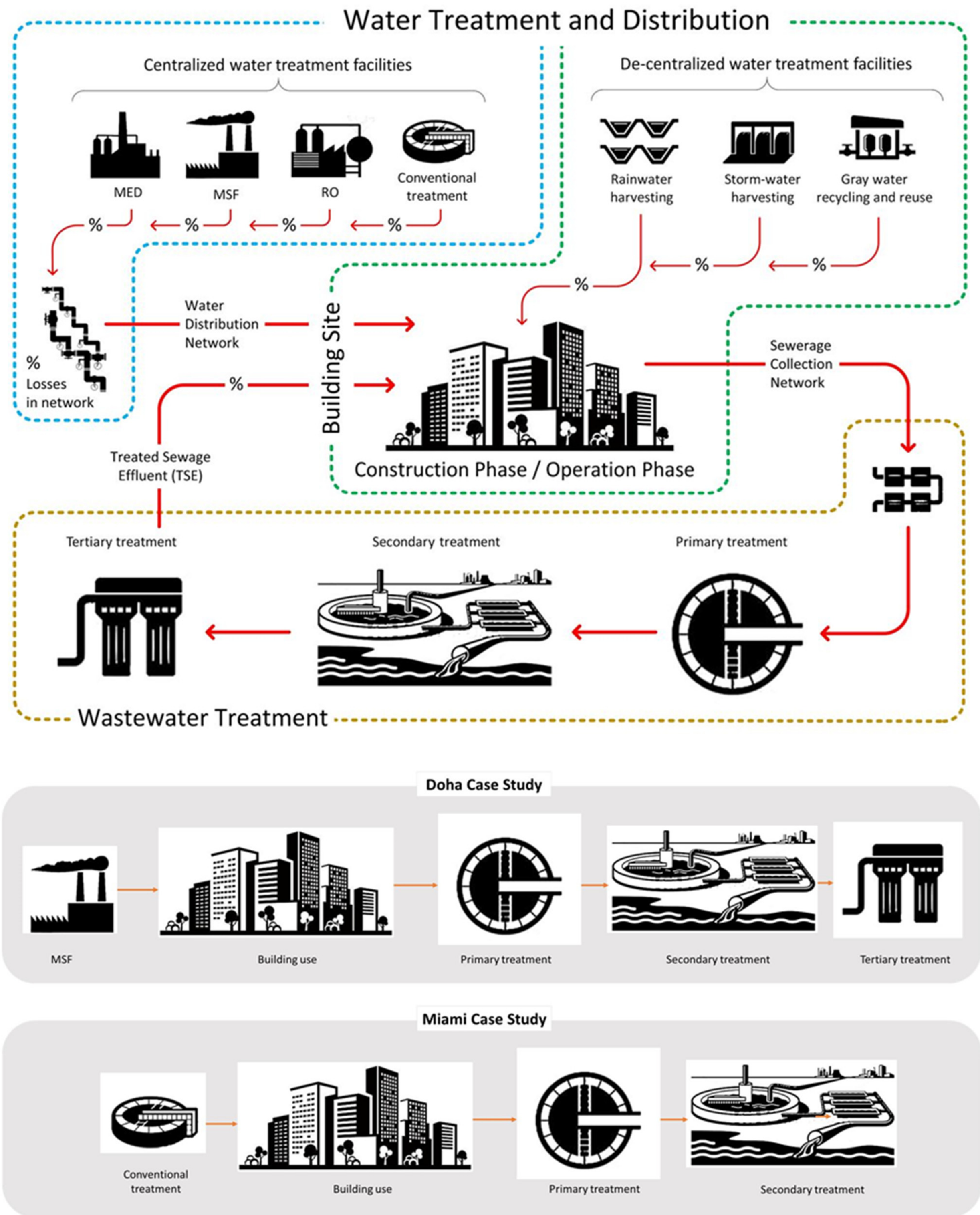


Figure 3. Simplified diagram of water use stages for residential buildings in both Doha and Miami. Top: the general water-use stages for built environments including various forms of treatment opportunities applied in different countries. Bottom: the specific water use cycle for Doha and Miami case studies showing the differences in water treatment and wastewater treatment stages.

2.2.1. Water Treatment and Distribution

Potable water demand in Qatar is met entirely through seawater desalination. Due to some site-specific conditions (e.g., high salinity seawater, overall water quality, process reliability, and lack of experience in other desalination techniques), thermal desalination has maintained popularity in this region [35]. In particular, multi-stage flash desalination (MSF) has been used in Qatar for more than 50 years, with a technology share of 75% in recent years. In the MSF process, seawater is extracted and undergoes physical and chemical pre-treatment. Usually, pre-treatment includes screening for removal of large particles and chlorination to avoid any biological growth in the stream. The seawater is then heated to around 110 °C using steam and is kept pressurized before it enters the heat recovery chamber. In this vacuum chamber, seawater flashes into steam at each successive lower pressure stage and condensation from the produced steam forms the distillate (fresh water). Anti-scaling and anti-foaming agents are used in the thermal desalination process. The step following distillate formation is post-treatment where fresh water is treated with re-mineralization chemicals (calcium hydroxide) and chlorine to ensure the potable quality and the non-corrosiveness of the produced water. Energy is the main resource in thermal desalination. For the Qatar case study, electricity is used for desalination by several pumping stations at the seawater intake, brine recirculation, brine blow-down, and distillate collection phases. The amount of energy consumed in each pumping station is based on the characteristics of the flow stream. For the assessment, a Qatar-based MSF plant was selected, and the total required electric and thermal energy were 4.05 kWh/m^3 and 127 kJ/kg, respectively [36]. Transportation water loss was accounted in this study. According to the Qatar General Electricity & Water Corporation (Kahramaa), the real loss (due to leaks, burst pipes, and overflows) was 30.5 million m^3 in 2014 (approximately 6.3%) [5]. In this study, it was assumed that all the water is coming from MSF-based desalination plants (Figure S3).

