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LOCAL, REGIONAL AND GLOBAL BEST PRACTICE FOR WATER

Assessing water, energy and emissions reduction from water conservation measures in buildings: a methodological approach

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Abstract

Water-energy nexus is a cornerstone in modern societies, with significant impacts at social, environmental, and economic levels. In addition to the issue of water scarcity that several regions of the world already face or are forecasted to face in the near future due to demand increase and availability reduction (e.g. pollution, climate changes), water consumption in buildings entails substantial energy consumption. In most cases, part of this energy is produced from non-renewable sources, encompassing greenhouse gas emissions. The present research effort presents a generic methodology to assess the cascade impact of water efficiency measures in buildings in terms of water, energy and emissions reduction. The methodology is applied to the Mediterranean climate zone context for two different types of non-residential buildings: university buildings and hotels, with very distinct water end use and consumption patterns. Lastly, are performed sensitivity analyses between the proposed methodology and simplified approaches. Is observed that assuming a linear relationship between flow rate and water consumption can lead to overestimations of up to 64% in water savings. Is also explored the relevance of the water consumption and energy mix seasonality typical of climates with marked dry and wet seasons, such as the Mediterranean region. The importance of the seasonality is discussed in terms of the time scale considered to apply the methodology, revealing that adopting a simplified (annual) approach, instead of the proposed approach, can lead to relative differences between − 62 and 233% in the presented case studies.

Keywords Water efficiency · Water conservation · Buildings · Urban water cycle · Water consumption · Energy consumption · Greenhouse gas emissions · Carbon emissions

Introduction

The water-energy nexus

Climate changes and microplastics are examples that the effects of human activity on the environment are becoming global rather than local or regional. Within this context, a deeper understanding of the interlinks between human activities is required for understanding the causes, sources and underlying mechanisms and identify, assess, and implement the best solutions to tackle present and future challenges (Bauer et al. 2014). The inextricable intertwine between the water and energy sectors has received attention at various levels (e.g. individual researchers, organizations, governments) under the designation of "water-energy nexus".

The natural and extensive interlink between water and energy has been explored in various research efforts by addressing topics such as (i) water use for energy production and supply in electricity generation (Macknick et al. 2012; Zhang and Anadon 2013; Cai et al. 2014; Feng et al. 2014), oil and gas production (Mcintosh and Ferguson 2019) and total energy production (Cai et al. 2014; McNabb 2019); and (ii) energy consumption for water abstraction, treatment, end use, reclamation and disposal (Mo et al. 2014; Santana et al. 2014; Ananda 2018). The scale of these studies also varied, from worldwide (IEA 2016), nationwide (USDA 2014; Hardy et al. 2012), region wide (Khalkhali et al. 2018), citywide

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(Fang and Chen 2017) and building wide (Kenway et al. 2019) to a specific end use or technological solution (Retamal et al. 2009). Water and energy are two key basic resources used virtually in any modern human endeavour and these studies demonstrated (i) the strength of the relationship between water and energy and (ii) the cascade influence throughout the communities. They also reveal the context specificity of the topic despite being a global issue.

Within the context of climate changes, several researchers have also explored the additional connection with greenhouse gas emissions. The greenhouse gas emissions have been analysed in different components/stages of the water-energy nexus, both from the energy production (Karmellos et al. 2016; Ali et al. 2017) and water consumption (Zhou et al. 2013) perspectives, which brings another layer of complexity to the problem, since the greenhouse gas emissions will vary significantly depending on the sources of energy in the energy mix, making this problem even more context-specific.

In addition to the studies focused on establishing the present water-energy-greenhouse gas emissions scenarios in various contexts and scopes, there have been also some authors exploring the potential benefits from either water or energy efficient or cleaner solutions (Zou et al. 2016; Harmsen and Graus 2013; Wheatley 2013). Even if these research efforts contribute to the better understanding of the benefits of the studied actions, they tend to be context-specific and scope limited due to the growing degree of complexity that hinders analysing all aspects and dimensions of the water-energy-greenhouse gas emissions problem.

Environmental benefits from water efficient measures in buildings

State of art The European Union is paying particular attention to water and energy performance of buildings. On one side, the increasing population in the EU and the potential effects of climate change induce human pressure on water bodies (BIO Intelligence Service 2012); on the other side, buildings are responsible for about 40% of the energy consumption and 36% of the CO_2 emissions in the EU, making them the single largest energy consumer in Europe (EC 2019).

Considering the "energy for water" perspective of the water-energy nexus, it is observed that reducing water use in buildings would reduce the energy needs and GHG emissions, since energy is embedded in the water used (BIO Intelligence Service 2012). This energy is consumed directly in the building, in pumping or heating water, and indirectly, at the urban level, in the water and wastewater services.

According to Nair et al. (2018), from the total water-related energy use about 80% is associated with the end use stage and 20% with the urban stage, with the former mostly related with water heating. Additionally, in an average household in the European Union, 16% of the total energy requirement is to heat water, whilst in Australia is 23%.

However, most attention has focused on individual energy-intensive consumers, such as inter-basins transfers, energy-intensive water pumping or desalination (Escriva-Bou et al. 2015). This might be mainly because of the heterogeneity of the end users, ranging from a single household to a large 5 starts hotel.

A number of studies have been performed in the past 10 years focusing on water-energy or water-energy-emissions reductions linked to water efficient measures (Table 1).

Fidar et al. (2010), Beal et al. (2012) and Escriva-Bou et al. (2015) focused on different water efficiency scenarios in households in the UK, Australia and California, respectively, whilst Nair et al. (2018) developed the study in a University building, where the benefits of changing the existing conventional shower taps with non-concussive push taps and of accessing the shower room with a card were acknowledge. Instead of considering technical interventions, Willis et al. (2010) explored the benefits of behaviour change through the use of alarming visual display monitors, set to alarm when the water consumed in a shower event reached 40 l (i.e. based on a 5-min shower at a flow rate of 8 l/min).

Ward et al. (2011), Talebpour et al. (2014) and Valdez et al. (2016) focused on the benefits of using rainwater harvesting (RWH) systems. All of these studies focused on pressure-driven systems, in opposition to the not so common gravity systems. The first two studies were centred on RWH systems where treatment was not needed, whilst Valdez et al. (2016) considered different scenarios of water treatment (e.g. UV disinfection, chlorination). Due to the novelty of the theme, none of these studies explored the potential energy gains of RWH systems to offset their own energy consumption through emerging technologies that follow the principles of hydropower, harnessing kinetic energy from moving water to generate energy (Ward et al. 2012).

Lastly, the United Nations Framework Convention on Climate Change (NFCCC) presented a generic method to calculate the energy savings from low-flow devices (BIO Intelligence Service 2012).

However, context-specific or generic, all of these studies miss to take into account the seasonality of the energy mix that is not negligible in cases where the portion of renewable energies is significant. Consequently, the seasonality of the water consumption has also to be taken into account. In addition, only a small portion considered the energy consumed in the entire urban water cycle in their calculations, taking into account both the energy consumed directly in the building and indirectly in the urban water and wastewater systems. Lastly, Fidar et al. (2010) and the NFCCC approach considered a linear relationship between flow rate and water consumption in water saving devices, assuming no behaviour change.

Table 1 Literature review of the environmental benefits from water conservation measures: studied parameters

	Water efficiency measure	Effective water consumption reduction	Energy consumed in the building	Energy consumed in the urban systems	Seasonality of water consumption	Seasonality of the energy mix
Fidar et al. (2010)	Water efficiency scenarios	No	Heat water	Yes	No	No
Beal et al. (2012)	Water efficiency scenarios	No	Heat water, washing machine and dishwasher	No	No	No
Escriva-Bou et al. (2015)	Water efficiency scenarios	No	Heat water	No	No	No
Escriva-Bou et al. (2015)	Water conservation measures in the showers	Yes	Pump and heat water	No	Yes	No
Willis et al. (2010)	Alarming visual display monitors in showers	Yes	Heat water	No	No	*
Ward et al. (2011)	RWH system	–	Pump water	No	No	No
Talebpour et al. (2014)	RWH system	–	Pump water	No	No	*
Valdez et al. (2016)	RWH system	–	treat and pump water	Yes	No	No

*Not focused on the study of the GHG emissions

Research contributions In lack of a comprehensive methodological approach that can be applied to different contexts, the main contribution of this study is to propose a generic methodology to assess the environmental performance of buildings, due to defined water conservation solutions, aiming to help decision-making at a strategic level, namely through policy initiatives and management priorities.

The study focuses on the water, energy and carbon emissions reduction associated with water conservation measures, taking into account the following key parameters:

- Characterization of the effective public water consumption reduction with a specific water conservation measure.
- Characterization of the energy consumption reduction linked to water conservation measures taking into account the energy consumed in the entire urban water cycle.
- Characterization of the emissions reduction linked to efficient water measures taking into account the proper energy source and provider, along with the seasonality of water consumption and of the energy mix.

