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# From self-sufficient provision of water and energy to regenerative urban development and sustainability: exploring the potentials in Mashhad City, Iran

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Increased resource demand due to rapid urbanization has made cities like Mashhad highly dependent on their surroundings for resource supply and waste disposal, and has negatively impacted their local-regional hinterlands. To reduce the metabolic footprint of cities and create an environmentally restorative relationship between cities and their supporting ecosystems, a transition toward local alternative and renewable sources is essential. This paper explores potentials for water and energy self-sufficient provision in Mashhad using the Urban Harvesting method to practically illustrate how cities could seek opportunities to meet their needs within their boundaries before relying on external supplies. Results showed that solar photovoltaic and biogas could provide 4495.2 and 472.6 GWh/yr electricity, altogether enabling Mashhad to offset 100% of its consumption. Water cascading and recycling have the potential to meet 72% of the demand, and replace around 125 mcm/yr of imported water. Similarly, water self-sufficiency would increase by 5%–8% (8.6–14.7 mcm/yr) when collecting rainwater from rooftops.

**Keywords:** Regenerative design; Self-sufficient Resource Provision; Urban Energy; Urban Harvesting; Urban Water

## 1. Introduction

Over the last three decades, since 1990, the world has experienced a rapid growth in urban population (UN-Habitat 2016). With accelerating population growth in urban areas, cities have become much more dependent on their surroundings for both resource supply and waste disposal (Bai 2007). Cities, like living organisms, require a large amount of resources in order to sustain their function. They use water, food, raw materials and fuel coming from outside the urban boundaries and give back waste (Kennedy, Pincetl, and Bunje 2011). Whilst many cities today have a linear metabolism and take resources from nature, discarding the remains with no consideration for waste origin and destination or reuse of the outputs, nature's own ecosystems enjoy a circular zero-waste metabolism in which every output is used as an input for another process (Giradent 1999). If cities continue to exploit resources and produce waste in a linear way, the ecosystem upon which they rely and the services freely provided by the ecosystem can be seriously damaged, as overexploitation of natural resources and massive waste disposal have recently caused severe resource depletion and pollution at local and global scales (Duh *et al.* 2008; Bandara, Patrick, and Hettiaratchi 2010).

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Mashhad is a good example of a city that relies heavily on substantial imports of water and energy from outside its boundaries. During the second half of the 20th century, Mashhad experienced an eight-fold growth in population, contributing to a greater water demand and a lower per capita water resource availability. Scarcity of water resources due to accelerating urbanization, coupled with climate variability and droughts in recent decades, has placed high stress on local water supplies in Mashhad and it has made the city much more dependent on distant sources. Nearly 100% of electricity demand in Mashhad is also met by centralized power plants mostly using fossil fuels, including natural gas, gasoline (petrol) and fuel oil (mazot) while use of mazot at some of Mashhad's power plants has been recently identified as one of the main causes of Mashhad's air pollution. Overall, groundwater depletion due to overexploitation, pollution caused by uncontrolled sewage disposal and effluent from wastewater treatment plants, air pollution and increased greenhouse gas emissions coming from burning fossil fuels are among the environmental impacts resulting from linear metabolism of water and energy in Mashhad.

To reduce the metabolic footprint of the city and lower the pressure on supporting ecosystems, a change in approach from the old linear metabolism to a new circular one is needed. It should be studied how the urban system can mimic the circular metabolic system found in nature and how it can become a resource generator. Cities are the biggest consumer of natural resources (Dodman, Diep, and Colenbrander 2017), but on the other hand, they can play a key part in protection of local environmental assets providing ecosystem services. Cities are able to provide a large part of provisioning services provided by nature through capturing primary sources and reusing or repurposing secondary sources (Pedersen Zari 2017; Byrne *et al.* 2017; Yamagata *et al.* 2003). Use of these great alternatives not only reduces impacts on the environment (Braga *et al.* 2018; Nizami *et al.* 2017), but it also makes a positive contribution to the currently degraded conditions of our ecosystems, as it can help cities develop a benign regenerative relationship with their supporting ecosystem, which lies at the heart of urban regenerative development (Girardet 2014).

This paper investigates potentials for water and energy self-sufficient provision in Mashhad as a major fast-growing city in a developing country, and explores opportunities toward regenerative sustainability.

The rest of the paper is organized as follows: Section 2 reviews urban metabolism (UM) studies from a methodological perspective in brief and compares two robust methods exploring potentials for water/energy supply internalization and opportunities to improve resource cycles and metabolic processes throughout the urban system under the banner of UM. It also mentions recent studies focusing on water/energy self-sufficiency in cities. Section 3 introduces the study area and explains the original method of UH developed by Agudelo-Vera, Leduc, *et al.* (2012) in detail. It is then applied to Mashhad as a major city in a developing country context. The results are described and discussed in Section 4 and concluded in the final Section.

## 2. Previous UM studies and methodological approaches

According to Kennedy, Pincetl, and Bunje (2011), a UM study "involves 'big picture' quantification of the inputs, outputs and storage of energy, water, nutrients, materials and wastes for an urban region". UM has been widely used as an appropriate approach to assess the metabolic performance of cities and understand how efficiently cities use resources and manage outputs (e.g. Kennedy, Cuddihy, and Engel-Yan 2007; Bristow and Kennedy 2013; Moore, Kissinger, and Rees 2013; Hoekman and Blottnitz 2017; Lei, Liu, and Lou 2018; Tanguy, Bahers, and Athanassiadis 2020). It has also been used for accounting or inventory of greenhouse gas emissions (e.g. Lin *et al.* 2013; Islam 2017; Pioletti, Brigolin, and Pastres 2018; Yin *et al.* 2018), and exploring the potentials for reduction in resource consumption and reuse of the outputs throughout the urban system (e.g. Ghisi, Montibeller, and Schmidt 2006; Dandy *et al.* 2019; Cheng *et al.* 2020; Yaman 2020). Previous studies have developed various methodological approaches under the banner of UM. Research methodologies in UM studies have evolved from simple accounting-based analysis of cities to complex dynamic mathematical models. Daniels (2002), Daniels and Moore (2002), and Zhang (2013) provided a comprehensive overview of methodological approaches for quantifying metabolic flows and evaluating urban metabolic processes, of which the two methods of material flow analysis and energy flow analysis have been frequently used in previous UM studies. Although a few earlier studies on UM focused on water (Kennedy, Pincetl, and Bunje 2011), recent studies have shown much interest in understanding hydrological flows and water-related fluxes, quantifying water efficiency, exploring alternative water servicing options or opportunities for water localization or internalization of supply, and they have used a variety of methods from mass balance analysis to dynamic metabolism modeling and WaterMet (Venkatesh *et al.* 2014; Behzadian and Kapelan 2015; Farooqui, Renouf, and Kenway 2016; Renouf *et al.* 2018; Paul *et al.* 2018; Jeong and Park 2020). Kenway, Gregory, and McMahon (2011) developed UWMBA under the UM framework allowing a comprehensive study of the urban water cycle. The method of UWMBA considers all components of an urban water cycle and it generates indicators to measure water intensity and self-sufficiency, explores local water sources, and quantifies their recycling or reuse potentials. Farooqui, Renouf, and Kenway (2016) extended the Kenway, Gregory, and McMahon (2011) UWMBA, and added the quantification of energy related to water flows to the model. The UWMBA method, overall, is a robust accounting method for all water sources, including wastewater, stormwater and rainwater from rooftops, applicable to all cities, including fast-growing cities in developing countries where water loss is a significant component of urban water flows (Paul *et al.* 2018). However, the original method and its further development just focus on water and energy related to water, originally intended to evaluate urban water metabolism and monitor hydrological performance of urban-regional systems. In comparison, Agudelo-Vera, Leduc, *et al.* (2012) suggested the method of UH based on the concept of UM so as to investigate all possible options for harvesting different sorts of local and renewable resources within a city toward a circular metabolism. It was extended and applied to quantify the water cycle at a residential building by Agudelo-Vera, Mels, *et al.* (2012) and to quantify the energy cycle at a residential block by Leusbrock *et al.* (2015). The method of UH provides helpful information on water and energy saving potentials, possible options for reuse or recycling, and contribution of harvesting measures to UM improvement. It highlights the influence of technical interventions on urban metabolic performance and resource cycles, and suggests a hierarchy of strategies to optimize urban resource management in cities, although it still offers little in the way of a holistic evaluation of urban resource cycles in terms of energy, nutrients and carbon (Leusbrock *et al.* 2015) and does not provide a holistic approach for resource flow identification and quantification considering all components.