In Miami, groundwater serves as the main source of water supply for residential buildings. Though the quality of the groundwater is much higher than surface water, it still requires treatment as groundwater contains chemicals from agricultural runway and filtration. The energy required to pump groundwater to the treatment plant depends on several factors including depth of the aquifer, well and pipe friction, and distance. According to Miami governmental information, the lift distance for the Biscayne Aquifer is roughly 24 m [37]. Groundwater is treated through several techniques including aeration, sand filtration, charcoal filtration, softening, decarbonization, disinfection process, and chlorination. Chlorine was used for the disinfection process, and activated carbon was used for organics removal process. All these data were collected from GaBi database specifically designed for groundwater treatment in Florida region in the United States. Water leak detection by Miami-Dade Water and Sewer Department (MDWASD) currently reported real losses of around 9.73% [38]. Figure 4 represents the potable water treatment system in each location.

Water distribution after treatment also requires significant energy. Around 2–3% of global electricity consumption is used to move water around network systems [39]. In Doha case study, the transportation energy has been collected from personal communication and accounted to 0.449 kWh/m^3. This value has been reported as 0.274 kWh/m^3 for Miami case study [40].

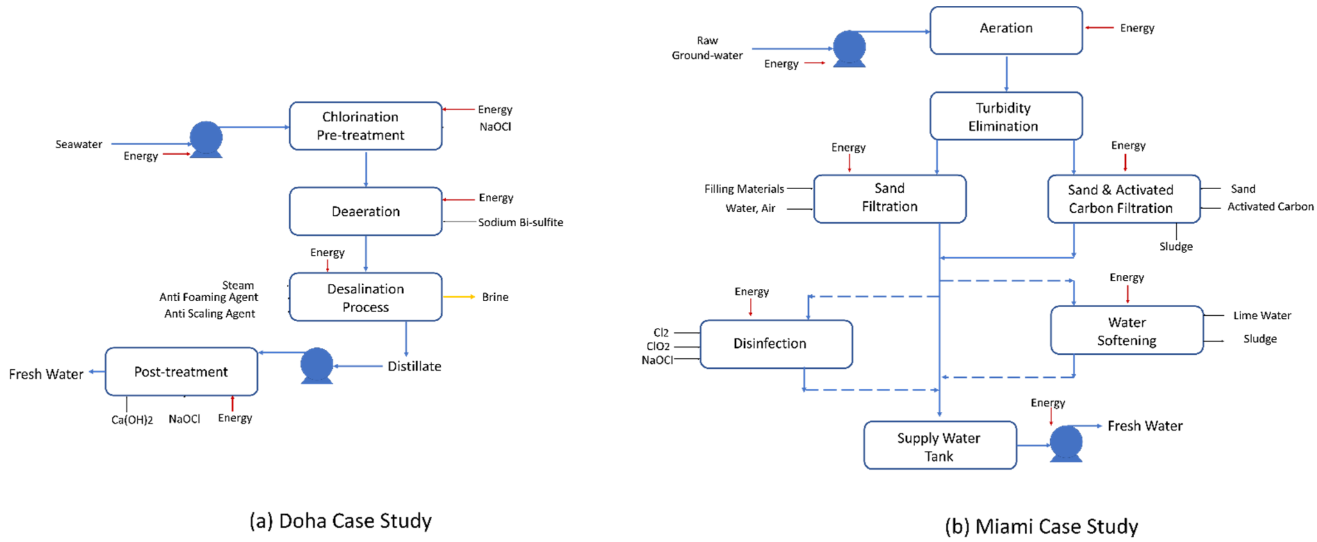


Figure 4. Simplified diagram of water treatment system in Doha (**a**) and Miami (**b**). In Doha seawater desalination is the primary source of water for residential buildings while groundwater treatment acts as the main source for Miami.

2.2.2. Water Use within Homes

Within the building, the impacts of water use are mainly from house pumps and water heating. Other forms of domestic water use that consume energy are water use in dishwashers, washing machines, cooking devices, and other appliances. However, this energy consumption is minimal compared to water pumping and heating [41]. House pumps are mainly used to transport incoming water from the network to elevated tanks located on the roofs of residential buildings. Centrifugal pumps are most the common pumps used in residential units. A study in Taiwan estimated that for a six-story residential building, 0.14 kWh of electricity is required to pump a cubic meter of water [41]. The same study investigated the energy required for water heating and found that around 5.55 kWh is required per cubic meter of water heated.