The manuscript ends with the discussion of the benefits of water conservation measures and the highlight of potential errors, consequence of usual simplifications.

Modelling approach

A methodological approach is proposed, which links the water savings from water conservation measures in buildings to the corresponding energy and greenhouse gas emissions reduction considering the specificities of the context. The methodology departs from the baseline that all the water consumed in the building comes from the public water supply network, and requires calculating: (i) the water savings from each water efficient measure (m^3); (ii) the energy reduction resulting from the water savings (kWh); and (iii) the greenhouse gas emissions reduction (e.g. g CO_2 for carbon emissions) resulting from the energy reduction.

Water reduction model

The quantification of the water savings can be estimated with Eq. (1). The equation represents a mass balance between the water consumption in each fixture or group of fixtures and the corresponding savings for each water conservation measure.

$$V_x = \sum_{i=1}^{n} \left[\sum_{j=1}^{12} \left(MC_j \times PC_i \times PR_i^X \right) \right] \quad (1)$$

where V_x is the potential for annual water savings due to water efficiency solution X (m^3); MC_j is the water consumption in the building in the jth month (m^3); PC_i is the water consumed in the ith fixture in percentage of the water consumed in the building (%); PR_i^X is the effective reduction of water consumption in the ith fixture due to the water efficiency measure X (%). The quantification of the water savings in this model considers the effective reduction on water consumption due to water conservation measures, bearing in mind a consequent behavioural change in users.

Whilst some water end uses can be strongly seasonal (e.g. Romero and Dukes (2016): irrigation), the proportion of the majority of the water end uses in buildings are roughly constant throughout the year. As such, in most cases, Eq. 1 may be simplified considering the total annual consumption and a constant end use breakdown. In practise, this may be the only option available since the generality of the water end use breakdown studies presented in the literature do not account for the seasonality and present only a split based on the total annual water consumption. Considering this limitation, Eq. (1) was simplified into Eq. (2) that can be used when only water savings are to be evaluated.

$$V_x = \sum_{i=1}^{n} \left(AC \times PC_i \times PR_i^X \right) \tag{2}$$

where $AC = \sum_{j=1}^{12} \left(MC_j \right)$, which is the total annual water consumption in the building (m^3); and PC_i is the water consumed in the ith fixture, in percentage of the total annual water consumption (%).

Water-related energy reduction model

Energy reduction can be estimated using Eq. (3), representing the energy balance associated to the water conservation measure X. This model accounts for the energy used in the entire urban water cycle: (i) direct energy consumed in the building, namely to heat or pump water; (ii) indirect energy consumption in the urban services, namely in water abstraction, treatment, end use, reclamation and disposal.

$$EE_x = \sum_{i=1}^{n} \left[\sum_{j=1}^{12} \left(MC_j \times PC_i \times PR_i^X \times EM_j \right) + \sum_{j=1}^{12} \left(MC_j \times PC_i \times PR_i^X \times EP_j \right) \right] + \sum_{i=1}^{n} \left[\sum_{j=1}^{12} \left(MC_j \times PH_i \times PR_i^X \times EH_j \right) \right] - EC_X + EG_X \tag{3}$$

where EE_x is the potential for annual energy reduction due to water efficiency measure X (kWh); EM_j is the energy intensity consumed to use 1 m^3 of water in the jth month (kWh/m^3); EP_j is the energy intensity consumed to pump 1 m^3 of water inside the building in the jth month (kWh/m^3); PH_i is the hot water consumed in the ith fixture, in percentage of the total annual water consumption (%); EH_j is the energy intensity consumed to heat 1 m^3 of water in the jth month (kWh/m^3); EC_X is the energy consumption of solution X (kWh); EG_X is the energy produced/gained with solution X (kWh). In Eq. (3) EP_j (and the corresponding entire parcel) is null when the water is supplied directly from the public system and no pumping is needed inside the building and EH_j is null when only cold water is used. Any energy, and EC_X in particular, can be seen as a direct energy consumption (e.g. energy to pump water from a rainwater harvesting reservoir to the supplied fittings) or as an embodied energy of any action inherent to the water supply (e.g. embodied energy of the chemicals used to treat recycled grey water).

The potential for energy reduction from a water conservation measure may vary throughout the months of a year and between years depending on the sources used for public water supply and the water/wastewater treatment conditions. In California, groundwater accounts for a significant portion of the water supplied only between the months of April and October (CIEE 2010,b). Since the energy intensity to supply water varies depending on the water source, the specific energy is different each month. In CIEE (2010,b) is also demonstrated the influence of the water year in the water sources contributions. In most regions of California, dryer years require larger proportions of groundwater supply to replace the reduction on the local surface water available.

Water-related GHG emissions reduction

The greenhouse gas (GHG) emissions reduction due to a water conservation measure can be estimated using Eq. (4), which links the energy savings with the GHG emissions taking into account the energy source (e.g. electricity, coal) and the energy provider, in order to consider the proper energy mix.

$$GE_x = \sum_{i=1}^{n} \left[\sum_{j=1}^{12} \left(MC_j \times PC_i \times PR_i^X \times EM_j \times GHG^S{}_j \right) + \sum_{j=1}^{12} \left(MC_j \times PC_i \times PR_i^X \times EP_j \times GHG^P{}_j \right) \right] + \sum_{i=1}^{n} \left[\sum_{j=1}^{12} \left(MC_j \times PH_i \times PR_i^X \times EH_j \times GHG^H{}_j \right) \right] - GHG_X \tag{4}$$

where GE_x is the potential for annual GHG emissions reduction due to water efficiency solution X (e.g. GHG_{CO2}^X in g CO_2); GHG^S_j, GHG^P_j, GHG^H_j are, respectively, the GHG emissions due to the consumption of 1 kWh of energy in the jth month with the use of water from the public system, the pumping of water inside the building or the heating of water inside the building; and GHG_X are the GHG emissions of solution X. Note that the GHG emissions due to supplying water from the public system and the GHG emissions due to pumping water inside the building or heating water are only different when the energy source is different (e.g. electricity, diesel, coal, natural gas) or when is supplied from different companies (S, P and H, respectively) with different energy mixes. In addition, if the energy consumed in the public part of the urban water cycle comes from different energy sources or suppliers, this mix should be taken into account in Eq. (4).

Material and methods

Case study The model is implemented to Portugal, to illustrate the specificity of the Mediterranean context. In this country, the urban water consumption accounts for only 8% of the total volume of water consumed per year, with agriculture representing the largest share accounting for 87%. However, urban water consumption is responsible for 48% of the total annual water costs due to the infrastructure needed and resources spent on water treatment and supply (PNEUA 2012). If the urban water savings have limited benefits in terms of the water balance in Portugal, the benefits of water efficiency in buildings considering the water-energy nexus is strongly acknowledged in PNEUA (2012). Water consumption in buildings makes up the largest share of urban water consumption and the energy used in the urban water cycle is a significant driver of the water costs, representing 6–18% of the energy consumption in Portuguese cities (PNEUA 2012). In PNEUA (2012), the energy used for pumping or heating water at a building level or for collecting and treating wastewater is not accounted for, neither the costs with the greenhouse emissions, meaning that the potential benefits are even higher.

With no resources in terms of non-renewable energy sources (e.g. coal, oil or gas) and to meet the emissions goals set in the European Union, Portugal has made an effort to use its renewable energy resources, in particular, water, wind and sun. However, with a Mediterranean climate, characterized by marked wet and dry seasons, the contribution of the renewable sources to the energy mix varies significantly throughout the year. The energy mix dictates the emissions, resulting in substantial differences between dry and wet seasons.

To assess the influence of the water utilities context variability, five cities in five regions spread from north to south of the mainland territory were considered: (i) North Region: Gondomar; (ii) Centre Region: Aveiro; (iii) Lisbon Region: Cascais; (iv) Alentejo Region: Beja; (v) Algarve Region: Portimão. These cities are serviced by distinct and independent water utilities operating in different contexts and with diverse operational efficiency, resulting in distinct energy intensity data for the urban water cycle. They cover most of the Portuguese mainland territory, where the large majority of the population lives, and where most of the water is consumed. The cities were selected to capture a wide range of contexts for the water utilities, from predominantly rural (Beja) to mostly urban (e.g. Cascais), from concentrated population (e.g. Cascais) to dispersed (e.g. Aveiro), from mountain topography (e.g. Gondomar) to flatlands (e.g. Aveiro), from locally water abundant (e.g. Gondomar) to water scarce (e.g. Portimão), from highly touristic (e.g. Portimão) to mostly residential (e.g. Beja). The largest cities, Lisbon and Porto, were excluded because they are relatively unique in the Portuguese context and their comparison with other cities would be misleading.

Finally, to illustrate the relevance of the water consumption seasonality when estimating the GHG emissions reduction from water savings, two types of buildings were analysed: university buildings and hotels. These two types of buildings show opposite water consumption patterns, with the university buildings having lower water consumption during the summer months, whilst the hotels have the highest water consumption on those months. Also, hot water consumption in the majority of the university buildings in Portugal is minimal or non-existent. On the other hand, hotel buildings present high proportions of hot water consumption.