There are some studies reviewing renewable energy and water in cities, such as Barragán-Escandón, Terrados-Cepeda, and Zalamea-León (2017) and Rygaard, Binning, and Albrechtsen (2011), and many others like Nm de Souza *et al.* (2014), Singh and Banerjee (2015), Elnaggar, Edwan, and Ritter (2017), León-Vargas, García-Jaramillo, and Krejci (2019), Tang *et al.* (2019), Arcos-Vargas, Gomez-Exposito, and Gutierrez-Garcia (2019), Macintosh *et al.* (2019), Barragán-Escandón *et al.* (2020), and Grewal and Grewal (2013) focusing on energy self-sufficiency in cities. Similarly, Ezenwaji, Nzoiwu, and Eduputa (2016), Ibne Bashar, Rezaul Karim, and Imteaz (2018), and Vaz, Ghisi, and Padilha Thives (2020) explored potentials for water supply localization. In all these studies, various methods varying from simple computing to complex modeling tools (e.g. GIS), and assessment techniques (e.g. life cycle assessment and energy balance analysis) were picked and applied according to the scope and objectives of the studies, as well as the data availability and quality.

## 3. Methodology

### *3.1. Methodological framework*

The paper applied the UH method originally developed by Agudelo-Vera, Leduc, *et al.* (2012). It consists of multiple steps and starts with the creation of an average tissue. Urban Average Tissue (UrbAT) was first introduced by Rovers (2007) as a conceptual approach for UH to conceptualize resource consumption and production in relation to urban land use and it is a representation of all urban functions in an average hectare (Leduc and Rovers 2008). Figure 1 demonstrates our research methodology, developed in four steps, as detailed below:

i. *Land Use Investigation:*
The starting point of the UrbAT method is an investigation of current land uses and creation of a standard hectare illustrating the distribution of functions in an average hectare of an urban area. The first step to create a standard hectare is determination of urban surface area (Leduc and Rovers 2008) referring to the amount of territory that is occupied by zones of development or of potential development within city limits (Acebillo 2011). The next step is measurement of the land area occupied by each land use type. The area of each function is finally rescaled to squared meters per one hectare of urban land (Leduc and Rovers 2008).

ii. *Demand Investigation:*
Demand Investigation is quantification of demand. It also includes a hierarchical identification of the qualities required for a variety of uses (Agudelo-Vera, Mels, *et al.* 2012), according to the principle of fit-for-purpose

iii. *Supply Investigation:*
Supply Investigation is quantification of the amount of water and energy sources available within the city limits, or that could become available from the city. It includes an investigation of current resource supply, and an exploration of all possible harvesting options (Agudelo-Vera, Leduc, *et al.* 2012). There are four major strategies for harvesting local resources, including multi-sourcing, cascading, recycling and recovery. The former three are looping actions primarily aimed at output minimization. There is also multi-sourcing, replacing the

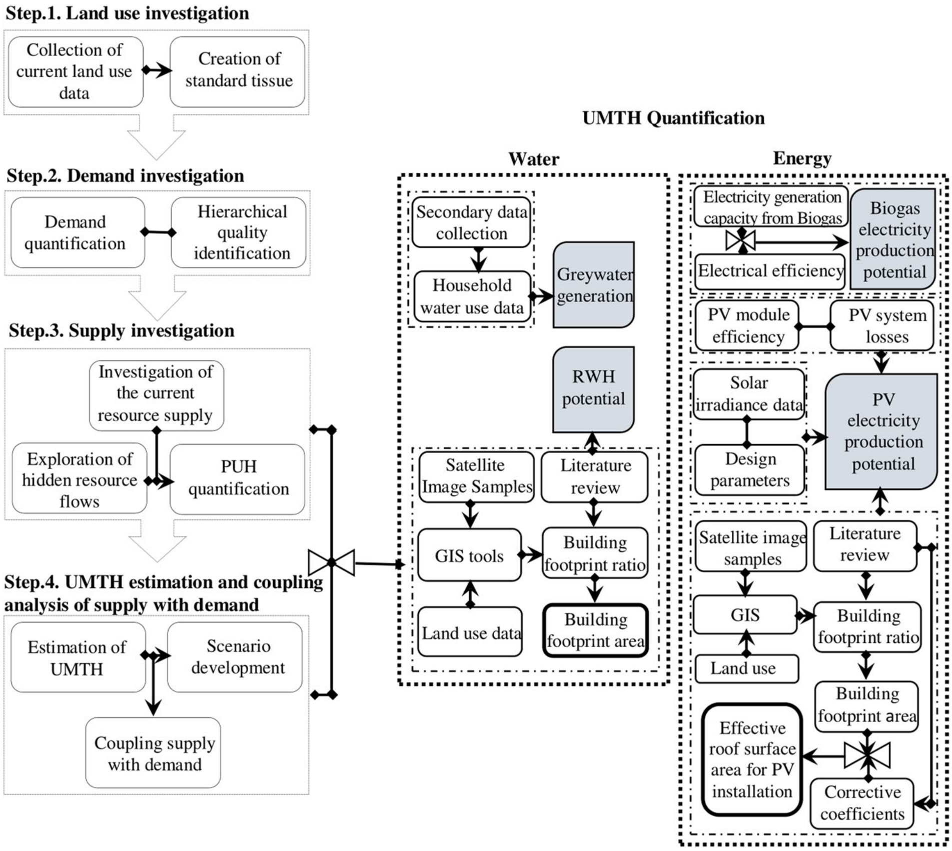



Figure 1. Research procedure.