In both case study locations, Doha and Miami, electricity is the main form of energy used to heat water in residential units. Despite the warm climate, the energy required for water heating is around 14% of total indoor energy use in Florida [42]. This value validates this study result from GBS, where it was found that water heating used 16% of total energy use in the model building for the case study in Miami, while for Qatar this value was 13.5%. Further calculations using GBS data revealed that the total energy required for water use in the buildings in Doha and Miami was 9.64 and 10.70 kWh/m^3, respectively.

2.2.3. Wastewater Transport and Treatment

Traditionally, wastewater is managed through centralized facilities for wastewater collection, transportation and treatment [43]. In USA, the engineered water infrastructure consists of a wastewater collection network and wastewater treatment plant together with the raw water treatment and supply network upstream [44]. The energy requirement for wastewater transportation for Doha and Miami has been collected through personal communication and available government data and are 0.08 and 0.058 kWh/m^3, respectively [40]. In Qatar, 99.9% of buildings in Doha are connected to public sewage systems, and the majority of wastewater in Doha is treated at one of three large tertiary treatment plants with capacities ranging between 180,000 and 245,500 m^3/d [5]. These plants follow a relatively similar treatment layout with a few minor differences in the secondary treatment and whether ultraviolet disinfection is included in the process train. Doha West Wastewater Treatment Plant is the largest of these three and was used as the modelled system for the Doha case study. Wastewater flowing to the plant first undergoes primary treatment including fine screening to remove large particles and vortex de-gritting to remove sand and other dense, small suspended particles. This is followed by activated sludge secondary treatment using an A20 process for organic, nitrogen, and phosphorus removal with secondary clarifiers for solids separation. The tertiary treatment includes rapid sand filtration, ultrafiltration, and chlorination for further polishing and disinfection.

In Miami, wastewater follows a similar treatment process where it is first screened through automatic bar screens to remove all the large solid particles (rags, plastics, etc.) and passes through an aerated grit chamber to separate small dense suspended particles. Metals are removed using precipitating agents such as $FeSO_4$ and $Ca(OH)_2$. pH values are regulated by H_2SO_4 and $Ca(OH)_2$. At the secondary treatment stage, wastewater passes to an aeration basin to remove organic elements followed by a settling tank to retain the biomass in the system. The process flow diagrams for both wastewater treatment plants are described in Figure 5.

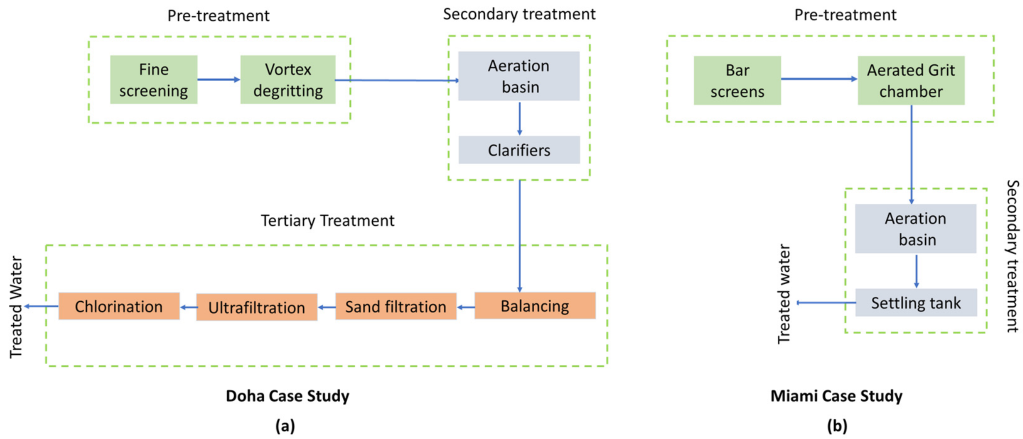


Figure 5. Wastewater treatment processes in Doha and Miami. (**a**) represents the process flow diagram of the Doha West wastewater treatment plant in Doha, while (**b**) is the representation of Miami-Dade wastewater treatment plant in Miami. In Doha, treatment is to tertiary level whereas in Miami it is to secondary level.

Both plants consume energy during the operation of each treatment step, releasing emissions to the atmosphere. According to the United States Environmental Protection Agency (EPA), energy use in wastewater treatment ranges from 0.1–0.3% of the nation's total energy use. Data for wastewater treatment in the Florida (Miami) region has been taken from the GaBi database specifically for municipal wastewater for EPA region 4. On the other hand, for the Doha case study, the energy requirement and the chemical consumption data have been collected from the Public Works Authority of Qatar (Ashghal) (Public Works Authority of Qatar). More detailed information of the energy and chemical requirements can be found in SI, Table S3.

2.3. LCA Framework

Four steps, goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and an interpretation phase, comprise the LCA model framework according to ISO 14040 [12]. This section briefly discusses the LCA framework used to assess the impacts of water use for the case study buildings.

The goal of this study was to quantify the life cycle impacts of water use in residential buildings. Hence, the functional unit was 3130 m^3 of high-quality potable water used annually per residential unit, calculated as the basic water requirement by GBS. The scope of this work is limited to operational water use. Raw water treatment, conveyance, water use within the residential unit, wastewater transport, and finally wastewater treatment stages were included in the system boundary for the assessment (Figure 6). The construction and dismantling scenarios for treatment infrastructure and the building itself were omitted from the system. The analysis for brine from the desalination plant in Doha has not been considered in this study due to the lack of enough data. The analyzed input streams were water, electricity, and chemicals (in both raw and wastewater treatment). In the analysis, water was considered in cubic meters (m^3) while the electricity unit was kilowatt-hours (kWh).