Methods The following steps allow the application of the generic model to the water conservation solution x:

Step 1 (water reduction): (i) determination of the baseline monthly distribution of water consumption in the building, MC_j; (ii) determination of the portion of water consumed in the building in each fixture (in %), PC_i; (iii) determination of the percentage of water reduction in each fixture with the water conservation measure, PR_i^x; (iv) calculation of the water savings through Eq. (1).

Step 2 (energy reduction): (i) determination of the energy needed to use 1 m^3 of water from the water utility and dispose in the urban wastewater system (values obtained from the water and wastewater utilities) in each month, EM_j; (ii) determination of the energy necessary to pump 1 m^3 of water inside the building (consumption obtained measuring the operation of the pump), EP_j; (iii) determination of the energy necessary to heat 1 m^3 of water inside the building (consumption obtained measuring the operation of the water heater), EH_j; (iv) determination of the annual energy consumed by solution x, EC_x; (v) determination of the annual energy produced by solution x, EG_x; (vi) calculation of the energy savings through Eq. (3).

Step 3 (emissions reduction): (i) determination of the energy source(s), provider(s) and energy mix (es) of the energies, EM_j, EP_j, EH_j, and EC_x; (ii) calculation of the emissions of the energies presented in (i), respectively GHG_i^S, GHG_i^P, GHG_i^H, and GHG_x; (iii) calculation of the emissions savings through Eq. (4).

Results

Water

Baseline water consumption

University building The Department of Civil Engineering of the University of Aveiro (DECivil), Aveiro, was selected to represent a typical water end use pattern in a university building in Portugal with water consumption predominantly in WCs. The community in the DECivil building is composed of roughly 300 individuals, mostly students, but also researchers, professors and administrative and lab workers. The building has several water consumption points, namely the WCs (accounting for 70% of the total water consumption) and the laboratory (accounting for almost 30% of the total water consumption). The building cleaning services consumes a minimal amount of water.

The implementation of the methodology is focused only on WC water consumption, not only because it is the most water consuming area in the building but also because it has domestic uses that can be compared between different types of buildings.

The option for this building was due to the previous studies by Meireles et al. (2014, 2017), providing not only detailed water consumption and end use patterns, but also measured water consumption reduction due to the installation of aerators in the WCs washbasins.

Since the middle of 2010, the water consumption measured in the DECivil building through a totalizer water metre has been recorded at an hourly rate by telemetry. So, the total water consumption in the DECivil building was retrieved from the records between 2011 and October 2016. From November 2016 onwards, a water audit in the building contributed to sequential changes in the discharge patterns of the fixtures, making those values not comparable with the previous.

In order to transform the hourly water consumption data into a monthly basis, certain assumptions had to be considered to circumvent missing records situations. These missing records situations did not imply a loss of water measurement but simply a larger time interval between measurements. When the telemetry system failed to register water consumption at an hourly rate, then it recorded the total water consumed since the last measurement. So, when a gap on the water records of more than 7 days existed in the beginning or the end of a month, the corresponding month was excluded from the analysis. In all of the other situations an expert analysis was performed to distribute the recorded volumes of water through the corresponding periods of time. The records of the years of 2013, 2014 and 2016 allowed taking into account all the months. In the contrary, 2011, 2015 and 2012 presented 10, 9 and 3 months of reliable data.

The average monthly water consumption distribution in the DECivil building between 2011 and 2016 is presented in Fig. 1, along with the maximum and minimum values per month, and the total annual volumes. The annual water consumption decreased 13% between the first and the last year of the studied period, reflecting the reduction on the number of students enrolled in the Civil Engineering degree from 2012.

The monthly consumption pattern accompanies the academic calendar and the expected affluence of users. August, which corresponds to the summer holidays, is observed to have the minimum water consumption, with the lowest record of 7.33 m^3 in 2013. The two maximum values registered took place in March 2014 (91.49 m^3) and in April 2015 (85.42 m^3) which correspond to periods in the middle of the summer semester (not far from the registered 74.85 m^3 in November 2015, the maximum in the second half of the year, which falls into the middle of the winter semester), where classes take place. In addition to that, there may also have been more intense laboratory activities, as well as sporadic events organized in the department that lead to these occurrences.

The water end use breakdown measured by Meireles et al. (2014, 2017) was used to estimate the amount of water consumed in each WC fixture (Fig. 2). The six main WCs of the DECivil building (three for female users and three for male users) have 14 washbasins, equally distributed between the female and male WCs, 11 flush toilets (6 for female users and 5 for male users) and 10 urinals, that contribute for 12%, 51% and 8% of the total water consumption in the building, respectively.

The baseline situation consisted on the existing laminar flow push taps with an average flow rate and shut off time of 6.7 l/min and 6.1 s, respectively, corresponding to an average water consumption of 0.85 l per use, and manual push flush toilets and urinals with discharged volumes of 7.24 l and 1.53 l per use, respectively.

The baseline water consumption in the university building is the one presented in Fig. 3, irrespectively of the building's location, since it is considered that the users' behaviour does not change with climate within mainland Portugal.

Hotel For the five different regions, travelBI (2016) presents the average occupancy rates of hotels in 2015 (Fig. 4, left). Soares (2010) presents the occupancy rates for the Hotel Vila Galé Porto, in 2009, which are consistent with travelBI (2016) (Fig. 4, right), although always higher since respect to a hotel in the centre of Porto, one of the main destinations for tourism in Portugal in the last years.

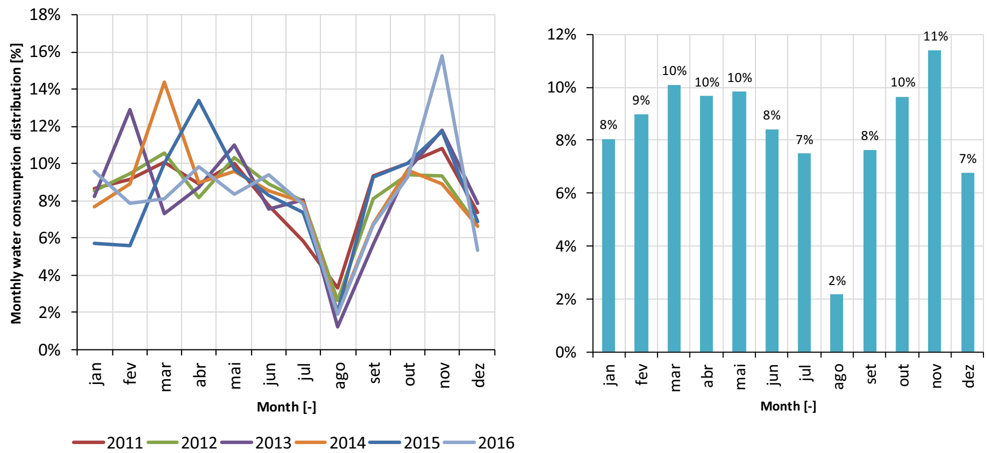


Fig. 1 Monthly water consumption pattern in university buildings: yearly differences (left), on average (right)

The hotel Vila Galé Porto was consequently selected to represent a typical hotel in Portugal. This 4 stars hotel is located in the centre of Porto and possesses 292 guest rooms.

According to JRC (2013a), the primary determinant for water consumption in showers, toilets and washbasins, laundry processes and kitchen processes is the number of overnight guests. In the contrary, "fixed" water uses (e.g. pool maintenance and irrigation of green areas) can make water use per guest night (in those processes) inversely proportional to occupancy rate. However, in accordance to ITP (2014), the former uses amount to over 70% of the total water consumption and the latter to less than 10% in Mediterranean climate zone hotels. This allows to assume a direct relationship between occupancy rate and water consumption and to estimate a monthly water consumption distribution from the total annual water consumption data (Fig. 5).

The left side of Fig. 6 illustrates a typical constitution of water consumption in hotels located in the Mediterranean climate zone, obtained from a fully sub-metered 270-room hotel in Lisbon, Portugal, with total annual water consumption of 51,276 m^3 (819 l per guest) (ITP 2014). The right side of Fig. 6 presents the distribution of water consumption in a guest room (JRC 2013a) in cold and hot portions of water in each of the installed fixtures.

From the distribution presented in Fig. 6, the baseline water consumption in the hotel is computed. Contrarily to the university building, water consumption changes from city to city due to differences in the occupation rate (Fig. 7).

Water consumption reduction The water conservation measured considered in this case study is the retrofit of the water fixtures located in the WCs.

To perform the calculations, only the consumptions of water in the year of 2015 were considered. This option does not allow assessment of the influence of the interannual variability but (i) the water consumption in the DECivil has decreased with the reduction of the number of enrolled students and the water audit and consequent changes implemented after 2015 may have modified the water end use pattern; and (ii) considering the boom in the tourism sector in Portugal in the last years, extrapolating the occupancy rates to other years might entail significant error.