Table 1. UH strategies.

| | |
|---|---|
| Cascading or direct use | Refers to reuse of outputs without any further processing for activities with lower-quality demand. |
| Recycling or reclamation | Refers to reprocessing resource outputs before reusing for the other purposes. For example, use of reclaimed wastewater for irrigation or groundwater discharge. |
| Recovery | Includes energy recovery or extraction of useful materials from wastewater, waste, etc. |
| Multi-sourcing | Refers to harvesting local and renewable resources such as rainwater, solar or wind energy. |

remaining demand with local and renewable resources (Agudelo-Vera *et al.* 2013; Leusbrock *et al.* 2015; Williams 2019) (Table 1).

iv. *Urban Maximum Technical Harvest (UMTH) Calculations and Supply-Demand Coupling Analysis:*

The final step includes calculation of UMTH, defined as achievable water or energy of a specific technology given technical efficiency, climatic variability restrictions and land use constrains. When capturing or harvesting local resources, even if the best technologies are implemented, there are some limiting factors influencing harvesting potentials, Equation (1).

$$\mathrm{UMTH} = \mathrm{UHP} \times \text{Ø}_{tech} \times \text{Ø}_{urb} \times \text{Ø}_{temp} \times \text{Ø}_{\ldots} \quad (1)$$

Here, UHP represents urban harvesting potential, and $\text{Ø}_{tech}$, $\text{Ø}_{urb}$ and $\text{Ø}_{temp}$ are reduction factors associated with technical efficiency, urban typology and temporal restrictions respectively.

Different scenarios are developed in this stage. It also ensures that the quality of water/energy is as high as required for the use, but not higher, by applying the principle of multi-sourcing, cascading or recycling (Agudelo-Vera, Leduc, *et al.* 2012).

Calculation details are described in Table A.1 in the appendix (online supplemental data).

### *3.2. Mashhad City/case study*

Mashhad metropolis is the capital of Razavi Khorasan province, situated in the northeast of Iran in the valley of the Kashafrud River, the main river in the watershed of Mashhad plain, between two mountain ranges of Binalood and Hezar Masjid, close to the borders of Afghanistan and Turkmenistan. Mashhad, with a population of around 3 million, is the second-highest populous city in Iran. It is also the most popular pilgrimage destination amongst Shia Muslims in which temporary and seasonal tourist peaks are noticeable. Mashhad is naturally a water scarce city and is now facing the biggest drinking water crisis in Iran. The current water crisis in Mashhad has several major drivers, including accelerating population growth coupled with a growing number of tourists, inefficient agriculture, mismanagement and thirst for development. More than anything, the current water crisis in such a city has resulted from decades of mismanagement. Water management in Iran is reactive rather than proactive, which focuses more on immediate short-term solutions such as digging more wells, building more dams and transferring water from distant sources rather than seeking out new opportunities and sustainable measures to deal with any threats or problems before they emerge. Some examples of these kinds of measures are the construction of Doosti Dam in 2005, which is not reliable in the long term, and also the plan for desalinization and water supply from the sea of Oman (situated around 2,710 km far from Mashhad in southern Iran). Although such actions may be able to control the crisis in the short term, they cannot solve them forever and may cause another problem in the long term. While Mashhad is wrestling with the water scarcity problem, it faces no problem with electricity production, as Iran is rich in energy resources. The biggest challenge related to energy in Mashhad is fossil fuel power plants which are a major source of air pollutants such as CO, $PM_{10}$, $NO_x$, and HC as well as GHG emissions. In addition to the existing concerns about air pollution, fluctuating oil prices since the lifting of sanctions in 2015 has made the development of renewables in Iran essential. The main characteristics of Mashhad city are described and detail in Figure B.1 and Table A.2 in the Appendix (online supplemental data).

### *3.3. Data collection and estimation*

Data was obtained from official statistics, technical reports and publications. The historical climate data were sourced from I.R.OF IRAN Meteorological Organization

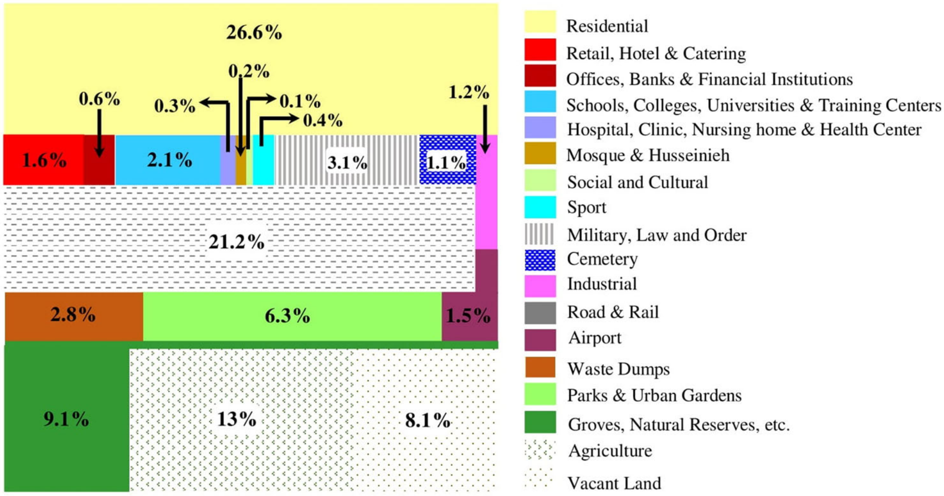



Figure 2. Mashhad's average urban tissue.

(IRIMO) dataset for the period 1982–2017 (www.irimo.ir/far/index.php). Data for water and population were assembled from Mashhad Statistical Yearbook for the year 2016. Data on electricity were received from Mashhad Electric Energy Distribution Company (MEEDC), and land use data was obtained from Mashhad land use dataset (2013) and Mashhad Spatial Data Infrastructure (SDI) (http://sdi.mashhad.ir/sdi). Roof surface area was calculated in this study. To estimate the total building footprint area (BFA), we applied the BFA ratio derived from Mashhad's development plans. To check the reliability, we randomly took image samples of buildings of each relevant land use type. Next, using satellite imagery from Google Earth™ (2017) and GIS package, the BFA ratio for each land use type was calculated and compared with the derived values. The total roof surface area was finally calculated by multiplying the total surface area of each land use type by the BFA ratio corresponding with each type of land use.

## 4. Results and discussion

Results are presented in three sections. In the first section, a standard tissue is developed for Mashhad city. The other two sections represent and discuss the results of the remaining steps for water and energy separately.

### *4.1. Mashhad's land use distribution*

Figure 2 illustrates land use distribution in one hectare of the city of Mashhad.