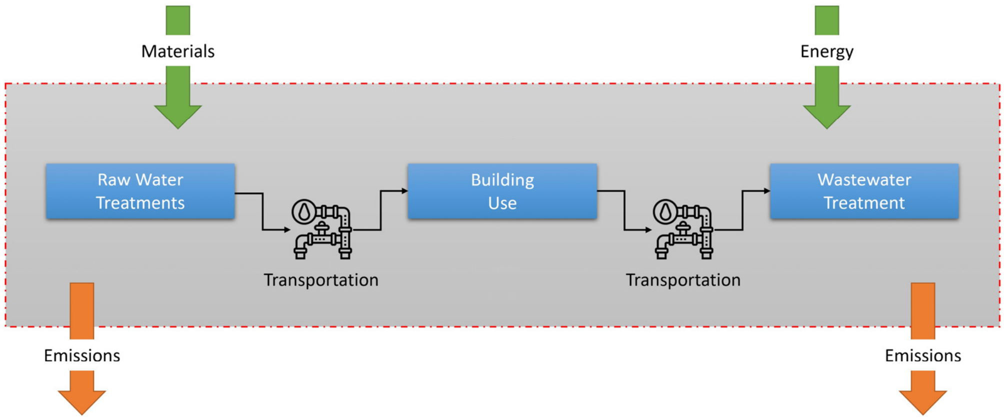


Figure 6. General system boundary for assessment of water-use.

For the second step, LCI included the inputs and outputs from each process. Resource consumption (e.g., electricity input) in each process was described earlier for both case studies. Data collection was mainly based on primary resources (real-life data) and secondary resources (published literature values and GaBi local databases). The LCA modeling for raw water treatment in Doha has been performed as the first part of this study and details can be found in the literature by mannan et al., 2019 [36]. The raw water treatment data for Miami was collected from the GaBi database (Figure S4). Household water use data were collected from GBS for the modelled residential unit. Wastewater treatment data were collected from published literature, governmental websites, and the GaBi database. The electricity grid mix data for Qatar (reference year 2013, valid until 2019) and Florida (FRCC grid mix, reference year 2012) were taken from the GaBi database (Figure S5). Electricity production in Qatar is completely dependent on natural gas (NG), while for Florida, the grid mix includes natural gas (68.06%), hard coal (19.42%), and nuclear power (8.46%) [45]. The data for grid transmission losses were sourced from GaBi for both case studies. More LCI inputs for the model are provided in the SI, Tables S4 and S5.

In the third step, LCIA aimed to evaluate the magnitude of water use environmental impacts in different impact categories. The LCA tool GaBi 6 was employed to translate the environmental loads from inventory results into environmental impact scores. Impacts were assessed with the help of the ReCiPe midpoint assessment method. Different impact categories were investigated including climate change (kg CO_2-eq), fossil depletion (kg oil eq), terrestrial acidification (kg SO_2 eq), and marine eutrophication (kg N-eq), which have been discussed further in Section 3.

3. Results

Since this study aimed to estimate the impacts of water use in residential buildings, the water-use impact for the two case study buildings was first calculated using LCA. Subsequently, a comparison of the impact from water use to electricity use was undertaken for both buildings.

3.1. Impacts of the Water Use Stages

Figure 7 represents the water-use impacts in terms of CO_2 emissions for each building. Variations in the total impact were expected for the two cases due to differences in the water use stages. Given that the two case study locations have an identical annual water requirement, it is clear that water use in the residential building in Doha has an overall larger impact than in the Miami case. The overall annual CO_2 emissions from the Miami water-use cycle is nearly 65% lower than in Doha, and the water treatment and distribution stage was the key difference between the two case study buildings. Grouping the total emission of different water use stages clarifies that the largest impact is due to the raw water treatment and distribution stage for Doha while the building use stage contributes most in Miami. As mentioned earlier, the treatment of raw water in Doha is completely dependent on MSF thermal desalination, which consumes a large amount of energy (fossil fuel) for operation. Groundwater treatment in Miami is less energy intensive in nature. The use of steam for supplying thermal energy, and electricity use for pumping in the desalination process, were the main contributors to the CO_2 emission compared to small contributions from chemical use in pre- and post-treatment.

