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Research article

Managing the kinetic energy of descending greywater in tall buildings and converting them into a valuable source

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ABSTRACT

Harnessing energy from descending greywater (GW) in tall buildings (TBs) is an innovative concept that combines water management with renewable energy generation and applying simulation methods. This study proposes a novel approach to enhancing sustainable energy recovery in TBs by capitalizing on the kinetic energy inherent in descending GW. Greywater, derived from non-toilet fixtures such as showers, bathroom sinks, and washing machines, offers a readily accessible source of potential energy due to its gravity-driven flow through the plumbing system. This gravitational potential energy could feasibly be converted into useable electricity through the incorporation of specialized energy-recovery mechanisms, such as turbines, hydroelectric generators, and piezoelectric devices. The study addresses the technical, economic and environmental aspects of implementing this idea in TBs. It describes the challenges of system integration, maintenance requirements and adherence to regulatory standards, as well as the potential benefits in terms of water conservation and reduced reliance on conventional energy sources, through a comprehensive analysis encompassing modeling, experimental validation and feasibility assessments. The research offers insights into the potential viability of harnessing downward-flowing GW as an alternative and sustainable green energy resource.

1. Introduction

1.1. Response to water scarcity: greywater (GW) reuse

The scarcity of high-quality water is one of the biggest global challenges, to arid areas in particular. The issue of water availability is also gradually encroaching on megacities worldwide, due in large part to massive resident migration [1–4]. Water shortages are indirectly reflected by the many seawater-desalination plants that are emerging along the world's coasts [5]. A promising solution for impending water shortages is to use treated domestic and industrial wastewater, primarily for agricultural irrigation, thereby releasing larger quotas of high-quality water for public demand, mainly drinking purposes. However, the continuous expansion of urban areas

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and the rapid increase in megacities have created problems of waste transportation, wastewater treatment and disposal [6].

Along with this, the public has begun to realize that shortages of energy resources and supply are constituting a real problem. It is anticipated that over the next decade, the size of the urban community in the developing world will grow by a few billion residents [7,8]. This presents and highlights a complex set of challenges involving water shortages, dwindling demand for energy supply and urbanization processes. The vast expansion of megacities is associated with larger distances for influent transportation to treatment facilities and effluent transport to areas for its reuse. These changes in urban demographics, along with climate change, are anticipated to affect the global hydrological cycle. Innovative solutions and a multifaced approach are required to address these issues. The concurrent rise in energy prices is sending a warning alarm to the global community.

Climate changes have the potential to significantly impact rainfall pattern and storm events, leading to both increased precipitation in some areas (resulting in floods) and decreased precipitation in others (enhancing droughts events) [9,10]. In some cases, the combination of climate changes and community growth trends presents basic challenges in providing water to all urban consumers while considering the most sustainable principles. Water, which is essential for human life, is a deficient commodity worldwide. Greywater reuse can be an effective strategy for water conservation, reducing the strain on freshwater resources, while also potentially offering other benefits such as energy generation [11–13] (Fig. 1). However, careful planning, treatment and adherence to regulations are essential to ensuring the safety and effectiveness of these reuse systems.

The waste and disposal of wastewater from every household consists of three major contaminating components: (i) solid (black) wastewater that contains human feces, fractions of urine compounds and other organic components [14–16]. Black wastewater streams include primarily toilet wastes; (ii) medium-quality GW which emerges mainly from the kitchen sink (various food residues) and the dishwasher (remnant food); and (iii) grey-wasted water, which includes waste from the bathroom tub, shower and sink, and washing machines [17]. Local regulations in Australia determine that GW includes all non-toilet wastewater (referred to as sullage) [18]. It is important to note, however, that the definition of GW can differ from one region to the next, so it is essential to refer to the specific guidelines provided by the relevant authorities in each area (Fig. 1).

Black wastewater discharge usually constitutes 40 %–60 % of a family's total water supply [19,20]. According to assorted studies, the amount of GW is in the range of 30 %–40 % of total low-quality waste]of from every household, independent of the inflow amount [21]. The flow rate of GW depends, to a substantial extent, on the individuals living in the apartment. Subject to the above assumption of flow rates, it can be assumed (according to Israeli conditions) that water is supplied in the range of 140–200 L per capita per day, where these numbers have been used for simulation procedures [22].

It can be further assumed that GW contains around 10 % nitrogen (ammonia, nitrite and nitrate) and low amounts of organic matter. Black wastewater (toilet) contains a much higher concentration of pollutants. The low content of pollutants in GW enables its consideration for energy generation and irrigation. A brief settling period, filtering and successive disinfection might be satisfactory for treatment and energy generation in the context of tall buildings (TBs) [15,23–26]. Further reuse of the GW for irrigation of agricultural crops or ornamental plants is always an option however, this use is not considered in this work [27–29].