### *4.2. Energy*

Demand was initially investigated to identify the largest energy consumer. Accordingly, urban functions were first classified into five categories, including residential, commercial, public services, industry and agriculture, and electricity demand for each land use category or sector was determined. Results demonstrated that households are the biggest electricity consumers in Mashhad. Residential electricity use comprises 44% of the total electricity consumption, compared to electricity use by public services and the industrial sector, each accounting for 14% and 24% of the total electricity consumption (Table A.3 in the Appendix, online supplemental data). Annually 4,967,864 MWh electricity is consumed in Mashhad of which 8243.5 MWh (a mere 0.2%) comes from renewable sources. To achieve a 100% renewable electricity supply, 4,959,620.5 MWh renewable electricity should still be generated. Barragán-Escandón, Terrados-Cepeda, and Zalamea-León (2017) provided a classification of renewable energies in cities and recognized ten types of energy source, including biofuels, biomass, municipal solid waste, sewage sludge, energy from the sea, wind power, geothermal, hydroelectric, photovoltaic solar energy, and solar thermal, which can be used as alternative sources of energy in cities and are suitable for urban integration. They also introduced the best possible technologies to harvest each type of energy source within or from the city. Our preliminary reviews showed that there are great opportunities for production of electricity from renewable sources in Mashhad. Several projects involving biogas power plants, solar power plants and (large-scale) rooftop solar photovoltaic systems have been recently defined and implemented in Mashhad city, but there is still considerable capacity for solar energy and biogas. Other sorts of energy sources such as tidal energy, wind power and geothermal have no potential or application for Mashhad's energy integration owing to resource unavailability or limitations, according to Iran's wind energy resource atlas developed by the Renewable Energy Organization of Iran (SUNA) (2010), suggesting windy areas for the installation of wind turbines or the establishment of wind farms for elevations of 25, 50, 80, 100, 120 and 200 meters which has categorized Mashhad into regions with a weak wind regime (annual average wind speed of below 4 m/s, which is not sufficient to operate with any degree of efficiency), and Iran's geothermal atlas created by SUNA (1998) determining regions with geothermal potential, in which Mashhad has been considered as an area with no potential for geothermal power plant installation. There are some the opportunities for generation of hydroelectric power in Mashhad, for instance, through establishment of hydroelectric power plants on the river Atrak (situated 155.3km northwest of Mashhad) as well as in five of Mashhad's water treatment plants and three dams at Kardeh, Torogh and Ardak, which are used for Mashhad's water supply and agricultural irrigation. Similar projects such as the project for locating the small pumped-storage hydropower plant in the water transmission line running from the Doosti dam (situated 165 km northeast of Mashhad at the border of Iran and Turkmenistan) to Mashhad's water storage reservoir have also been implemented in Mashhad recently. However, they are excluded in this study as implementation of such a technology is subject to the existence of generating resources within the city limits according to the UM principles (Barragán-Escandón, Terrados-Cepeda, and Zalamea-León 2017). There are also five wastewater treatment plants in Mashhad of which three have the potential to generate hydroelectric power, but at a very small scale (SATBA 2018) making a negligible contribution to the municipal electricity supply, and thus, disregarded in this study.

Overall, two different scenarios for electricity production from renewable energy sources were developed for the city of Mashhad, as detailed below:

Scenario i: PV installations (with a median efficiency of 16% and an internal loss of 20% that are oriented S-facing and fixed on an annual optimum tilt angle of 30° for better utilization of energy) on 17% of current residential, commercial, industrial and public buildings' roof surfaces with a tilt of 0 degree; PV installations on 22% of Mashhad's current vacant land; and energy recovery from biomass, municipal solid waste and sewage sludge by means of thermal conversion technologies (incineration and gasification) and bioconversion (landfill gas and anaerobic digestion) with a total efficiency of 80%. These measures would provide around 59.5%, 31.1%, and 9.4% of Mashhad's remaining electricity demand respectively.

Scenario ii: PV installations (with highest efficiency of 21% and internal losses of 20% that are oriented S-facing and fixed on an annual optimum tilt angle of 30°) on 17% of current residential, commercial, industrial and public buildings' roof surfaces with a tilt of 0 degree; PV installations on 7% of Mashhad's current vacant land; and energy recovery from biomass, municipal solid waste and sewage sludge by means of thermal conversion technologies (incineration and gasification) and bioconversion (landfill gas and anaerobic digestion) with a total efficiency of 80%. These measures would provide around 78.1%, 12.5%, and 9.4% of Mashhad's remaining electricity demand respectively.

Mashhad with a huge source of organic waste has an appropriate potential to use biogas as an alternative source for electricity generation. Major sources of biogas in Mashhad include municipal solid waste, municipal wastewater and agricultural waste. On average, around 665,395 tons of solid waste are generated annually within Mashhad's boundary of which about 255,500 tons are recycled, and the remaining is disposed of in landfill. There is also an annual capacity of 34.4 million tons of biomass in Mashhad which is able to generate a noticeable amount of electricity. Now, at Mashhad's biogas power plant, a ton of solid waste can yield 192 $m^3$ biogas. With the nominal capacity of 660 kW, Mashhad's biogas power plant delivers 4,363 MWh electricity annually. It accounts for just up to 0.1% of Mashhad's current electricity demand while if the recovery potential of the biomass and solid waste annually disposed of in landfill could be fully utilized, the amount of electrical power generation capacity delivered to the network would increase to 49.55 MW. It would yield 347,246 MWh electricity per year comprising about 7% of Mashhad's annual electricity consumption. With an additional electrical power generation capacity of 17.89 MW coming from 42,789,906 $m^3$ sewage sludge biogas, approximately 472,619.5 MWh electricity in total would be generated, contributing up to 10% of Mashhad's annual electricity supply. To achieve the 100% local electricity generation target, supplemental energy sources are required.

1 $m^2$ optimally inclined surface in Mashhad could potentially catch 1,939.5 kWh solar energy annually. There is a total 7,075 ha of roof surfaces in Mashhad which account for 20% of the total hard surface. Assuming that only 1,189 ha of rooftops are suitable and available for installation of rooftop PV systems, due to limiting factors such as shading, slope, roof size and existence of chimneys, dormers, air-conditioning apparatus etc., reducing available roof surface area for PV installation, depending on the PV module technology, Mashhad could yield from 2,951 up to 3,873 GWh electricity annually, of which 74% would be provided by residential buildings, compared with public, commercial and industrial buildings each accounting for 15%, 7% and 3% of solar electricity generation. This means that residential buildings could be the largest potential contributor to rooftop PV electricity generation and energy supply in Mashhad. However, public buildings are also significant, as they can provide sufficient space for future large-scale rooftop PV systems.

Rooftop solar PV could cover 59% up to 78% of Mashhad's annual electricity demand in total, when incorporating additional energy technologies such as energy storage which can increase the energy self-sufficiency by 1% (in Scenario i) and 5% (in Scenario ii). It would meet 24%–109% (in Scenario i) and 32%–143% (in Scenario ii) of Mashhad's monthly electricity demand, creating a 9% up to 43% electricity surplus during certain months of the year (Figure 3). The coefficient of variation (CV) for monthly values was estimated to be 31%, indicating a low seasonality in solar radiation.