University building The retrofit scenario assumes the installation of aerators (flow rate of 2.0 l/min), dual flush cisterns and flush-free urinals, contributing to, respectively, 0.43, 3.5 and 0.0 litres of water per use.

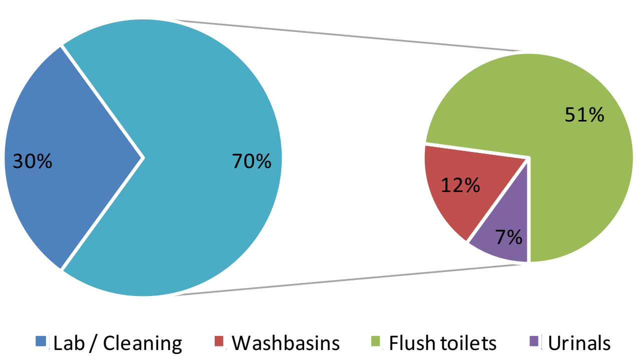


Fig. 2 End use water consumption distribution in university buildings: by areas (left), by fixtures in the WCs (right)

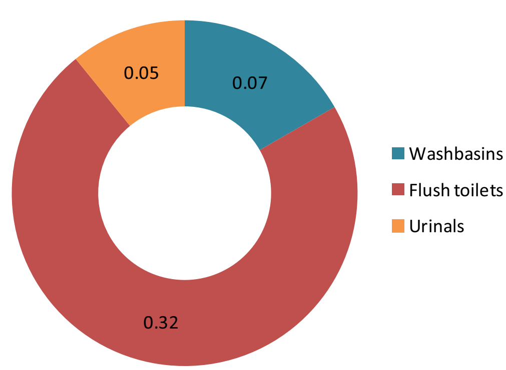


Fig. 3 Baseline end use water consumption (in thousand m^3): university building.

	North	Centre	Lisbon	Alentejo	Algarve
jan	25%	16%	33%	15%	16%
fev	29%	22%	39%	20%	26%
mar	37%	24%	48%	25%	33%
abr	44%	29%	61%	28%	42%
mai	51%	34%	66%	30%	48%
jun	53%	37%	65%	41%	62%
jul	59%	42%	70%	47%	77%
ago	73%	60%	78%	66%	83%
set	62%	45%	72%	47%	65%
out	50%	35%	64%	32%	48%
nov	34%	23%	44%	23%	23%
dez	31%	22%	37%	19%	17%

Source: travelBI (2016)

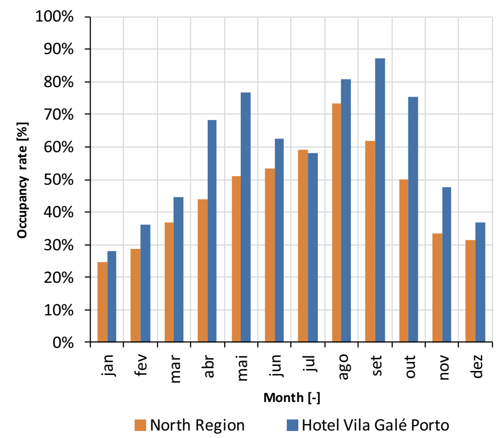


Fig. 4 Occupancy rate: average values in the 5 regions of mainland Portugal in 2015 (left), comparison between North Region hotels in 2015 and Hotel Vila Galé Porto in 2009 (right)

The water consumption reduction in the washbasins was measured during two subsequent academic years. The measurements were done resorting to in situ campaigns based on questionnaires and direct observation (Meireles et al. 2014, 2017). The efficiency due to the use of dual flush toilets depends on both the discharge reduction and the proportion of full and reduced discharge uses. The average flush volume of 3.5 l per use in dual flush toilets was set by JRC (2013b) as the target to fulfil the proposed Ecolabel criteria, being considered in the calculation of the average flush volume a proportion of 3 reduced discharges per full discharge. Flush-free urinals eliminate the need for water. In order to calculate the use of water in the flush toilets, the use frequency of flush toilets and urinals is considered unchanged in the building. Figure 8 presents the corresponding potential of water consumption reduction of the different devices.

Figure 9 presents the effective savings estimated for the university building in the five cities. Since the only difference in the simulation is the energy intensity of the urban water cycle in the different cities, the water savings are equal in all cities.

Hotel The water benchmarks for luxury fully serviced hotels provided by ITP (2014) for water consumption per overnight guest presented in the left side of Fig. 10 were used in this study although the intervals are less stringent than those presented by Cobacho et al. (2005). The benchmark results fall into three categories: (i) excellent—the best that typical hotels could expect to achieve; (ii)

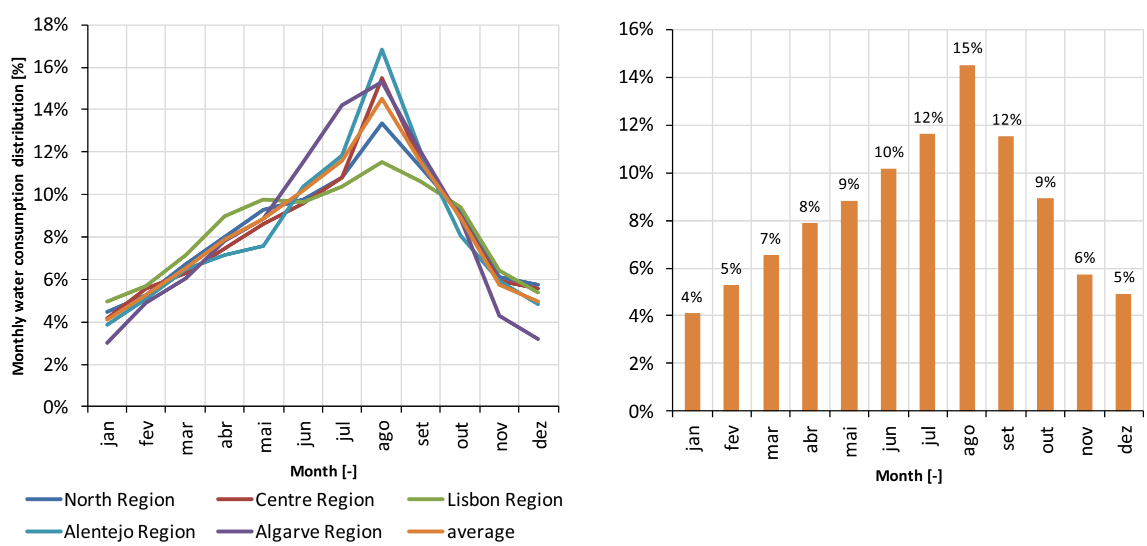
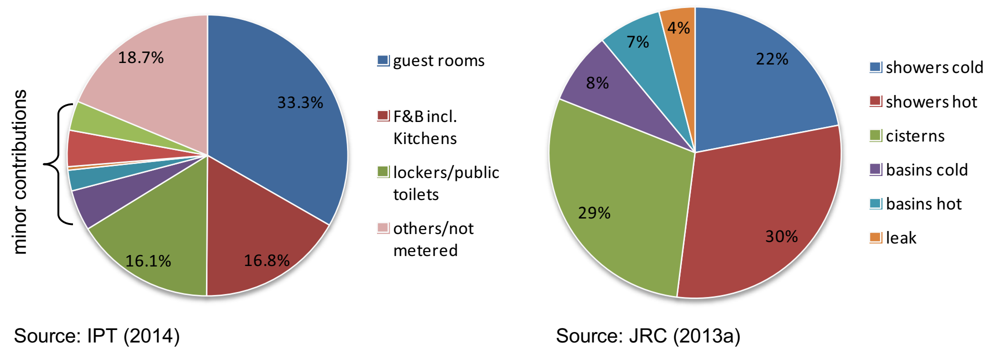


Fig. 5 Monthly water consumption pattern in hotels: regional differences (left), on average (right)

Fig. 6 End use water consumption distribution in hotels: by hotel areas (left), by fixtures in guest rooms (right)



satisfactory—the gap between the best and average performance; (iii) high—the gap between the satisfactory level of performance and high consumption. Consumption greater than this last value is considered excessive by ITP (2014), illustrating poor resource management practises.

The potential of water savings in a hotel can, then, be considered as the difference between high and excellent water consumption (Fig. 10, left), which corresponds to savings of about 50% in any climate zone (Fig. 10, right). This assumption is in accordance with findings from JRC (2013a), being water-inefficient hotels able to typically reduce water consumption by over 50%, mainly through relatively simple and inexpensive installation of water efficient fittings which have a relatively high frequency of replacement.

The implementation of the methodology is focused only on guest rooms, since it is the most water-consuming area in the building, and also where domestic consumption exists. In this regard, it is considered a potential reduction of 50% in the water consumed in the guest rooms.

Figure 11 presents the savings estimated for the hotels in the five cities. The differences in terms of water savings result from distinct average occupancy rates in the cities.