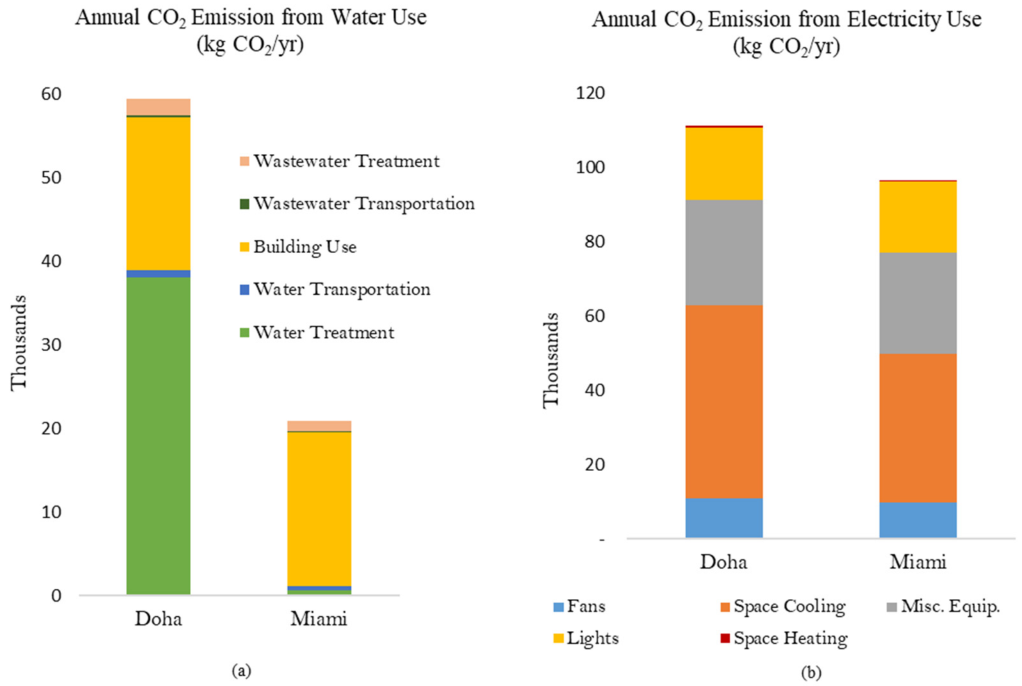


Figure 7. Annual CO_2 emission from three water-use stages and electricity use in two case study buildings. (**a**) clearly shows the main variance generated from the raw water treatment and distribution stage for Doha, where the other two stages resulted in similar emission scores. (**b**) represents the CO_2 emission potential for case study building in both locations for annual electricity use.

On the other hand, the impact of water-use within the buildings had a similar pattern in terms of CO_2 emissions: 18,249 and 18,399 kg CO_2 for Doha and Miami, respectively. The slightly higher results for Miami likely occurred because of the 11.4% higher water heating requirement compared to Doha. For the wastewater treatment stage, the CO_2 emission for Doha case study was higher due to the additional tertiary level treatment, resulting in 2044 and 1264 kg CO_2 for Doha and Miami, respectively. The CO_2 emissions for the transportation of potable water for Doha and Miami case studies were 907 and 550 kg, respectively, whereas for the wastewater treatment it was found to have a value of 170 and 99.9 kg, respectively.

According to the specifications of the electricity grid mix for Qatar and the FRCC grid mix for Florida (Miami) in the GaBi database, the annual CO_2 emissions for both locations were investigated (Figure 7). Calculation of the CO_2 release from the annual electricity (basic required) use for both cases revealed that building in Doha was responsible for slightly higher CO_2 emission due to the more space cooling requirement. The annual CO_2 emission values for electricity from Doha and Miami case study building were 111,314 and 96,585 kg, respectively.

Life-cycle impact assessments for four different impact categories showed much higher impacts for the Doha case study compared to Miami (Figure 8). As previously discussed, the water treatment stage in the Doha case study is the major contributor for the higher impacts in each impact category. Excessive thermal energy use in water treatment ultimately resulted into much higher GHG emission, affecting the global warming potential, which acts as the characterization factor for the climate change impact category. Similarly, the combustion of fossil fuels in achieving the required thermal energy and dumping the hot effluent to adjacent water body for Doha case study resulted in higher fossil fuel depletion and marine eutrophication compared to Miami case. The deposition of different inorganic chemicals, mainly the sulfates, nitrates, and phosphates, in the atmosphere changes the characteristics (acidity) of soil, which is considered harmful for specific plants and has been represented as the terrestrial acidification category; Doha case study resulted in 68.8 kg SO_2 eq. while this value was 32.1 kg SO_2 eq for Miami.

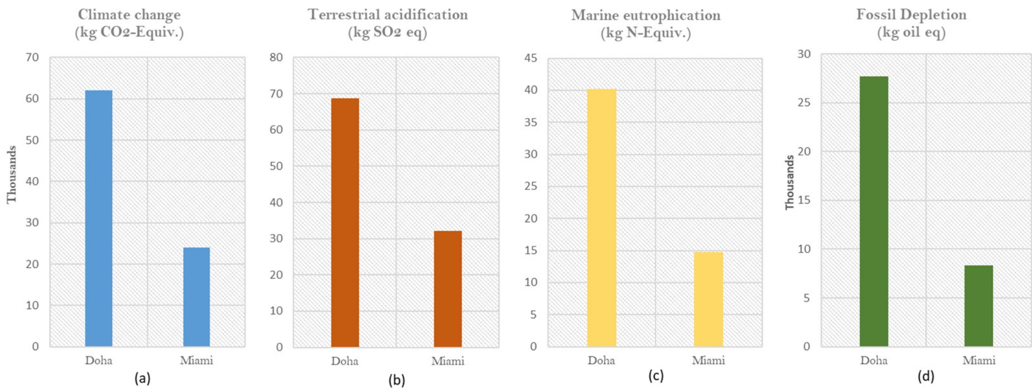


Figure 8. Impact assessment results for two case study buildings.