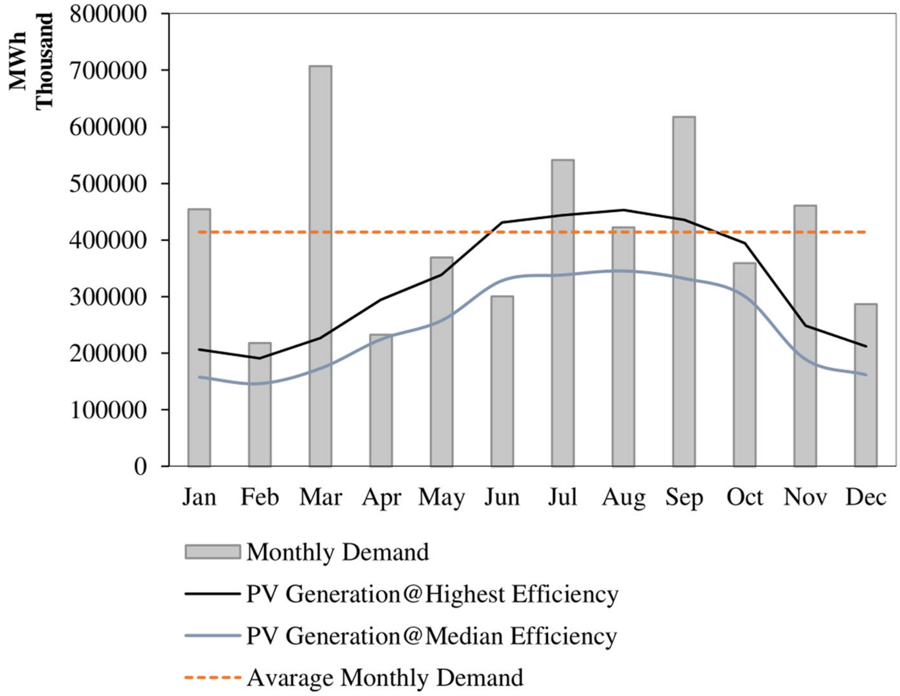
Rooftop photovoltaic in combination with biogas could enable Mashhad city to totally offset 69% up to 88% of its annual electricity consumption. To supply the remaining demand, 622 GWh up to 1,544 GWh electricity should still be generated locally, which would be achieved by PV installation on approximately 191 up to 622 hectares of Mashhad's current vacant land (Table A.4 in the Appendix, online supplemental data).

Overall, biogas and solar photovoltaic have great potential to serve as alternative energy sources in Mashhad and would be able to reduce at least 54,296 tons in $CO_2$ emissions coming from annual burning of 24,408 mcm natural gas in Mashhad's fossil-fueled power stations. However, a big challenge in implementing a renewable-energy-based power generating System in Mashhad could be the high costs of renewable electricity production due to higher building and operating expenses that are estimated to be at least four times as high as the costs of electricity generation from conventional sources. Electricity production from Biogas would be much more cost-effective compared with solar photovoltaic power generation, so that the installation cost of a 1 MWh solar photovoltaic system is around seven times as large as the costs of installing a biogas power plant with the same capacity (Ghaemi Asl *et al.* 2017). The recent sanctions imposed on Iran have made the situation even more complicated, causing a doubling in the installation costs of solar photovoltaic systems and, this itself, has increased the return on investment to over three years, and consequently, reduced the popularity of domestic solar photovoltaic systems with the general public. In addition to financial barriers to the development of renewable energy, the intermittency of renewables such as solar energy is often cited as a barrier to their large-scale integration into the grid (Hart, Stoutenburg, and Jacobson 2012) and the problem can be tackled if an appropriate energy storage technology is developed (Barragán-Escandón, Terrados-Cepeda, and Zalamea-León 2017). Otherwise, biogas combined with solar technology could not necessarily remove the problems related to the accessibility or availability of electric power at all times.

### *4.3. Water*

Water demand was first determined based on the current water consumption of different urban functions categorized into residential, commercial, industrial, public services, and urban green spaces (Table A.5 in the Appendix, online supplemental data). Next, the functions with the largest water demand were identified.

Household water use accounts for over 80% of the total water consumption, compared with 12% for commercial and public uses, and below 4% for industrial use. In Mashhad, per capita daily water use for households is about 126 liters per person, totaling approximately 140 mcm water per year. At household level, only 7% of water is used outdoors. Over 80% of water is used indoors, mainly for bathing and flushing



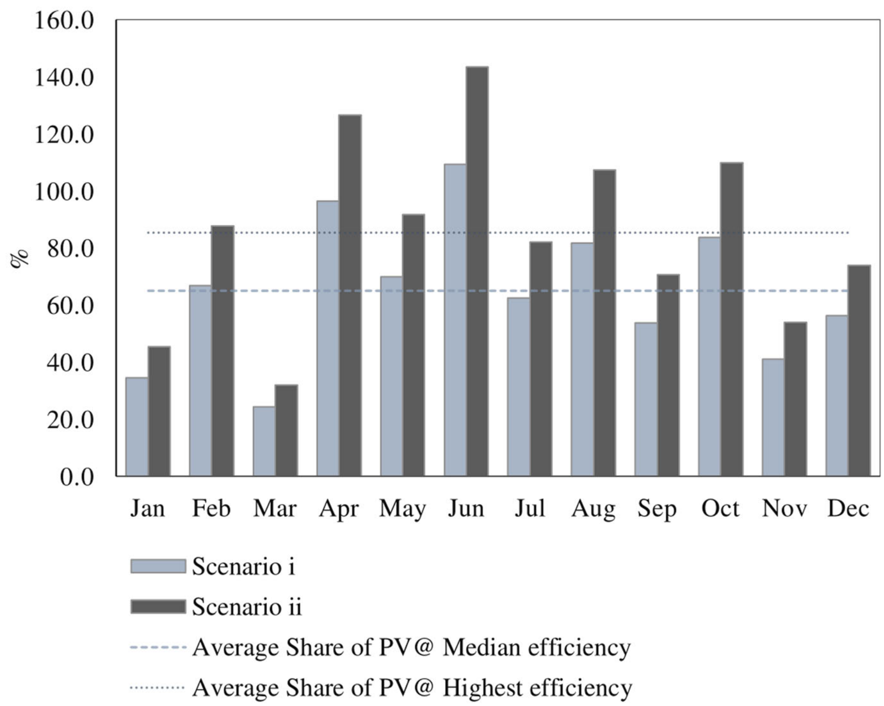




Figure 3. (a) Monthly demand and PV electricity generation. (b). Electricity saving in different scenarios.

toilets, comprising 41% and 25% of total household indoor water consumption. Around 82 mcm (53%) of water for potable uses in Mashhad comes from groundwater resources and the remaining 91 mcm (47%) is sourced from surface water. Gray water reuse for irrigating urban green spaces has also been recently practiced in Mashhad city, although it contributes just 0.2% of the total water supply. Recent gray water reuse projects in Mashhad include establishment of two individual on-site treatment systems with a total capacity of 100 $m^3$/day treating greywater originating from washbasins in two public parks.