Energy

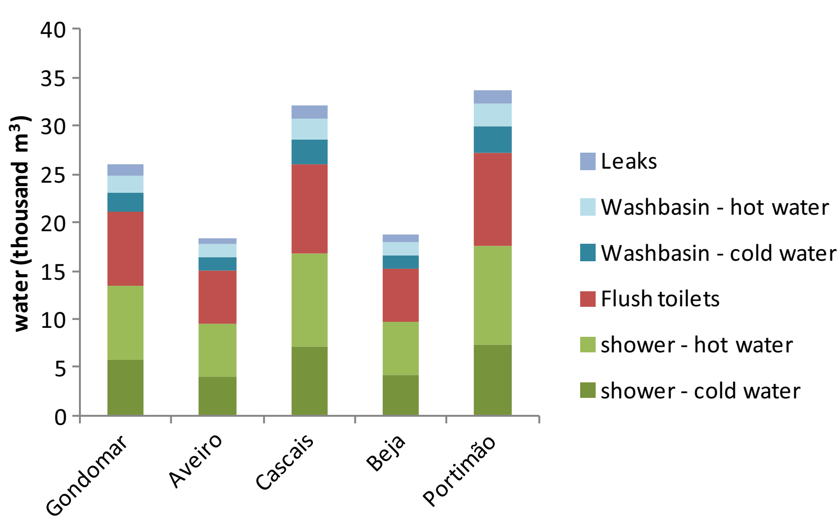
Energy mix

Since the most common option for the urban water cycle is to use electricity from the public electrical network, the energy mix of the electric energy provider is considered.

Nowadays, the electrical market in Portugal is liberalized and has several players. However, the information about the share of each energy provider to the water utilities is unavailable. Since EDP–Energias de Portugal has the biggest market share, a scenario of 100% of energy provided by *EDP* was considered. This option may entail some bias due to the difference on the energy mix from the various retailers operating in Portugal. However, the energy mixes are not so distinct and, considering the monthly uncertainty in the energy sources, it is possible to assume that the effect of such bias is negligible.

EDP generates electricity through different technologies and primary energy sources that can be renewable or non-renewable (also called traditional sources). Electricity from traditional sources is produced by burning fossil fuels (coal and natural gas) in nuclear reactors (imported) and through

Fig. 7 Baseline end use water consumption: hotel



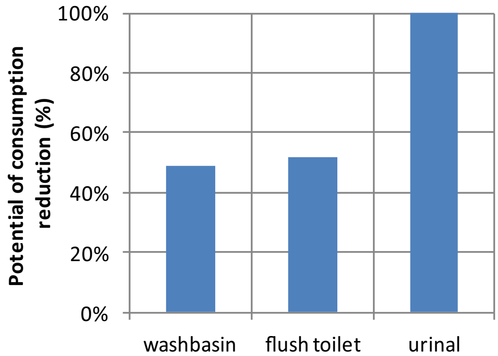


Fig. 8 Potential of water consumption reduction

cogeneration. Water, wind and sun are the most common renewable generation sources.

The information on the energy sources and the corresponding carbon emissions from electricity production between 2008 and 2017 were obtained from *EDP* reports. Figure 12 presents the evolution of the relative weight of the clean (blue scale) and non-clean (brown scale) energy sources in the energy produced by *EDP*. Clean energies are understood as CO_2, SO_2, NO_X and radioactive waste–free. The annual distribution of energy shows a clear trend towards an increase in clean energy sources, reflecting the commitment to the Sustainable Development Agenda. The largest change occurred between 2008 and 2011, with an increase in clean energy sources from 26 to 60%. For that reason, and since the energy sources classification defined by the regulator (ERSE–Entidade Reguladora do Sector de Energia) also changed in 2011, the monthly energy source distribution includes only data from 2011 to 2017 to avoid bias due to the energy sources distribution in the previous years.

The year of 2009–2010 represented an important mark in the energy sector in Portugal. On one hand, the wind energy capacity growth stabilized after increasing from little over 500 MW in 2004 up to almost 4000 MW in 2010. In 2016, the installed capacity was 5300 MW, implying that it is still growing, but at a lower rate. On the other hand, the start of the natural gas turbines in the Lares and Pego power plants in 2009 and 2010, respectively, and the closure of the Barreiro power plant in 2010 represented the "virtual" closure of the fuel-oil power plants and reduced the relative weight of the coal power plants in the energy mix. These investments result from a national strategy for the energy sector that is driven by internal and external factors of various natures (e.g. political, economic, environmental) and their modelling falls outside the scope of the present research.

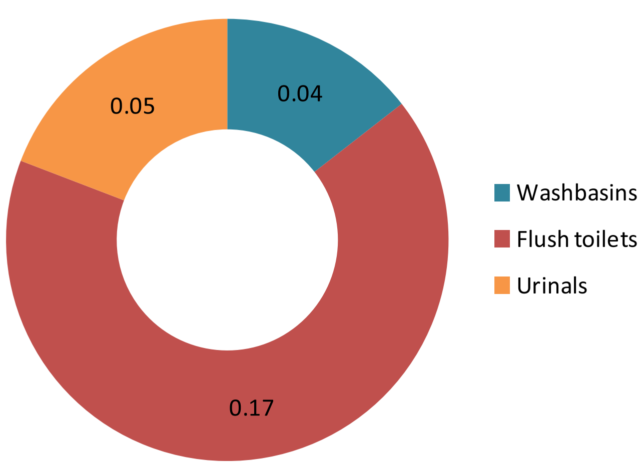


Fig. 9 Potential for water reduction from water efficient fixtures (in thousand m^3): university building

Between 2011 and 2017, the clean energy sources weight varied between 60% and 75%. Part of this variation is due to investments in other clean energy sources in addition to wind power. In the fourth quarter of 2011, *EDP* kicked-off operations at Picote II and Bemposta II, two power increase investments totalling 437 MW. In December 2012, *EDP* started up operations at Alqueva II (a 256 MW power plant with pumping). In 2015, *EDP* started operating the dam of Ribeiradio/Ermida (82 MW) and, in 2016, the dams of Salamonde II (223 MW) and Baixo Sabor (151 MW). In 2017, Venda Nova III (780 MW) and Foz-Tua (263 MW) new power plants started operating. These new power plants were built in existing dams to increase the installed power and used reversible groups to pump water using the excess of wind energy during the night. Therefore, their contribution to the energy mix is more related to the performance of the wind energy generation, which power was mostly installed until 2011. Therefore, for the scope of the present study, it was assumed that the variations in the energy sources distribution between 2011 and 2017 were mainly due to weather and consumption conditions.

Further investments are expected, such as the construction of the Daivões dam in the Tâmega River (118 MW) scheduled to be concluded in 2020. In 2017, *EDP* also completed the process of decommissioning the Energy cogeneration plant and continued the deactivation of three other thermal generation facilities, namely Carregado, Setúbal and Tunes, respecting the plan submitted to the Portuguese Environmental Agency. The continuous investments are changing the energy mix and affect the results obtained in the present research. Still, the methodology can be replicated to account for new contexts.

Baseline energy consumption

Water and wastewater urban services In mainland Portugal, the government has supported the creation of a corporate management structure led by *Águas de Portugal* in partnership with the municipalities, which results in unique solutions of management in each municipality. Usually, different companies manage the drinking water abstraction and treatment and wastewater treatment at the regional level ("bulk" utilities) and the water distribution and wastewater collection and

Climate zone	Water consumption (m^3 per overnight guest) Excellent	Satisfactory	High
Temperate	<0.3	<0.45	<0.7
Mediterranean	<0.4	<0.6	<0.8
Tropical	<0.8	<1.0	<1.4

Source: IPT (2014)

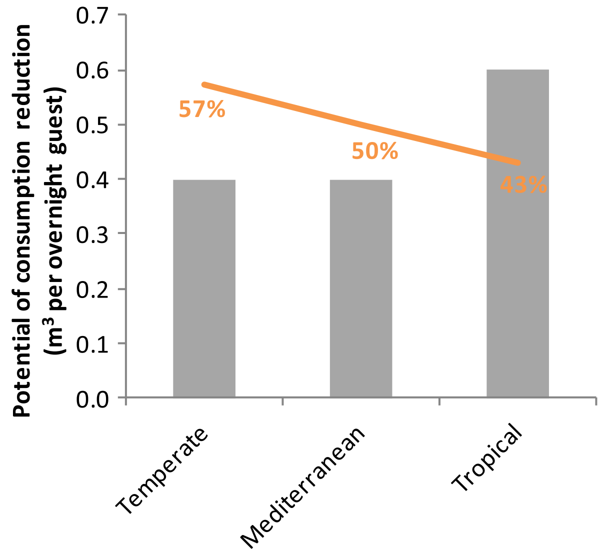


Fig. 10 Water consumption in hotels per climate zone: levels of consumption (left), potential of reduction (right)