Nevertheless, briefly, GW for irrigation is applicable mainly through subsurface drip irrigation, which depends on several factors, including the quality of the GW, the soil type and the plants being irrigated. Reuse of GW for irrigation is subject to local regulations, requires no human contact and no need for extra disinfection. Before implementing such a system, it is essential to assess the quality of the GW and to guarantee that the system is well-designed and installed adequately, complying with the relevant guidelines and thus preventing potential health and environmental risks. A pilot project for GW reuse was developed for a rural Alaskan village on an American native reservation [30]. High-quality GW was accepted for diverse purposes, taking into account mainly health aspects. Greywater can also be applied for the irrigation of golf courses, public parks and lawns, and for groundwater recharge [31]. Despite the higher health risk, GW can also be used for toilet flushing. A preliminary permit was given in Israel to reuse residual shower water in public sport centers [32,33]. The matter of residual detergents content in GW is of minor importance due to their rapid biodegradation [34]. The remarkable development in GW use raises the dilemma of application in the private ***vs.*** the public sector.

The guidelines for GW in Australia offer a refund of 500 Australian dollars for the installation of reuse systems [18,35]. The

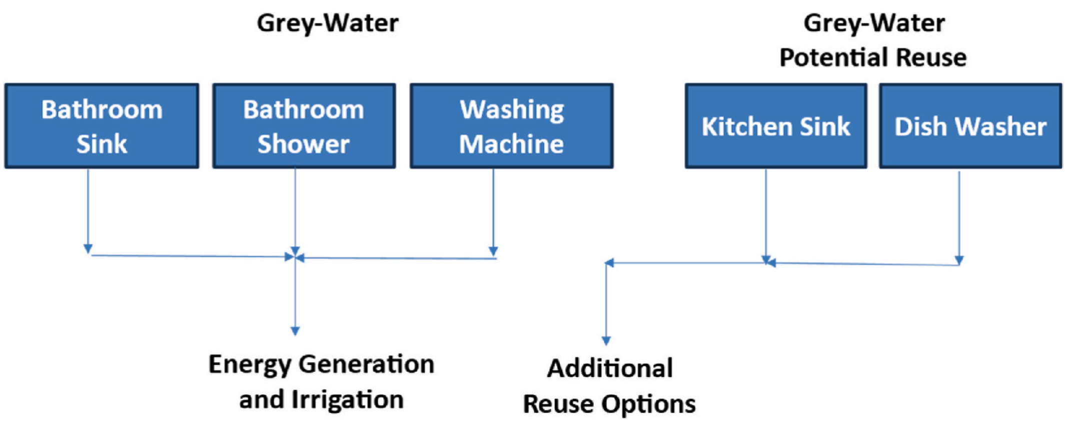

Fig. 1. Options for a greywater collection and reuse system for energy recovery.

situation is slightly different in the USA: the federal government has not yet issued clear guidelines for GW use. However, there are several states (most of them located in dry regions that suffer from water shortages) that offer financial support and encourage the residents to install GW-reuse systems in their living areas. Several other countries, such as South Korea, China, Cyprus, Israel and Spain, have established programs for installing GW-reuse systems [36–38]. Several municipalities, including Sant Cugat del Vallès near Barcelona (Spain] and others in Catalonia, have passed regulations to promote GW reclamation in multistory buildings [39]. In Tokyo (Japan), installing GW-reuse systems is mandatory for building complexes with a building floor surface area larger 30,000 m^2, or with a potential flow rate of over 100 m^3/d. European Council Directive 91/271/EEC dictates that “treated wastewater shall be reused whenever appropriate.” However, the methods for realizing this goal remain unclear to the consumers [40,41].

1.2. Tall buildings

Tall buildings are considered a solution to the limited space in densely populated urban areas, especially those experiencing migration from peripheral regions. However, while they can help in alleviating space scarcity, several challenges are emerging with their increased presence [2,42]. Tall buildings can contribute to more traffic congestion in the vicinity due to a higher number of residents and businesses presenting in a limited space. This can strain the transportation infrastructure and lead to longer commute times. Water supply to the highest floors of TBs can be challenging, because of high water pressure is required. Disposing of wastewater from these buildings calls for more complex and efficient plumbing systems. Managing the solid waste generated by a substantial number of occupants necessitates efficient waste-disposal systems, including a sophisticated collection system, recycling and disposal strategies. From a societal point of view, providing adequate playgrounds for children and recreational spaces within or around TBs has also become a challenge. Living in a TB can sometimes lead to a sense of social isolation due to the limited interaction among residents in comparison to traditional low-rise communities. More green areas will ensure a higher quality of life for the residents, especially in cases where the surrounding areas lack open spaces. Lack of green spaces around TBs can adversely impact the overall aesthetics of the urban environment. Energy demand in TBs can be substantial for lighting, heating, cooling and elevator operation. Implementing energy-efficient technologies and sustainable design practices has become essential to minimizing adverse environmental effects.

Urban planners, architects, engineers and policymakers need to collaborate to develop comprehensive solutions. These might include efficient transportation networks, innovative water-supply and waste-management (reuse) systems, thoughtful architectural designs that prioritize community spaces, sustainable energy solutions, and integration of green areas into urban landscapes [43]. It is important to balance the benefits of space optimization with the well-being and convenience of residents in an urban environment.