Rygaard, Binning, and Albrechtsen (2011) reviewed 113 cases and 15 in-depth case studies in order to find solutions to increase water self-sufficiency in urban areas, and they introduced seven concepts and techniques for urban water self-sufficiency, classified into the three main solutions of wastewater reclamation, rainwater collection and desalination (from local shores). Wastewater reclamation is a drought-proof and renewable water supply (Pereira, Duarte, and Fragoso 2014), and three applications of this in urban areas identified by Rygaard, Binning, and Albrechtsen (2011) include non-potable reclamation, indirect potable reclamation and direct potable reclamation; the former two are applicable to Mashhad city. Non-potable reclamation is reuse of domestic wastewater for non-potable purposes such as irrigation, industrial processes and toilet flushing. Domestic wastewater is typically composed of a mixture of black water and gray water, and gray water is the kind of domestic wastewater flow which is frequently used and can be separated, and then, treated at source. Li, Wichmann, and Otterpohl (2009) reviewed possible technologies for gray water reclamation, as summarized in Figure B.2 in the appendix (online supplemental data). Gray water treatment technologies highly depend on gray water characteristics. Generally, kitchen gray water and laundry gray water are higher in both organics and physical pollutants rather than shower gray water. Bathroom and washbasin gray water are less contaminated by microorganisms than any other gray water streams, and are categorized into light or low-strength gray water, compared with laundry and kitchen gray water categorized into dark or high-strength gray water (Li, Wichmann, and Otterpohl 2009; Albalawneh and Chang 2015). In Mashhad, 47.99 mcm/yr (low-strength) gray water from bathrooms is available to supply 29.02 mcm/yr water for toilet use which would account for 20% of the total household demand and 17% of Mashhad's annual water consumption.

Recent studies demonstrate that while larger (mid-size) decentralized systems are the least energy intensive and able to reduce energy intensity for cost-effective urban water services, small-scale decentralized systems consume a significant amount of energy and are even more energy intensive than centralized systems (Paul, Kenway, and Mukheibir 2019; Singh and Kansal 2018; Singh, Kansal, and Carliell-Marquet 2016). Mid-size decentralized water recycling systems have been recently developed in countries like Australia (Paul, Kenway, and Mukheibir 2019) and such systems have also been newly taken into consideration in Iranian cities as in Mashhad city where there are plans for the establishment of fourteen intermediate-scale treatment systems (with a total capacity of 21,686.4 $m^3$/day) that treat sewage collected in-the-middle-of-the-pipe in local wastewater treatment plants connected to the existing sewerage network, mainly for urban landscape irrigation. Only 52% of this capacity would completely meet Mashhad's current annual irrigation demand. The remaining 48% would annually provide about 3.7 mcm water for other non-potable uses. Overall, water demand for non-potable uses, including toilet flushing (in both residential and non-residential buildings), landscape irrigation, and other purposes (e.g. firefighting and street cleaning) can be fully supplied in Mashhad, if decentralized water recycling systems with a total capacity of around 42.4 to 47.3 mcm/yr are created which accounts for 24% to 27% of the total annual municipal water demand.

Direct potable reuse is not permitted in Iran and past experience has also confirmed that negative public perceptions of potable reuse can be a big obstacle to implementation of these kinds of projects (Hurlimann and Dolnicar 2010). Thus, wastewater can be recirculated to drinking water after blending with natural sources, including surface water or groundwater. Approximately 139 mcm wastewater is estimated to be generated in Mashhad yearly, of which around 125 mcm would be available to be pumped back into natural sources after treatment and it could replace approximately 72% of the water withdrawn from the aquifer. However, indirect potable reuse is conditional on advanced treatment, and risk management, control measures, and monitoring for contaminants are fundamental. Otherwise, health risks and environmental impacts can be significant, and possible consequences may be irreparable, as although past experience has demonstrated that advanced treatment is able to produce water of equal or even better quality than that of the existing untreated or treated drinking water supplies, it does not necessarily guarantee the safety of the recycled water (Rodriguez *et al.* 2009).

Overall, cascading and recycling would totally reduce water withdrawal from external sources by 72%. In order to increase water self-sufficiency, multisourcing should still occur by rainwater collection from hard surfaces.

Rooftop rainwater generally enjoys better quality than stormwater, and thus, its collection at source before it is mixed with other pollutants leads to more efficient use of available water (Domènech 2011). The rainfall data for the period (1982–2017) was used to quantify the rainwater harvesting potential (RWHP) in Mashhad. The value of CV for annual rainfall was estimated to be 28%, indicating moderate variability in rainfall. Average annual rainfall depth in the normal, drought and wet years of Mashhad is 246.76 mm, 192.95 mm and 331.08 mm respectively. Suppose 35% of water, on average, is lost from the rooftop catchments, due to factors of roofing material texture, evaporation, surface retention, and inefficiencies in the collection process, 9.6 mcm, 8.6 mcm, and 14.7 mcm water annually in the normal, drought and wet years can be collected from the 6,845 ha residential, commercial and public buildings' rooftop catchments available in Mashhad, and on average, it would replace 5% to 9% of Mashhad's annual water consumption, although it is subject to the suitability of all the roofs for rainwater collection and the existence of adequate space for installing groundwater storage reservoirs. Monthly CV values (estimated to be 95% for normal years, 82% for drought years and 87% for wet years) demonstrate that there is a strong seasonality in rainfall which could highly influence need and design for rainwater collection in Mashhad. Maximum RWHP occurs from January to May and it hits a peak in March. Rainwater collected from rooftops can be used for domestic outdoor use such as yard cleaning and watering lawns and gardening. In the rainy months, it exceeds domestic outdoor demand and the opposite happens in the months with few rainy days (Figure 4). The rainwater collected from residential rooftops would replace 75% to 115% of outdoor water use at household level and contribute to from 5% to 8% savings in Mashhad's water consumption in total. Irregular distribution of rainfall resulting in several consecutive rainy days and little precipitation during the rest of the year makes storage necessary in normal and drought years to meet parts of the household outdoor water demand in dry seasons. The rainwater collected