3.2. Relative Impacts of Water and Electricity Use

An examination of the relative impacts showed that the environmental impact of water use in Doha was 17% higher than that in Miami in terms of CO_2 emission from the case study buildings, which clearly indicates the contribution of water treatment technologies used in Doha (Figure 9). The overall annual CO_2 emission from water use in Doha case study was 59,440 kg CO_2, while this value for electricity use was found to be 111,314 kg, as depicted in Figure 7. On the other hand, for the Miami case study, the emission values were 20,931 and 96,585 kg CO_2 for water and electricity, respectively. Hence, water use was attributable for more than 50% of the electricity impact in Doha, and around one-fifth of the electricity impact in Miami. This result demonstrates the necessity of considering a water-use impact assessment for Doha and other countries, heavily dependent on energy intensive desalination, to establish more sustainable water use policies and reduce the overall environmental burden from the water-use perspective.

This relative comparison between energy and water also identifies the significance of the water-use impact assessment for building environment. Mostly the building related environmental impact studies consider the CO_2 emission and associated environmental damages from only energy that is used during the construction and operation stage. However, the huge amount of water required for daily life and associated impacts to the surroundings are often neglected and poorly understood in LCA studies. This situation results in underestimation of the overall impact of building environment as well as creates less interest to improvise the existing water policies for building sector. This evaluation had a significant outcome, as it clearly indicates the importance of conducting water use assessments in conjunction with energy assessments in buildings and the interrelationship between the two.

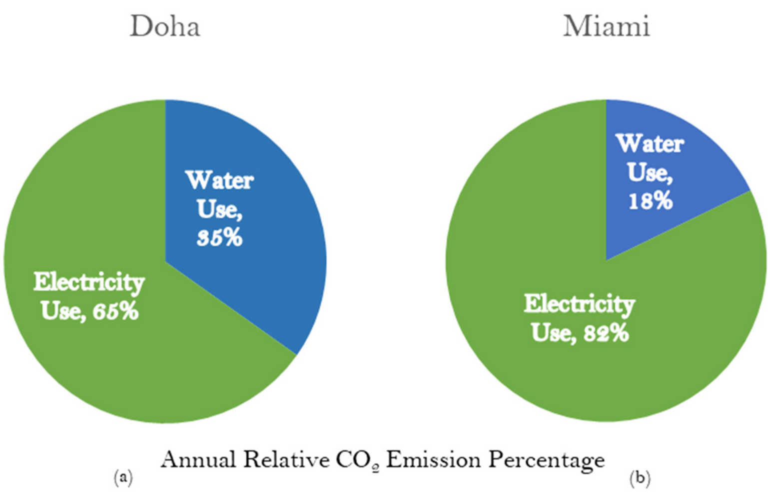


Figure 9. Relative impact assessment of water use in relation to energy use in Doha (**a**) and Miami (**b**).

4. Conclusions and Future Work

The analysis of the two case studies clearly indicates the difference in water-use impact in changing the building location, although having the same weather condition. Variations in water treatment system played the key role in the overall impact for these two case studies, further indicating the necessity and importance of water-use impact studies for those areas depending entirely on energy intensive water treatment processes. This comprehensive analysis creates the baseline, based on the quantitative scores, to settle more specific water policies and guidelines for buildings. The application of sustainable water-use strategies such as the installation of water saving fixtures in Middle East residential buildings will improve overall environmental conditions even more effectively than in North American contexts due to the significant reductions in burdens associated with water purification. Since the Doha case showed a significantly greater impact from water use than the Miami case, this result also indicates the need for establishing region-specific building rating standards (e.g., green building rating system such as LEED) in terms of water use and conservation [46]. As LEED and other globally used building rating systems have been established without or with little consideration for energy intensive treatments such as MSF desalination, the water conservation rules of these rating systems in countries similar to Qatar should be revised based on the overall situation of the country/region. Moreover, the results highlight the value in existing national research strategies at improving desalination efficiency, which will have a carry-on effect on significantly reducing building water-use impacts.

For a complete water-use impact assessment for buildings in future studies, embodied water should be included along with operational water. Embodied water use can be significant compared to the life cycle operational water use [11]. Therefore, the impact assessment for water use will provide a more comprehensive result if both construction and the operational phase is considered. Furthermore, we limited the study to residential units. However, there are several other building types that require complete impact assessments for water use. Therefore, this study can open the door to several other research opportunities, including embodied water, different types of buildings, and more locations, to assess the total impact of water use over a building's life cycle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings12010048/s1, Supporting Information: full modeling, calculations, and original data related to this article can be found in the supplementary data file attached.