A TB is roughly defined as a construction with over 10 floors (higher than 35 m). There are around 6500 buildings that are higher than 40 m in New York City, around 1300 in Chicago, and around 1400 in Shanghai [44] (Fig. 2). Buildings of that height can produce water heads of around 5 atm–20 atm, which can easily be used for energy production. A potential solution for energy generation in TBs is to install hydropower generators. The vision is to collect the GW separately from each apartment and allow its downward flow to operate turbines for energy generation. The hygienic quality of GW enables its safe allocation for energy generation with almost no risk to human health.

1.3. Energy in buildings

Passive energy in buildings, namely conservation means, stays for another tool of energy control in building. Using building preserving materials for building construction that covers energy leakage should be friendly to the dwellers. Mainly the bio-based materials have the potential to diminish over 3.2×10^5 metric tons of carbon dioxide emissions by the year 2050. The biomaterials and others similar effective constituents can decrease water absorption in building by at least 40 %, thus reducing energy consumption by close to 10 % [45]. Carbon di-oxide plays a key role as well in the energy status in building. It was mentioned that the building

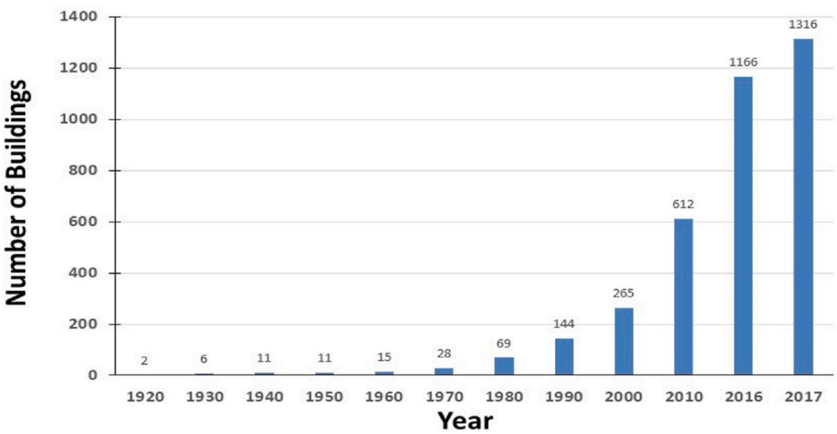

Fig. 2. Number of tall buildings higher than 200 m worldwide (updated to 2017).

industry is responsible for close to 35 % of worldwide energy consumption and around 40 % of CO_2 emission during the year 2020 [46]. A valuable tool for assessing the reaction and performance of the environment is the life cycle assessment (LCA). The LCA approach allows to quantify the sustainability of the environment [47]. The LCA models the implications of the many interacting systems that consider various products that provide valuable data information for the decision-making level [46].

The expanded consumption of construction materials is recognized as one of the major sources of global warming. Energy storage in general and primarily in buildings is of utmost priority. Nano technology is a promising tool and has an enormous potential for extensive applications, allowing encapsulation of materials in micro/nano-scale. A micro/nano-capsule comprises of a material core with a special purpose and a shell for the substance protection from miscibility, evaporation, reaction, or stress and frequently release in the controllable thermal energy region. Polyurea for example showed adequate thermal properties [48].

With the rapid expansion of the industry, a large amount of CO_2 are generated every year. Global carbon emission is around 35.5 billion tons during 2019 of which China's released approximately 10.7 billion tons which accounts for about 30.1 % of global emission. It caused to an environmental temperature increase of around 2^oC. It is assessed that average temperature will be 1.0 °C above pre-industrial levels and continues to upsurge by 0.2 °C per decade [49].

1.4. Turbines – energy-generating machines

The idea is to install a special-purpose turbine in the TB to generate electricity from the kinetic energy of the descending GW. Low-head turbines can be classified into diverse types according to flow; they include cross-flow, Francis, Kaplan, Turbo and Pelton turbines [50–54]. Generating electricity from the kinetic energy of descending water in a TB can be an efficient way to harness renewable energy and reduce electricity costs. The potential head has to be adjusted to the vertical distance between the water source (location of the GW-collection tank) and the placing of the installed turbine [54]. Different turbines are designed to work optimally at different pressure head levels. Low-head turbines are appropriate for operation with a minimal vertical drop, whereas high-head turbines are designed for locations with a significantly high vertical drop. Consequently, when designing an hydroelectric power system, engineers and project managers must carefully consider the potential hydraulic head, choose the right turbine type, and address efficiency issues to ensure the system's overall effectiveness and reliability (Fig. 3).

Energy production is given by the generic expression [55,56]:

$$P_a = \eta \text{ x } g \text{ x } \rho \text{ x } q \text{ x } \Delta H \quad (1)$$

where.

P_a - energy production from descending water, kWh.

η - overall efficiency of turbines performance (assumed around 70 % and taken as a fraction).

g - gravity term, 9.81 m/s^2.

ρ - specific weight of water, 1000 kg/m^3.

q - discharge of water, m^3/sec.

ΔH - water pressure head, m (Fig. 4).