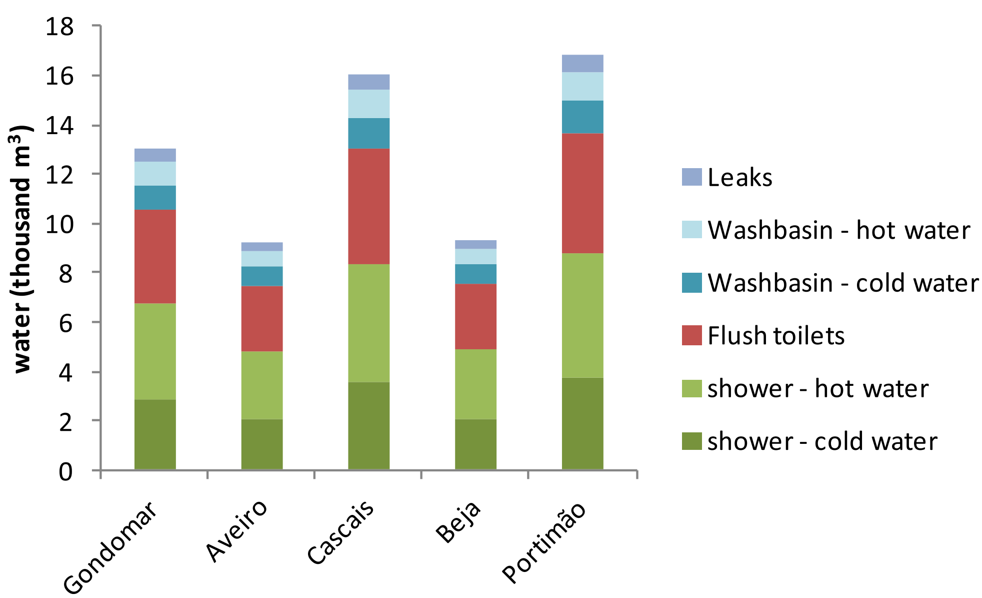
drainage at the municipal level ("retail" utilities). A similar model can also be found in Australia (Barraqué et al. 2015).

The energy consumption in the urban water cycle of the five cities, managed by different water and wastewater utilities (North Region: *Águas do Norte* + *Águas de Gondomar*; Centre Region: *Águas do Vouga* + *AdRA* + *Águas do Centro Litoral*; Lisbon Region: *EPAL* + *Águas de Cascais* + *Águas de Lisboa e Vale do Tejo*; Alentejo Region: *AgDA* + EMAS de Beja; Algarve Region: *Águas do Algarve* + *EMAR de Portimão*), was obtained from ERSAR (http://www.ersar.pt/pt), entity that regulates and supervises the public water supply and urban wastewater sanitation sectors in Portugal.

Data from 2011 to 2016 are publicly available and include all different stages in the urban water cycle, namely the abstraction, treatment and distribution of potable water, and the drainage, treatment and disposal of wastewater. The energy intensity for the water supplied in each city was calculated based on the weighted sum of these two components and referenced to the unit volume of potable water supplied. This implies that the energy consumption reported herein includes the losses in the water system and the infiltration/inflows in the wastewater system.

The data on the annual volumes of supplied water (which includes billed and unbilled water), and the corresponding energy intensity, are presented in Fig. 13 for the case of *AdRA*, as an example. Similar patterns were found in the remaining utilities, revealing that the specific energy consumption has remained relatively constant since 2011. The year of 2017 was not included since the report was not available when this research was carried out. It should be noted that unbilled water

Fig. 11 Potential for water reduction from water efficient measures: hotel



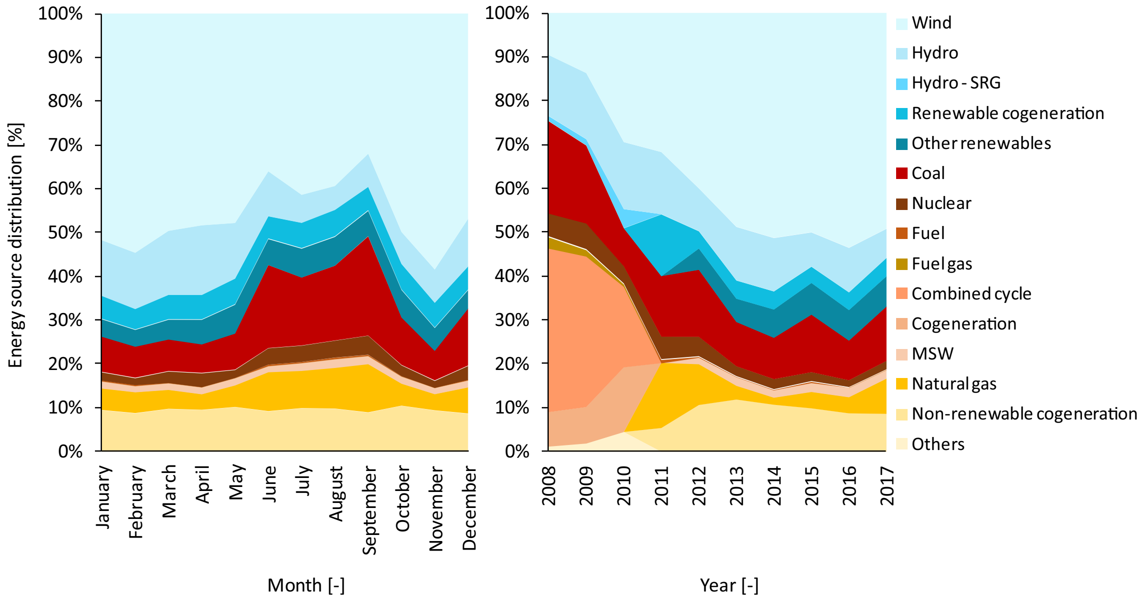


Fig. 12 Distribution of *EDP* energy sources at monthly (left) and annual (right) time scales

includes illegal abstractions, losses and leakages. The energy consumption is linked to the activities in the entire urban water cycle under the responsibility of *AdRA*, comprising mostly water distribution and wastewater collection. Water abstraction and treatment is mostly provided by *Águas do Vouga* and the wastewater treatment and disposal by *Águas do Centro Litoral*. A constant annual energy intensity was considered due to the lack of monthly information for all utilities.

The fluctuation on the volume of water supplied and on the energy intensity is due to the interconnected dependence on several variables that are unpredictably changing over time, namely (i) consumers habits that change and that are often a reflection of the economic situation; (ii) the water losses due to network deficiencies and the repair and maintenance operations implemented to tackle them; (iii) the affluence of undue flows in the periods of intensive precipitation; or (iv) the need to resort to underground abstraction in dry years.

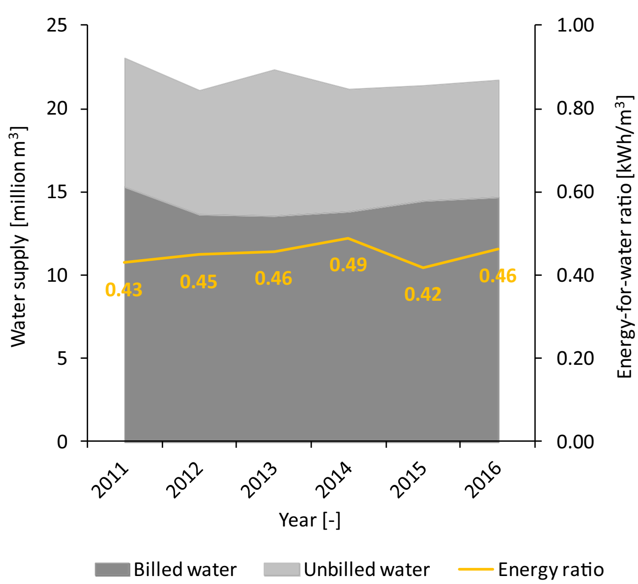


Fig. 13 Annual water supply and energy intensity at *AdRA*

Although the urban water cycle energy intensity has remained constant throughout the years, there is an ongoing trend for replacing local water abstraction (by "retail" utilities) by centralized water abstraction (by "bulk" utilities). A more recent initiative on energy efficiency in the water sector, started in the last years, may bring changes in the future. In this context, and considering the option taken for the water consumption, the energy intensity considered in this study reports only to the year of 2015.

Figure 14 presents the volumes of water supplied and wastewater drained and the corresponding energy intensity of the full urban water cycle for the five studied cities in 2015. It is interesting to notice that the cities in the regions further North and more water abundant (Gondomar and Aveiro) present higher energy intensities than the cities in the regions in the Centre (Cascais) and South (Beja and Portimão) of Portugal.

Baseline energy consumption In the university building, the baseline energy consumption depends only on the energy needed in the water and wastewater public services in each city, since no energy is needed to pump or heat water inside the building (Fig. 15, left). Since the flush toilets have the largest share of water, they are also the most energy consuming devices in the building.