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References

1. Arpke, A.; Hutzler, N. Domestic Water Use in the United States: A Life-Cycle Approach. *J. Ind. Ecol.* **2008**, *10*, 169–184. [CrossRef]
2. FAO-Aquastat, Water Uses, Colombia. 2010. Available online: http://www.fao.org/nr/water/aquastat/data/query/results.html?regionQuery=false&showCodes=true&yearRange.fromYear=1960&yearRange.toYear=2015&varGrpIds=4250,4251,4252,4253,4254,4255,4256,4257,4260,4261,4262,4263,4264,4265,4269,4270,4275,4451,4475,4490,4491 (accessed on 19 January 2021).
3. Glieck, P.H. Basic Water Requirements for Human Activities: Meeting Basic Needs. *Water Int.* **1996**, *21*, 83–92. Available online: http://www.pacinst.org/reports/basic_water_needs/basic_water_needs.pdf (accessed on 5 March 2021). [CrossRef]
4. United Nations World Water Assessment Programme. Facts and Figures; from the United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk. 2012. Available online: http://www.petrobras.com.br/fatos-e-dados (accessed on 12 January 2021).
5. Ministry of Development Planning and Statistics. Water Statistics in the State of Qatar. 2017. Available online: https://www.psa.gov.qa/en/statistics/StatisticalReleases/Environmental/Water/2017/Water-Statistics-2017-EN.pdf (accessed on 3 April 2021).
6. Ali, K.A.; Ahmad, M.; Yusup, Y. Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector. *Sustainability* **2020**, *12*, 7427. [CrossRef]
7. WorldGBC, New Report: The Building and Construction Sector Can Reach Net Zero Carbon Emissions by 2050. 2019. Available online: https://www.worldgbc.org/news-media/WorldGBC-embodied-carbon-report-published (accessed on 13 March 2021).
8. Cassidy, R. White Paper on Sustainability. Building Design & Construction. 2003. Available online: http://www.usgbc.org/Docs/Resources/BDCWhitePaperR2.pdf%5Cn (accessed on 12 January 2021).
9. Griffiths-Sattenspiel, B.; Wilson, W. The Carbon Footprint of Water. 2009. Available online: http://eec.ucdavis.edu/events/documents/water-energy_rivernetwork_carbon-footprint-of-water.pdf (accessed on 20 December 2020).
10. Arpke, A.; Hutzler, N. Operational Life-Cycle Assessment and Life-Cycle Cost Analysis for Water Use in Multioccupant Buildings. *J. Arch. Eng.* **2005**, *11*, 99–109. [CrossRef]
11. Stephan, A.; Crawford, R.H. A comprehensive life cycle water analysis framework for residential buildings. *Build. Res. Inf.* **2014**, *42*, 685–695. [CrossRef]
12. ISO. ISO 14040:2006 Environmental Management—Life Cycle Assessment—Principles and Framework. 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 29 July 2021).
13. Fava, J.A. Will the Next 10 Years be as Productive in Advancing Life Cycle Approaches as the Last 15 Years? *Int. J. Life Cycle Assess.* **2006**, *11*, 6–8. [CrossRef]
14. Bribian, I.Z.; Usón, A.A.; Scarpellini, S. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Build. Environ.* **2009**, *44*, 2510–2520. [CrossRef]
15. Lundie, S.; Peters, G.M.; Beavis, P.C. Life Cycle Assessment for Sustainable Metropolitan Water Systems Planning. *Environ. Sci. Technol.* **2004**, *38*, 3465–3473. [CrossRef]
16. Mannan, M.; Al-Ghamdi, S.G. Environmental impact of water-use in buildings: Latest developments from a life-cycle assessment perspective. *J. Environ. Manag.* **2020**, *261*, 110198. [CrossRef]
17. Bayer, P.; Finkel, M. Life cycle assessment of active and passive groundwater remediation technologies. *J. Contam. Hydrol.* **2006**, *83*, 171–199. [CrossRef]
18. Ortíz-Rodriguez, O.O.; Gallardo, R.A.V.; García-C, R. Life cycle assessment of four potable water treatment plants in northeastern Colombia. *Ambient. Agua-Interdiscip. J. Appl. Sci.* **2016**, *11*, 268. [CrossRef]
19. Mohamed-Zine, M.-B.; Hamouche, A.; Krim, L. The study of potable water treatment process in Algeria (boudouaou station) -by the application of life cycle assessment (LCA). *J. Environ. Health Sci. Eng.* **2013**, *11*, 37. [CrossRef]
20. Cabejskova, Z. Life Cycle Assessment of Water Treatment Technology. 2012. Available online: https://is.cuni.cz/webapps/zzp/detail/106279/ (accessed on 13 February 2021).
21. Raluy, R.; Serra, L.; Uche, J.; Valero, A. Life-cycle assessment of desalination technologies integrated with energy production systems. *Desalination* **2004**, *167*, 445–458. [CrossRef]