1.5. Containers for GW temporary storage

It was assumed that in order to maintain continuous energy generation several storage containers have to be installed as part of the systems. Up to five containers are constructed in the building (part of the simulation procedure). Every container volume is varying in the range of 2–12 m^3. Retention time of the incoming GW should not exceed 24 h due to pathogens development. However, the minimal retention time should be around 4 h, guaranteeing adequate settling. The flexibility in number and volume of containers is

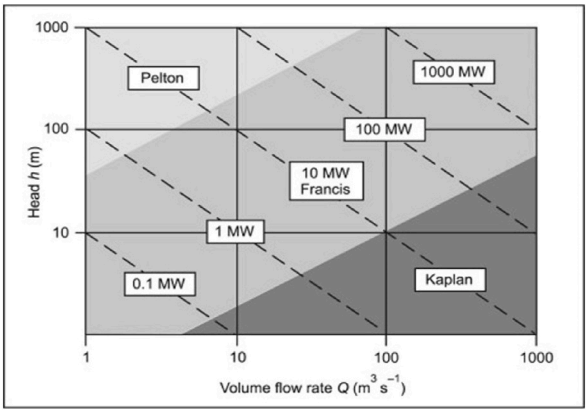

Fig. 3. Energy generation with installed turbines depending on pressure head and water discharge.

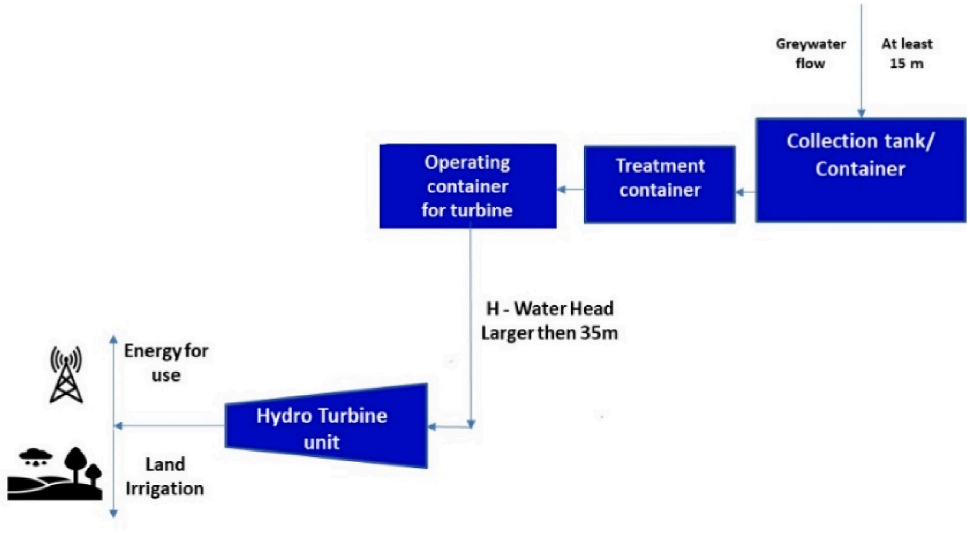

Fig. 4. Schematic description of the general dual greywater-collection system.

well demonstrated in the resalts (see Figs. 7 and 8).

1.6. *Scientific merits of using GW for energy generation*

Reuse of GW offers social, environmental and technological advantages. Successful implementation of GW utilization requires proper design, maintenance and consideration of local regulations and health guidelines to ensure the safety of both humans and the environment. In addition, not all GW is suitable for reuse for all applications; therefore, system design and treatment methods should be tailored to specific needs.

1) Environmental benefits of GW reuse include diminished demand for freshwater sources, preservation of natural ecosystems and reduced strain on local tap-water supplies. This aspect is particularly important in regions facing water scarcity or drought conditions.
2) Water conservation through GW reuse contributes to the overall sustainability of community life and regional quality, making it a valuable resource for future generations.
3) Diverting GW from the conventional sewage system for reuse diminishes the burden on wastewater-treatment plants. This can lead to energy savings and reduce the environmental impact associated with treating sewage.
4) When properly treated and applied, GW can enhance soil fertility and promote healthier green plant growth. It allows farmers and gardeners to reduce their reliance on freshwater sources and promotes advanced sustainable farming practices. Greywater can add nutrients and organic matter to the soil, which is especially beneficial in arid regions.
5) Grey-water reuse systems can reduce the need to expand the water-supply and sewage-disposal infrastructures, saving both money and resources.
6) For individual homeowners or businesses, reusing GW can lead to significant savings on water bills and less use of potable water for non-potable purposes such as toilet flushing and irrigation.

1.7. *Risks associated with greywater utilization*

Grey-water can contain minor amounts of nutrients that are beneficial for green plants growth. However, it can also include minimal amounts of pathogenic microorganisms, bacteria, protozoa, viruses and parasites. The health risks posed by these are generally negligible. Household detergents and soaps are also found in GW however, are rapidly biodegraded. Some pharmaceutical and health care constituents residues might make their way into GW, although these are typically present in minor quantities. The low content of chemicals ensures proper water flow in the soil [57]. Proper treatment and management of GW is thus essential to ensuring its safe reuse, while minimizing potential environmental and health risks. Management modeling allows to assess optimal resources allocation to the periphery [58]. The model takes into accounts regions of surplus and deficits of energy, including preservation aspects. It also considers the energy deficit queue requirements for energy consumption and provides optimal tools for solving the problem in a real-time manner.