The energy consumption in the hotel for the baseline depends on both the energy consumed by the public utilities and the energy needed to heat part of the water that is consumed in the washbasins and shower (Fig. 15, right). The energy

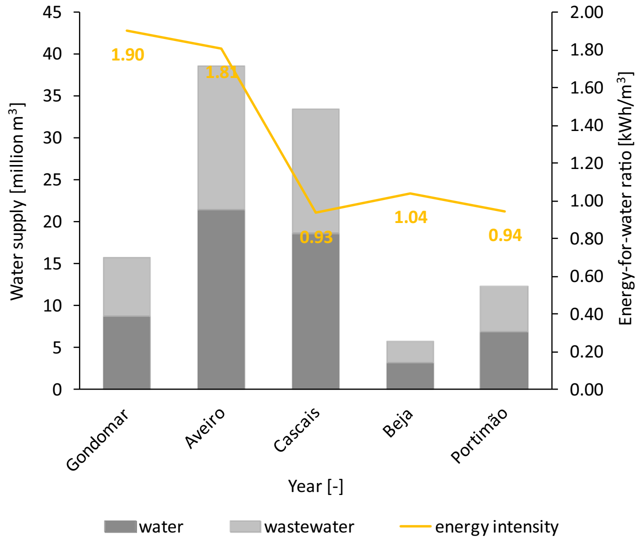


Fig. 14 Annual water supply and energy intensity in 5 different cities, in 2015

intensity of heating water is assumed constant for the five cities and equal to 52 kWh/m^3, which, according to JRC (2013a), is the amount of energy consumed for every m^3 of hot water consumed, assuming that water is heated by 45 °C. It is observed that comparing with the energy needed to heat water, the energy to flush toilets is marginal. This happens because the energy consumed per m^3 of supplied water in the public utilities (Fig. 14) is about 50 times smaller than the energy needed to heat water.

Energy reduction

Figure 16 presents the savings estimated for the university building (left) and the hotel (right), in the five cities, for the described water conservation measures, showing that the energy reduction patterns follow closely those presented for the baseline energy consumption. This allows us to conclude that in the university building the primary change should be focused on the flushing toilets and in the hotel on the water consuming devices (primarily showers, followed by washbasin taps).

Emissions

Specific emissions per kWh

The data on the amount of CO_2 emissions per kWh of electrical energy produced (Fig. 17) was also obtained from *EDP* and corresponds to the previously analysed circumstances of electricity generation.

The monthly and annual charts of CO_2-specific emissions are very similar to the ones presented in Fig. 12, since these emissions are a direct consequence of the energy mix.

Baseline emissions

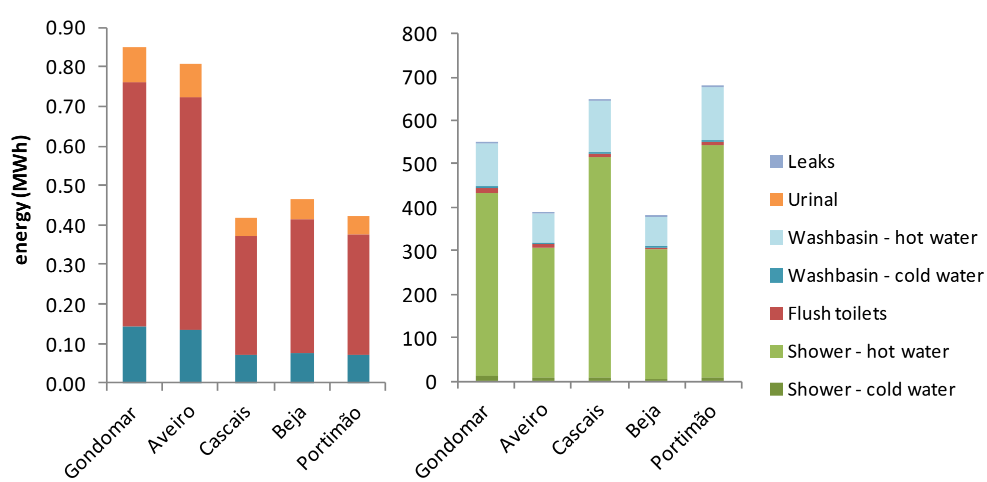
Figure 18 presented the emissions due to the consumption of water in the university building (left) and in the hotel (right), for the baseline situation.

Emissions reduction

Considering the high variability of the energy mix, the results and discussion presented for the greenhouse gas emissions consider the average value of the energy mix and corresponding carbon dioxide emissions from 2011 to 2017.

This may appear to entail some inconsistency, but it is not the case. The water and energy savings are directly correlated: a reduction in water consumption will result in proportional energy savings. Consequently, these two variables need to be consistent, and choosing a common year respects this requirement. Contrarily, the emissions reduction from energy savings depends on the energy mix. Since this is highly variable, between the years in Portugal and the year of 2015 may not be representative of a typical year in terms of the relative

Fig. 15 Baseline energy consumption: university building (left) and hotel (right)



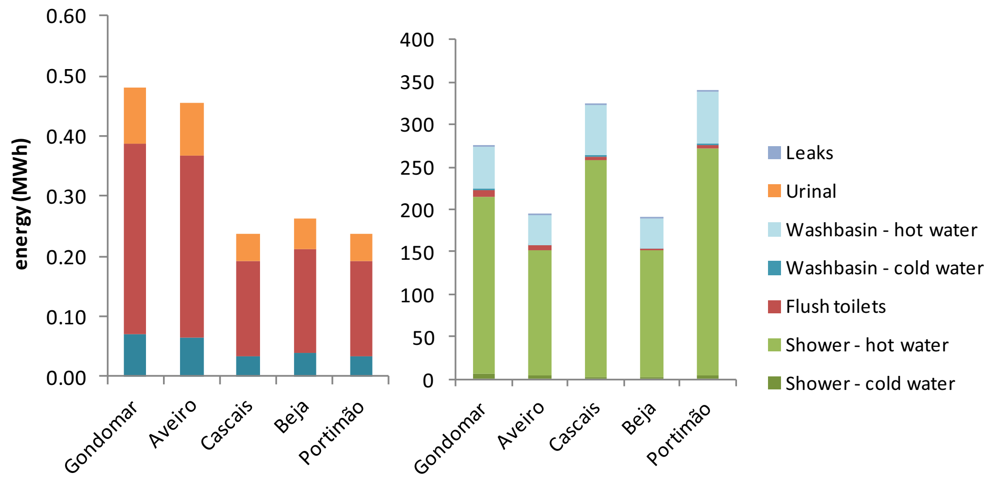


Fig. 16 Potential for energy reduction from water efficient measures: university building (left) and hotel (right)

contribution from the renewable and non-renewable sources, it was opted to use an average energy mix and corresponding carbon emissions.

Figure 19 (left) presents the savings estimated for the university building. The energy and emissions reduction vary proportionally and are larger in the cities where the energy intensity of the urban water cycle is higher. Figure 19 (right) presents the savings estimated for the hotel. Despite the similar values of the energy intensities of the urban water cycle in Aveiro and Gondomar, the differences in occupancy rates result in over less 20% emissions in Aveiro. The same logic can be applied to compare Cascais, Beja and Portimão.

The results from the case study demonstrate that substantial reduction in water, energy and emissions can be achieved by retrofitting water devices in buildings, in the Mediterranean climate context. Thus, if the considered interventions were performed, the consumption of water in the WCs of the university building would reduce in 56% and in the guestrooms of the hotel in 50%. The energy consumption and the production of carbon emissions would reduce in the same proportion. These reductions would correspond to annual savings of 250 m^3 of water, 335 kWh of energy and 57 kg of carbon emissions for the university building in comparison to the 2.0–6.1 thousand m^3 of water, 1.3–3.7 MWh of energy and 1.7–9.5 kg of CO_2 for the hotel's guestrooms.

Discussion

Simplifications to the proposed methodology can return significant errors. The most common simplifications are as follows: (i) simplification A—to consider consumption reductions proportional to flow rate reductions; (ii) simplification B—to consider the energy consumption to supply water to the

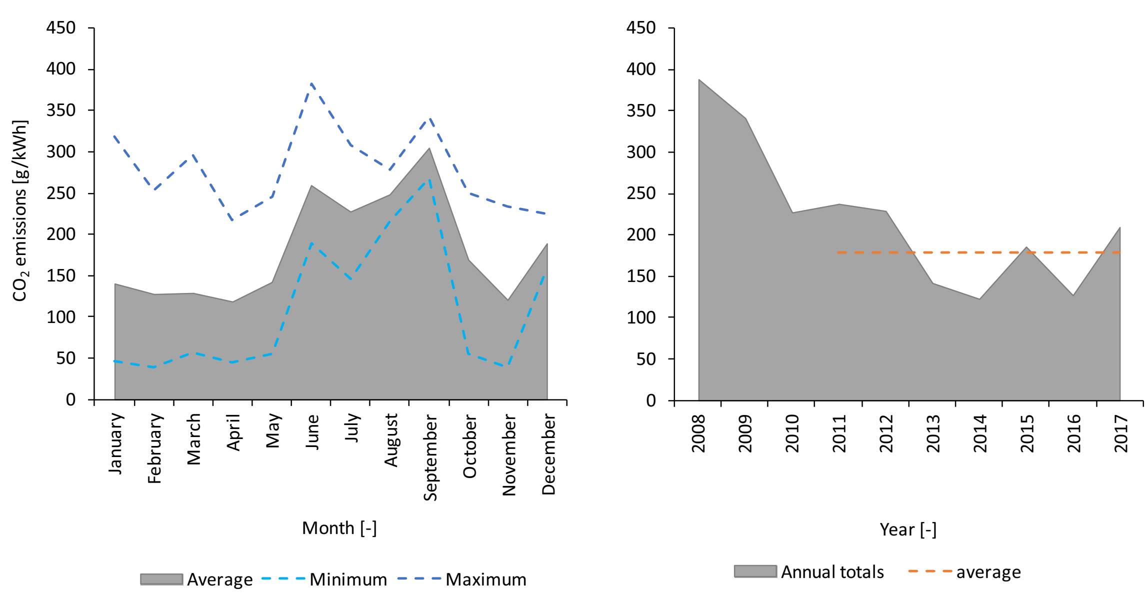


Fig. 17 Specific CO_2 emissions due to electricity production at *EDP* at monthly (left) and annual (right) time scales