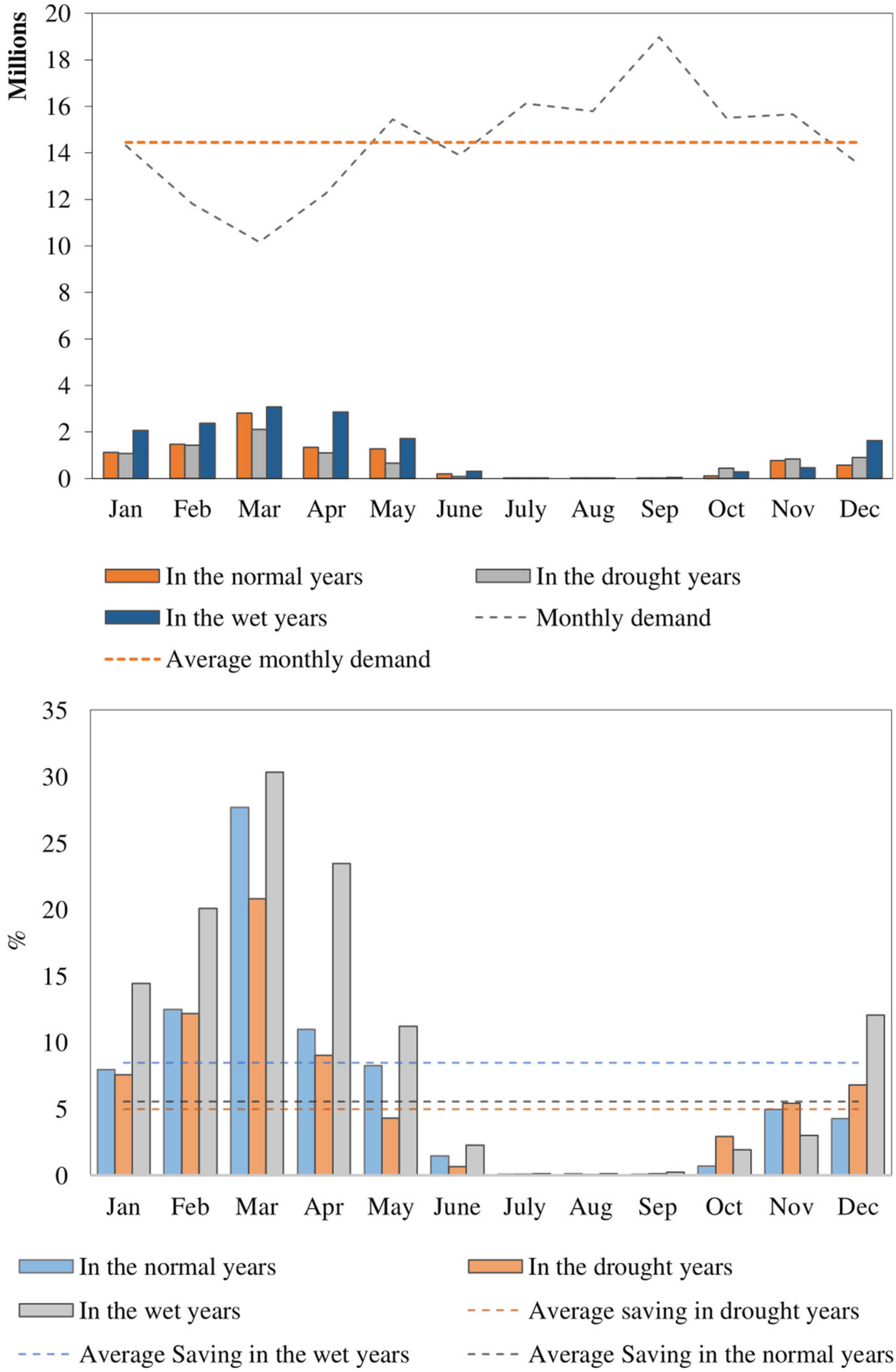



Figure 4. (a) Monthly demand and rooftop RWHP in the wet, drought and normal years. Water saving resulting from rooftop rainwater collection in different scenarios +.

from non-residential buildings could also substitute from 10% to 18% of water use in commercial and administrative buildings and reduce water imports by 1.2% to 2.1% in total.

Rainwater collection from rooftops for watering and irrigation uses has recently been considered as a solution to increase water self-sufficiency and tackle the water scarcity issue facing Mashhad city, and local authorities have begun to implement legislation regulating rooftop rainwater harvesting and have provided appropriate incentives to increase public participation in rainwater collection. Although rainwater collection from rooftops can improve water self-sufficiency and contribute to water conservation, it is more energy intensive compared with conventional water supply. Reviews of empirical studies on energy intensity of rainwater harvesting systems conducted by Retamal, Turner, and White (2009) and Vieira *et al.* (2014) show that the median energy intensity of such systems ranges from 1.4 kWh/$m^3$ to 1.5 kWh/$m^3$, which is three times as high as that of conventional water supply systems (0.5 kWh/$m^3$) in Mashhad, although the amount of energy use can be reduced by optimizing rainwater harvesting system configuration and operation (see: Vieira *et al.* 2014). Furthermore, it may be cost-burdened to individual households, as in arid regions, the occurrence of several consecutive rainy days and little precipitation in the rest of the year means a large amount of spending on developing infrastructures to harvest and store water while some of this equipment may not be used for most of the year. Little annual precipitation and irregular distribution of rainfall throughout the year are also reasons why stormwater reuse practices have not often received much attention in arid regions like Iran. Stormwater capture projects are generally divided into three main categories depending on size and use, including centralized recharge systems capturing stormwater in large infrastructure systems; distributed or neighborhood stormwater recharge systems (e.g. green street, park retrofits, and dry wells); and distributed systems for direct on-site use employing tanks and cisterns. Due to the asynchronous nature of rainfall, cisterns are impractical in arid regions, as for stormwater systems with seasonal or intermittent flows, large storage in order to store large amounts of water for six to eight months in dry seasons is required, and consequently, infiltration techniques seem to be the best choice for stormwater management practices in such regions (Luthy, Sharvelle, and Dillon 2019; Gautam, Acharya, and Stone 2010). However, urban stormwater for groundwater recharge, particularly in arid and semi-arid regions where pollutant concentrations are expected to be higher than humid regions due to the low frequency of storms poses the risk of groundwater contamination, and thus, careful design and appropriate monitoring practices are essential (Gautam, Acharya, and Stone 2010; Andres, Ballestero, and Musick 2018). At present, lack of a regulatory framework and uncertainty in treatment and water quality targets are barriers to widespread adoption of urban stormwater for groundwater recharge in Iranian cities, Mashhad is included. Considering these facts, scenarios for Mashhad's future water supply are developed based on wastewater reclamation and rainwater collection on a small scale (from rooftops), as detailed in Table A.6 in the Appendix (online supplemental data).