The socio-economic aspects of GW use are vital in the reuse procedures. These aspects refer primarily to the habits of each family-water-consumption customs and related behaviors. The regulations also refer to the efficient use practices enforced by each family in the building and an awareness of environmental issues [59,60]. A management model was developed for hot water use in buildings [61]. The WaterHub model was utilized to assess potential technologies for heating water. Hot water use is associated with extensive energy use in buildings. The developed model demonstrated the importance of warm water consumption and related energy use. Risk analysis should be based on applying holistic approaches which observe most related aspects and should use robust approximations [62,63].

1.8. Greywater reuse for energy generation

According to common forecasts, by the year 2050, close to three billion additional residents are anticipated to migrate and to reside in urban areas. These demographic changes are subject to the mutual effects of hydrological conditions and availability of land for the construction of new living facilities. Due to shortage of land, the general tendency is to construct high-rise buildings in cities. The building's height can allow treating the GW as an alternative energy source [23,64,65]. Isolating GW in houses (even single homes) can solve water-shortage, ornamental irrigation issues and food-production problems [10,66–68]. The freshwater provided to urban residents for drinking purposes is subject to several aspects: (i) water availability; (ii) water quality, expressed by extra treatment requirements to minimize health risks; and, (iii) characteristics of the delivery system.

The current work examines the dual possibility of GW accessibility for energy production in TBs. The hypothesis is that the number of TBs constructed will increase with time and that water supply will continue to be of predominant concern. Assembling a separate drainage system within the TBs will enable to use the GW for energy production. Water shortages in TBs should not be of specific concern since it is supplied continuously.

Greywater is a component of urban wastes, commonly wasted or reused, after adequate treatment, for crops irrigation. The treatment of GW in tall building is mainly for irrigation utilization. The innovative part of this work consists of several pillars: (i) separation between the black wastewater and the GW in the source of production allowing a widely better, further treatment and reuse; (ii) the tall buildings allow to surrogate the height of the structure into a source of potential energy to be turned into dynamic applicable energy source; (iii) storage capacity of the GW guarantees (less than 24 h) that water quality meets health standards (pathogen development); (iv) the GW, after being utilized for energy generation can be reused for ornamental and/or agriculture irrigation or any other purpose, and; (v) the storage tanks of the GW within the tall building can be used for energy supply during emergency periods.

2. Elucidation of regenerative systems aimed at harnessing energy for sustainable production

The main assumption of current work is the feasibility of assembling a distinct and separate collection system for using the GW from each apartment in a TB. The GW will be channeled to the specialized turbines for the purpose of generating energy. This assumption implies several key ideas.

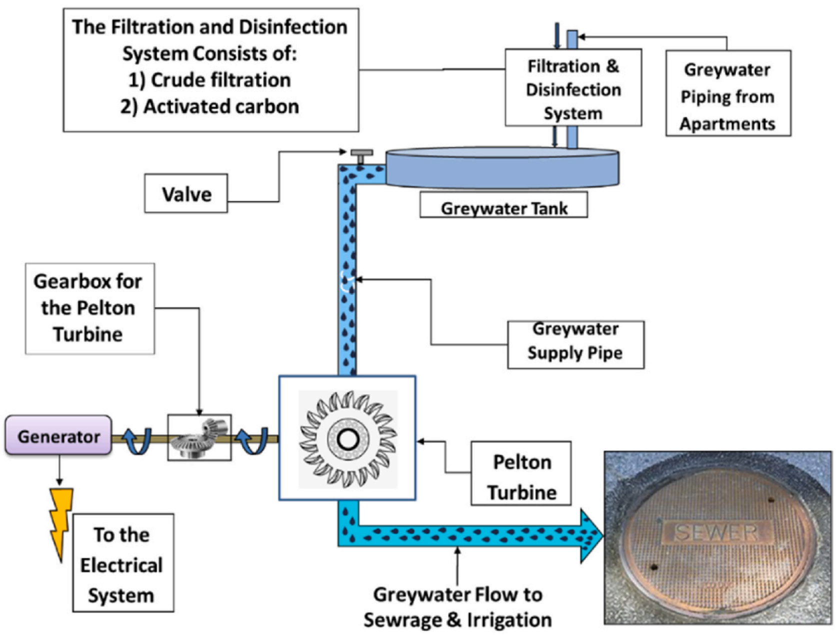

Fig. 5. Schematic description of greywater reuse for energy generation.