22. Raluy, G.; Serra, L.; Uche, J. Life Cycle Assessment of Water Production Technologies—Part 1: Life Cycle Assessment of Different Commercial Desalination Technologies (MSF, MED, RO). *Int. J. Life Cycle Assess.* **2005**, *10*, 285–293. [CrossRef]
23. Raluy, G.; Serra, L.; Uche, J.; Valero, A. Life Cycle Assessment of Water Production Technologies—Part 2: Reverse Osmosis Desalination versus the Ebro River Water Transfer. *Int. J. Life Cycle Assess.* **2005**, *10*, 346–354. [CrossRef]
24. Raluy, G.; Serra, L.; Uche, J. Life cycle assessment of desalination technologies integrated with renewable energies. *Desalination* **2005**, *183*, 81–93. [CrossRef]
25. Muñoz, I.; Fernández-Alba, A.R. Reducing the environmental impacts of reverse osmosis desalination by using brackish groundwater resources. *Water Res.* **2008**, *42*, 801–811. [CrossRef]
26. Shahabi, M.P.; McHugh, A.; Anda, M.; Ho, G. Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy. *Renew. Energy* **2013**, *67*, 53–58. [CrossRef]
27. Devkota, J.; Schlachter, H.; Apul, D. Life cycle based evaluation of harvested rainwater use in toilets and for irrigation. *J. Clean. Prod.* **2015**, *95*, 311–321. [CrossRef]
28. Junnila, S.; Horvath, A. Life-Cycle Environmental Effects of an Office Building. *J. Infrastruct. Syst.* **2003**, *9*, 157–166. [CrossRef]
29. Raghuvanshi, S.; Bhakar, V.; Sowmya, C.; Sangwan, K.S. Waste Water Treatment Plant Life Cycle Assessment: Treatment Process to Reuse of Water. *Procedia CIRP* **2017**, *61*, 761–766. [CrossRef]
30. Machado, A.P.; Urbano, L.; Brito, A.G.; Janknecht, P.; Salas, J.J.; Nogueira, R. Life cycle assessment of wastewater treatment options for small and decentralized communities. *Water Sci. Technol.* **2007**, *56*, 15–22. [CrossRef] [PubMed]
31. Al-Ghamdi, S.G.; Bilec, M.M. Green Building Rating Systems and Whole-Building Life Cycle Assessment: Comparative Study of the Existing Assessment Tools. *J. Arch. Eng.* **2017**, *23*, 04016015. [CrossRef]
32. ANSI/ASHRAE/IES Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings. 2019. Available online: https://www.techstreet.com/ashrae/standards/ashrae-90-1-2019-i-p?gateway_code=ashrae&product_id=2088527 (accessed on 3 April 2021).
33. Mayer, P.W.; DeOreo, W.B. *Residential End Uses of Water, Version 2*; Water Research Foundation: Denver, CO, USA, 2016.
34. Dziegielewski, B.; Kiefer, J.C.; Lantz, G.L.; Opitz, E.M.; Porter, G.A.; Mayer, P.; Dziegielewski, B.; Kiefer, J.C.; Lantz, G.L.; Opitz, E.M.; et al. *Commercial and Institutional End Uses of Water, Power*; American Water Works Association: Denver, CO, USA, 2000.
35. Mannan, M.; Al-Ghamdi, S. Life-Cycle Assessment of Thermal Desalination: Environmental Perspective on a Vital Option for Some Countries. In *World Environmental and Water Resources Congress 2019: Groundwater, Sustainability, Hydro-Climate/Climate Change, and Environmental Engineering*; American Society of Civil Engineers: Reston, VA, USA, 2019. [CrossRef]
36. Mannan, M.; Alhaj, M.; Mabrouk, A.N.; Al-Ghamdi, S.G. Examining the life-cycle environmental impacts of desalination: A case study in the State of Qatar. *Desalination* **2018**, *452*, 238–246. [CrossRef]
37. Miami-Dade County, Water Supply and Treatment. 2021. Available online: https://www.miamidade.gov/global/water/water-supply-and-treatment.page (accessed on 14 February 2021).
38. Miami-Dade Water and Sewer Department, Water Use Efficiency: Five Year Plan. 2006. Available online: https://www.miamidade.gov/waterconservation/library/reports/five-year-water-use-efficiency-plan.pdf (accessed on 9 June 2021).
39. Sarbu, I. A Study of Energy Optimisation of Urban Water Distribution Systems Using Potential Elements. *Water* **2016**, *8*, 593. [CrossRef]
40. Electric Power Research Institute. *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries*; Electric Power Research Institute: Washington, DC, USA, 2013.
41. Cheng, C.-L. Study of the inter-relationship between water use and energy conservation for a building. *Energy Build.* **2002**, *34*, 261–266. [CrossRef]
42. U.S. Energy Information Administration (EIA). Household Energy Use in Texas—A Closer Look at Residential Energy Consumption. 2009. Available online: www.eia.gov/consumption/residential/ (accessed on 5 May 2021).
43. Hendrickson, T.P.; Nguyen, M.T.; Sukardi, M.; Miot, A.; Horvath, A.; Nelson, K.L. Life-Cycle Energy Use and Greenhouse Gas Emissions of a Building-Scale Wastewater Treatment and Nonpotable Reuse System. *Environ. Sci. Technol.* **2015**, *49*, 10303–10311. [CrossRef]
44. Hasik, V.; Anderson, N.E.; Collinge, W.O.; Thiel, C.; Khanna, V.; Wirick, J.; Piacentini, R.; Landis, A.E.; Bilec, M.M. Evaluating the Life Cycle Environmental Benefits and Trade-Offs of Water Reuse Systems for Net-Zero Buildings. *Environ. Sci. Technol.* **2017**, *51*, 1110–1119. [CrossRef]
45. GaBi [Computer Software], Sphera, Echterdingen, Germany, N.D. Available online: http://www.gabi-software.com/international/index/ (accessed on 14 April 2021).
46. Al-Ghamdi, S.G.; Bilec, M.M. Life-Cycle Thinking and the LEED Rating System: Global Perspective on Building Energy Use and Environmental Impacts. *Environ. Sci. Technol.* **2015**, *49*, 4048–4056. [CrossRef]