### *4.4. Comparison with other case studies*

Due to differences in geography as well as scope, purpose and methodologies employed in different studies, direct comparison between case studies cannot be

Table 2. Comparison with other case studies.

| Type of source/City | Population density | Resource use intensity | Resource availability | Catchment surface area | Harvesting potential | Saving |
|---|---|---|---|---|---|---|
| *Energy* | | | | | | |
| Biogas | pop/ha | MWh/ha | $m^3$/tonne | – | MWh/ha | % |
| **Mashhad, Iran** | **88** | **143** | **192** | **-** | **14** | **10** |
| São Paulo, Brazil[a] | 14 | 11 | na | - | 5[b] | 45.5 |
| Oakland, United States[c] | 20 | 2.7 | na | - | 3.2[d] | 120 |
| Solar | pop/ha | MWh/ha | kWh/$m^2$ day | $m^2$/ha | MWh/ha | % |
| **Mashhad, Iran** | **88** | **143** | **5.3** | **343** | **85** | **59** |
| Lethbridge, Canada[e] | 8 | 64 | 3.8 | 191 | 24 | 38 |
| Newark, United States[f] | 42 | 0.6 | na | 99 | 0.082 | 14 |
| Mumbai, India[g] | 273 | 398.5 | na | 329.5 | 59 | 15 |
| Oeiras, Portugal[h] | 8 | 11 | na | na | 7 | 64 |
| Wageningen, Netherlands[i] | 35 | 126 | 2.7 | 1080 | 149 | 118 |
| *Water* | | | | | | |
| Rainwater (rooftop runoff) | pop/ha | $m^3$/ha | mm | $m^2$/ha | $m^3$/ha | % |
| **Mashhad, Iran** | **88** | **5,004** | **246.7** | **2,041** | **277** | **5.5** |
| Colombes, France[j] | 109 | 7,990 | na | 1,997 | 799 | 10 |
| Chittagong, Bangladesh[k] | 103 | 3,751 | 3000 | 1,578 | 750 | 20 |
| Enugu Town, Nigeria[l] | 53 | 31,857 | 169.1 | 7,069 | 956 | 3 |
| Wastewater | pop/ha | $m^3$/ha | – | – | $m^3$/ha | % |
| **Mashhad, Iran** | **88** | **5,004** | – | – | **3,601** | **72** |
| Bangalore, India[m] | 119 | 8,350 | – | – | 4,592.5 | 55 |
| Sydney, Australia[n] | 30 | 16,379 | – | – | 14,083 | 86 |
| Melbourne, Australia[n] | 20 | 10,637 | – | – | 8,383 | 79 |
| Perth, Australia[n] | 30 | 7,304 | – | – | 4,074.5 | 26 |

Note: na = not available.
[a]Nm de Souza *et al.* (2014).
[b]Considered landfill gas, incineration of municipal solid waste and incineration of refuse-derived fuel technologies for electricity generation.
[c]Shen *et al.* (2015).
[d]Considered anaerobic digestion technology in the wastewater treatment plants for electricity generation.
[e]Mansouri Kouhestani *et al.* (2019).
[f]Byrne *et al.* (2018).
[g]Singh and Banerjee (2015).
[h]Amado and Poggi (2014).
[i]Agudelo-Vera, Leduc, *et al.* (2012).
[j]Belmeziti, Coutard, and de Gouvello (2013).
[k]Akter and Ahmed (2015).
[l]Ezenwaji, Nzoiwu, and Eduputa (2016).
[m]Paul *et al.* (2018).
[n]Kenway, Gregory, and McMahon (2011).

straightforward. In order to make comparison of results possible, average tissue was applied as a standard unit or benchmark.

Differences between cities can be explained by differences in climatic and morphological or physical characteristics, such as characteristics of urban built form such as size, compactness, density, land use mix and characteristics of collective catchments such as slope and texture as well as socio-economic characteristics influencing resource consumption and production profiles of cities. For instance, Mashhad compared with Enugu Town receives 1.5 times greater rainfall but it has about three times smaller roof catchment area and a greater amount of losses from rainfall (35% compared with 20%) resulting in a smaller value for RWHP. However, a higher amount of water use in Enugu Town would contribute to a lower rate of water saving in total. Similarly, in comparison with Lethbridge and Wageningen, Mashhad receives 1.5 times and two times greater solar radiation and enjoys a two times larger and three times smaller catchment area, resulting in three times larger and 1.5 times smaller electricity yield respectively. In Mumbai, the higher amount of electricity consumption also contributes to a lower rate of energy saving. Other comparison results are summarized in Table 2.

## 5. Conclusion

This paper investigated the potential for energy and self-sufficient water provision in Mashhad. We explored the potential sources that are available within, or could become available from, the city when applying several harvesting strategies, including cascading, recycling, recovery and multi-sourcing using the method of UH. The results showed that biogas in combination with solar photovoltaic would completely meet Mashhad's annual electricity demand. Energy recovery from biomass, solid waste and municipal wastewater would yield 473 GWh/yr electricity, accounting for 10% of the total demand. The remaining 90% could be supplied by multi-sourcing achieved by solar energy harvesting when having solar PV systems installed on 17% of available rooftops, and 7% to 22% of current vacant lots, resulting in 4,495 GWh/yr in total. Water cascading and recycling could, in total, substitute 125 mcm of imported water annually and would enable the city to offset about 72% of its annual water consumption. Multi-sourcing by rainwater collection from rooftops would yield, on average, 9.6, 8.6 and 14.7 mcm/yr in normal, drought and wet years respectively, contributing between 5% and 8% to municipal water supply overall. Whether or not these goals are achieved depends on financial and technological feasibility and the ability to manage the potential risks. Only technical potential, given efficiency measures, land use characteristics and climatic constraints, were taken into account in this study with no consideration for costs, while cost-benefit analysis and environmental impact assessment are required to evaluate the sustainability and efficiency of the measures. Only electricity was addressed in this study while other qualities of energy such as heat and fuel should also be considered toward a 100% renewable energy city. In the case of water, related resource streams, including nutrients, organic matter and energy should also be addressed to achieve a comprehensive or an integrated solution to water resource scarcity and internalization of water supply. This study did not address urban stormwater as a suitable source for water supply in Mashhad firstly due to the asynchronous nature of rainfall highly influencing the viability of stormwater management practices such as cisterns, and secondly, due to legal, technological, structural, and economic impediments to successful implementation of practices such as infiltration. However, it is undeniable that stormwater could still be considered as a significant flow during wet seasons. It means that a holistic harvesting potential analysis for stormwater flow might provide better support for future planning in Mashhad. Demand minimization is also an important step in the transition to a circular regenerative system that has not been addressed in this study, whereas before any effort to produce more local sources, resource consumption should be reduced, and this can be achieved by changes in behavior, technological interventions and design practices. To improve accuracy, improved analyses of roof surfaces and improved data on urban land use and wastewater flows are essential. Analyses of daily rainfall data, typical hourly and daily electricity demand and the daily solar PV generation profile are also necessary for better planning. Our study highlighted the importance of urban gray surfaces in ecosystem services provision of water and energy and it practically showed how harvesting all resources that are available within city limits could serve the whole city at the same time, or at least enable the city to offset a large proportion of its annual consumption. We showed that there are several possibilities to reshape the environmental profile of resource consumption and production toward regenerative sustainability. The paper resulted in new findings helping decision makers in the future planning of Mashhad City by providing a basis for setting future design goals and creating policies facilitating redistribution of Mashhad's water and energy resource flows through redevelopment of the existing built environment. Although the existing structures will not be easily modified, at least the gray infrastructure can be effectively managed and retrofitted to boost the city's metabolic performance.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Supplemental data

Supplemental data for this article can be accessed here.

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