1) It is possible to design and implement a system in which each apartment has its own mechanism for GW collection and disposal. Greywater typically includes the wasted water from sources such as bathroom sinks, showers and washing machines. It implies that each apartment would have its own infrastructure for capturing and collecting the GW and transferring it to the main drainage system towards the turbines.
2) The GW collected from each apartment is directed toward the specialized turbines, designed to harness the flow of water and convert it into energy. This can be accomplished through various methods, such as hydropower or microturbines.
3) Turbine installation depends on the height of the building, the number of residents on every floor, and space allocated for energy generation.
4) Conversion of the kinetic energy is affected by the pressure head (ΔH, in m) above the turbines (Figs. 4 and 5).
5) Turbine efficiency is assumed to operate under 70 %.
6) An alternative electrical current or a direct current (AC/DC), using a specialized generator device, will be utilized (Fig. 5).
7) The generated electricity can be used directly within the building to power lights, appliances and other electrical devices. The combination of GW reuse and energy generation can help make the building more energy-efficient, environmentally friendly, and resilient to power disruptions. Energy storage is a critical component of this system. It enables saving the excess electricity generated during periods of high production (e.g., sunny days during which solar panels are used or windy days for wind-turbine utilization) for use during periods of high demand or when the primary energy sources are not available (e.g., night-time).

   in a tall building for energy recovery and irrigation.

8) Recycling of the GW collected from TBs for irrigation, whether through regular on-surface drip-irrigation systems or subsurface drip irrigation, is another sustainable, environmentally friendly practice however, was not considered in this study.

The feasibility and success of such a system depends on several factors, including the technical feasibility of collecting and channeling GW at the apartment level, the efficiency and reliability of the specialized turbines, regulatory and environmental guidelines enforcement. Implementing such a system will likely require careful planning, engineering and possible changes in building infrastructure, and will need to adhere to local regulations and environmental standards.

3. Materials and methods

3.1. Simulation of energy production from descending GW

WaterGEMS software is a commonly used tool for hydraulic system modeling, incorporating water distribution and wastewater facilities [69,70]. The focus is on understanding and evaluation of the energy-generation aspect, consumption and related costs associated with the management and distribution in TBs'. The "scenario of energy cost" is applied to assess the energy costs associated with the management and distribution of GW within the TB over the course of the lifetime of common family apartments [64,65,67].

3.2. Case studies

Five building heights were assumed in this study: 20, 40, 60, 80 and 100 floors, namely, heights of 70 m, 140 m, 210 m, 280 m, and 350 m, respectively. The height of each floor/apartment is approximately 3.5 m. Each apartment house occupies 4 to 5 people, and there are 4–5 families on every floor. Consequently, it was assumed that around 25 people live on each floor. A separate pipe system is installed in each apartment for GW drainage and collection. Greywater flow rate in each apartment is in the range of 400 L/d to 600 L/d namely, 80, 100, and 120 L per capita per day. Storage containers for GW collection are an integral part of the energy-generation system. The containers are installed at various levels relative to the bottom of the building. Up to five containers are installed, each having a capacity of 10 m^3. Every container is emptied several times a day (up to 12 times per day).

A Pelton turbine is chosen for the energy generation. Pelton turbines have low-energy characteristics and can generate controlled amounts of energy. Turbine locations are chosen at distinct levels below the storage containers, allowing for maximal energy generation relative to the different elevations of the GW containers. The choice of turbine location determines the available water head, which is a fundamental factor in energy production (Fig. 3). It is expected that taller buildings would be a better source for energy generation.

The Pelton turbine capital cost (shelf price) is approximately 4000 US $ [71–74]. This specific turbine is suitable for TB requirements in terms of flow-rates and capacity of energy generation. The container cost is assessed at 2000 US $. This cost is based on materials used, maintenance and operational expenses. The drainage pipe price includes the materials, labor for installation and annual maintenance (20 % and 2.5 % of the basic cost for installation and maintenance, respectively) and is assessed at 4.5 US $/m. The pipes are of medium schedule size with diameters ranging from 1.5″ to 4''. Pipe selection has to be adjusted to the planned discharge design and pressure head.

4. Results and discussion

4.1. Component costs

The hydro-economic modeling considered annual expenses for the various energy-generation system components. Annual costs were determined by multiplying the product of the shelf prices of the various components by the capital recovery factor (CRF), given by equation (2):

$$CRF = [i(1+i)^n] / [(1+i)^n - 1] \tag{2}$$

where n is the life span (in years) of the given system component and i is the interest rate (given as a fraction). A value of CRF = 0.130 was selected for the turbines (i = 6 % (=0.06); n = 10 years], namely, an annual cost of CRF x 4000 = 543.5 US $/turbine. For the pipe and storage container installation in the building, a CRF of 0.087 was selected [i = 6 % (=0.06); n = 20 years]. A total pipe length of 25 m was considered per floor (at around 6 m per apartment). Based on the CRF value, the annual cost for the pipe system was 0.39 US $/m. The annual cost of one container was taken as 184.0 US $. Various energy cost values were assumed for the input data in a further sensitivity analysis. The pattern of acceptable energy values was in the range 0.08–0.22 US $/kWh.

4.2. Descending greywater flow and energy generation

The flow rate can vary significantly depending on the building height, household facilities, number of persons living on each floor, water-use habits and local regulations. A maximal discharge for a TB with 60 floors (approximately 210 m high) can reach 180 m^3/d (25 x 0.12 = 3 m^3 per floor per day). A storage container installed on the 20th floor (70 m from the building bottom implies a daily GW flow of 120 m^3/d and a water pressure head of 70 m for a turbine located at the bottom of the TB). The storage tanks can be located at any height in the building, but at least 35 m should be maintained between the storage container and the turbine (Fig. 4). The minimum discharge subject to the data selected in current study is 20 m^3/d (10 floors × 25 people x 0.08 m^3/d). In practice, this means that a series of storage containers can be installed in the building at various heights.

Greywater release from the temporary (daily) storage containers is subject to the selection of turbine type, the building height, the given water head and the economic value of energy (Fig. 4). Selection of GW discharge, water head and turbine location level highlights the complexity of tackling the problem of energy retrieval and potential optimization issues; nevertheless, its solution comes with enormous benefits (Table 1).

4.3. Economic assessment

The options for energy recovery in TBs are given for representative cases-simulating five building heights (70 m, 140 m, 210 m, 280 m, and 350 m) and selection of only one turbine type. The simulation provides some general conclusions (Figs. 6 and 7). Overall, it can be concluded that taller buildings will result in higher energy retrieval.

1) Energy production depends on the height of the building and the relative location levels of the storage containers and turbines (Table 1).
2) Spacing between the GW container and the turbine location for various TB heights is a key factor determining the amount of energy produced.

Table 1
Energy production in a tall building as a function of greywater flow and number of floors.

Number of Floors	Number of Storage Containers	Turbine Power, kW	Electricity Production, kWh/year	Energy Generated Cost, $/kWh
80 L greywater per person per day				
20	**1**	**1.2**	**522**	**1.196**
40	**1**	**1.2**	**2089**	**0.394**
60	**1**	**1.6**	**4700**	**0.240**
80	**1**	**5.0**	**8355**	**0.159**
100	**4**	**10.0**	**20,887**	**0.151**
100 L greywater per person per day				
20	**1**	**1.2**	**453**	**1.956**
40	**2**	**1.2**	**3533**	**0.312**
60	**1**	**1.6**	**5875**	**0.192**
80	**1**	**5.0**	**10,444**	**0.131**
100	**4**	**10.0**	**26,109**	**0.124**
120 L greywater per person per day				
20	**1**	**1.2**	**783**	**0.797**
40	**2**	**1.2**	**4175**	**0.264**
60	**1**	**5.0**	**7049**	**0.160**
80	**1**	**5.0**	**12,532**	**0.117**
100	**3**	**10.0**	**29,372**	**0.106**

Table 2
Results of energy-generation simulation and recommended ranges of application subject to country and other local situations.

Parameter	Scenario 1: 80 l/ca/d	Scenario 2: 100 l/ca/d	Scenario 3: 120 l/ca/d	Ranges of energy costs, $/kWh	Recommendations for application
Number of Floors	Cost of Energy Production, US $ per kWh	Cost of Energy Production, US $ per kWh	Cost of Energy Production, US $ per kWh		
20	1.196	0.956	0.797	$ 0.180 <	Low priority
40	0.394	0.312	0.264	0.15 – 0.18	Moderate preference
60	0.240	0.192	0.159	0.12 – 0.15	Strong preference
80	0.159	0.131	0.117	0.08 - 0.12	Very Strong preference
100	0.151	0.124	0.106	< 0.08	Extremely preference

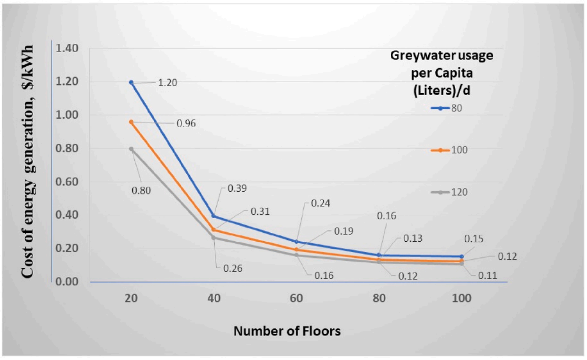

Fig. 6. Energy recovery in high-rise buildings as a function of greywater flow.

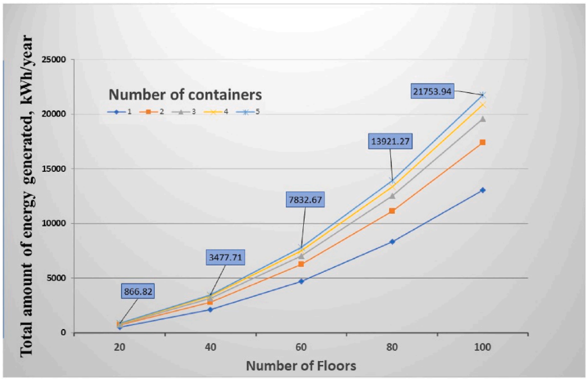

Fig. 7. Annual energy generation for greywatwe flow-rate of 80 l/ca/d.

3) A series of management experiments were conducted to find optimal relationships between elevation and spacing of the storage containers and turbines for every TB height.
4) Optimal solutions depend on the varying costs of basic energy prices.
5) A pattern of optimal energy costs is given in Table 2.

6) Under specific conditions, several turbines can be installed on different floor levels of the building, for the recovery of even more energy (Figs. 7 and 8). The turbine type is essential here, as its capacity and the GW pressure head under which it is operating.
7) Under specific conditions, it is possible to install GW storage containers in the upper part of the TB for emergencies.
8) The current work does not consider reuse of the GW for irrigation-an additional economic benefit.

5. Conclusions

Harnessing energy from descending GW in TBs using storage containers and turbines is a challenging concept that has the potential

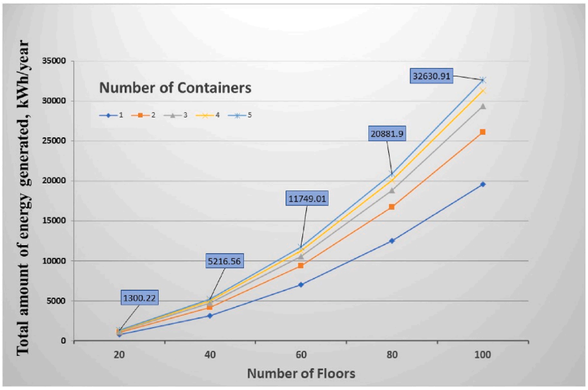

Fig. 8. Annual energy generation for greywatwe flow-rate of 120 l/ca/d.

to contribute to sustainable energy generation and water conservation. Greywater is high-quality wastewater generated from residential sources such as sinks, showers and washing machines. It is not suitable for drinking purposes, but it can be repurposed for non-potable uses and potentially, energy generation. Some basic conceptual parameters of such systems have to be considered.

Greywater is collected from the various sources on every floor of the TB. This GW should be filtered and disinfected to remove any debris and contaminants that could damage the turbines. The collected GW should be stored in temporary-daily storage containers for later energy generation. The stored GW then flows down through the building's plumbing system, and passes through turbines installed in the plumbing infrastructure. These turbines are similar to hydroelectric turbines and are designed to convert the kinetic energy of the flowing GW into mechanical energy. The mechanical energy produced by the turbines is converted into electrical energy and can be used to power various components of the building or be sent to the public (or national) grid. There is always the option of storing the electrical energy in batteries or other energy-storage devices in the building. This stored energy can also be used as a backup power source or for load balancing during periods of peak demand. After passing through the turbines, the GW can still be used for non-potable purposes, such as flushing toilets or irrigating green plants near the building. Energy and water-use efficiency in residential sectors addresses the sustainable management of both of these resources, involving numerous aspects (daily water and energy practices, renewable water and energy, health aspects) [7,75]. This dual-use of GW for both energy generation and water recycling can increase the system's overall efficiency.

The challenges and efficiency of this system depend-on the flow rates and pressure head of the GW, the design of the turbines, and maintenance of the system. The initial installation costs and ongoing maintenance expenses can be substantial. Future outlook for actual implementation include a series of variables. Here within kind of standard and simple cases were discussed. Actually, in the future and for distinct cases one has to consider to TB height (number of floors, surface area of each floor, container capacity, recommended flow rated for the selected turbine and its' efficiency. It will also be a real matter were, subject to the TB height to install the turbines. Building owners must therefore evaluate the long-term economic viability of such systems, to determine whether the cost and effort are warranted. Because the GW must be adequately treated to prevent damage to the equipment and to maintain water quality for non-potable uses, water filtration and disinfection are essential components of this setup.

Implementing water systems for energy generation from descending GW in TBs can be a promising sustainable initiative. As indicated (Table 1) the cost of energy generation is declining with increasing building height. In our case above a building height of 60 floors the energy production is in the range of $ dollars 0.12 to $ dollars 0.15 per kWh. When improving the efficiency of the turbines the energy cost can even be downgraded. However, it requires a careful evaluation of the technical, economic and regulatory aspects to ensure its viability and effectiveness. Further consideration should focus on environmental impacts, such as potential disruptions to local ecosystems. The feasibility of this system also depends on the scale of the building and the volume of GW produced. It may be more practical in large high-rise buildings with high water usage.

Consent for publication

Not applicable.

Data availability

Conventional and public data was adopted for the analysis. It was assumed every family consists of 5 persons and 6 families live on each floor. Costs of piping is of public domain.

CRediT authorship contribution statement

Gideon Oron: Conceptualization. **Yaar Or:** Data curation. **Jehonatan Shanni:** Data curation. **Eden Hadad:** Formal analysis. **Erez Fershtman:** Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Gideon Oron reports was provided by Ben-Gurion University of the Negev. Gideon Oron reports was provided by Gideon Oron, Researcher, Ben-Gurion University of the Negev. Gideon Oron reports a relationship with No personal financial support that includes: non-financial support. Gideon Oron has patent No patent pending to No number is required. The other authors are students of the University If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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