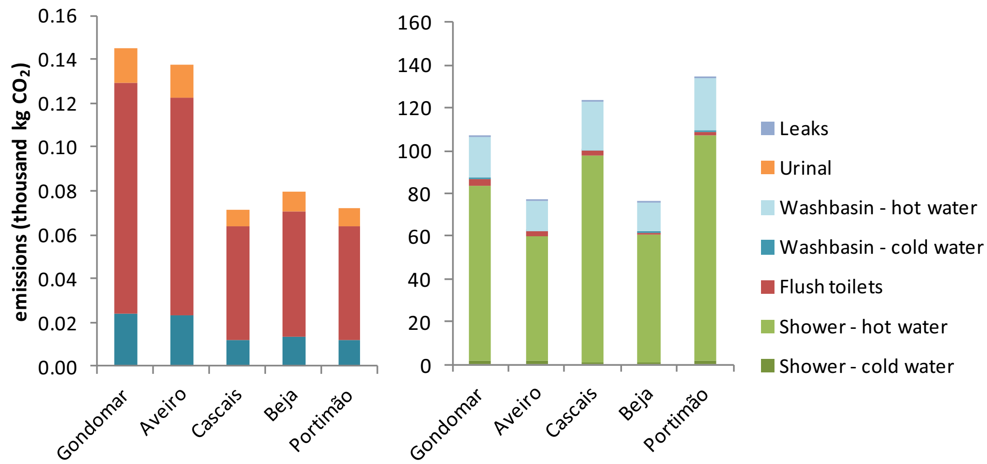


Fig. 18 Baseline emissions: university building (left) and hotel (right)

urban area constant through the year in zones where the supply seasonality is strong; (iii) simplification C—to consider constant values for the emissions throughout the year (annual time scale).

Regarding simplification A, user behaviour changes can reduce significantly the expected water savings of a certain fixture. According to previous studies, we observed that assuming a linear relationship between flow rate and water consumption could lead to real water savings up to 64% lower than expected in an audit (Meireles et al. 2017).

Simplification B can lead to significant errors when water is supplied from different sources in different times of the year. Mediterranean coastal zones have a significant increment in population during Summer, which is the time of the year when less water is available. To overcome this issue, these zones are forced to increase their availability of water, sometimes resorting to energy-intensive processes like desalination.

Performing the analyses at either monthly or annual time scales returns equal water and energy savings. On the opposite, differences are observed in the CO_2 emissions, since the energy mix varies from month to month, resulting in a variation on the CO_2 emissions throughout the year. In the present situation both approaches return similar annual CO_2 emissions, with a difference of only 5% or less. However, assuming simplification C (i.e. a simplified annual approach instead of the proposed monthly approach) returns relative differences for the CO_2 emissions as high as 198% in August, for the university building, and as high as 233% in January, in Portimão, Algarve, for the hotel. It also returns relative differences for the CO_2 emissions as low as − 48% in September, for the university building, and as low as − 62% in August, in Beja, for the hotel. This disparity is particularly visible in buildings affected by seasonal consumption variation, like the ones presented in this study (e.g. schools and touristic buildings), since greenhouse gas emissions are also season related.

On another note, the extent of the benefits of water conservation measures depends on the characteristics of the building and on its specific water uses. In this research, each of the studied buildings has roughly 300 users. However, the uses cannot be directly compared. Only cold water is consumed in the university building, but in the guestrooms of the hotel more than 50% of the water is consumed in showers. Even for the same device, the user pattern in a hotel and in a

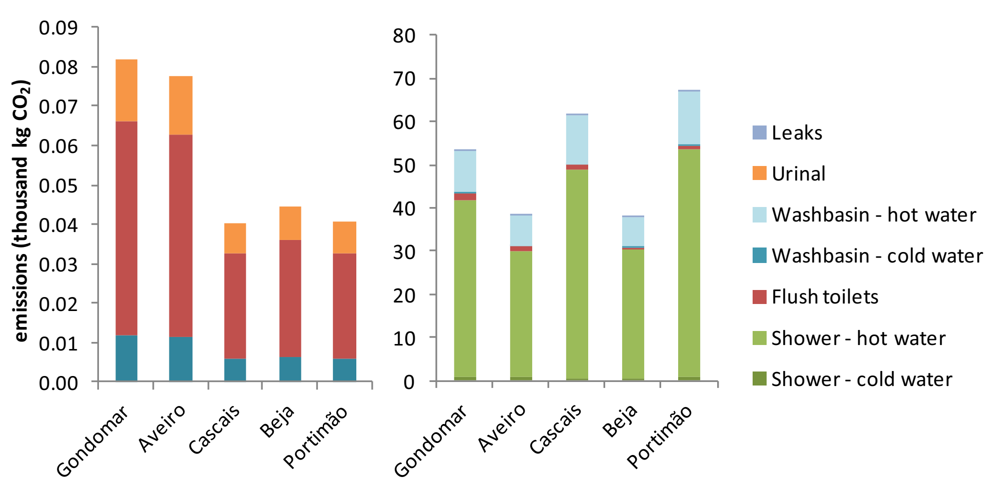


Fig. 19 Potential for emissions reduction from water efficient measures: university building (left), hotel (right)

university building are distinct. The water uses in a hotel are more water intensive since they coincide with the daily hygiene routines (e.g. bathing, shaving), whereas in a university building water uses are driven by physiological needs. Furthermore, the guestrooms are private areas and the water consumption at the university building takes place in public spaces, affecting the individuals' behaviour. The comparison between the 375 m^3 consumed in the flushing toilets and urinals of the university building with the roughly 7.5 thousand m^3 of water used in the guestrooms flushing toilets reflects these differences. The disparity in water consumption is much more pronounced when considering the total amount of water consumed in the WCs of the university building and in the guestrooms of the hotel (450 m^3 against 18.4–33.7 thousand m^3), mainly due to the showers in the guestrooms. However, the differences are larger when it comes to energy consumption and carbon emissions, primarily due to the consumption of hot water in the hotel. In fact, although the guestrooms consume, on average, 58 times more water than the university building, they contribute to 1020 times more energy consumption and 1169 times more gas emissions. This happens because although hot water corresponds to 37% of the volume of water consumed in the guestrooms, heating it contributes to 91–95% of the total energy and carbon emissions. This is consistent with Nair et al. (2018) statement that water-related energy consumption in end uses is mostly used to heat water. As a final point, in the university building 66% of the water, energy and emissions savings are due to flushing toilets retrofit, whilst in the hotel 67% of the water savings and 97–98% of the energy and emissions savings result from the retrofit of hot water use devices (showers and washbasin taps), particularly showers (78–80% of the energy and emissions savings). This demonstrates that heterogeneity among uses in different types of buildings results in absolute and relative water, energy and emissions savings significantly different. In this regard, for management purposes ranking prioritization of interventions for each type of building/users has high influence on the optimization of the water, energy and carbon emissions savings.

The benefits of water conservation measures also depend on the binomial type of water conservation measure–type of building. For instance, considering the Mediterranean climate zone, the potentiality of a RWH system would be maximized in a building where uses would decrease (or would be inexistent) during summer, like school buildings. In the contrary, if a RWH pressure driven system was to be installed in a hotel to flush rainwater in the toilets, the potential benefit of the system could disappear, or at least be minimized, by the systematic use of the pump either with rainwater in the winter, either with potable water in the summer, when rainwater would not be available and the occupancy of the hotel was the highest.

Lastly, when attempting to quantify potential benefits of different solutions to help decision-making and to manage priorities in long-term scenarios, tendencies should be taken into account. In Portugal, as well as in many other more developed countries, the energy mix has been evolving into a larger proportion of renewable water sources. This trend is forecasted to continue in the near future and should be considered when conducting long-term estimates to avoid overestimating the potential GHG emissions reduction.

Conclusions

A methodological approach is developed to model the reduction in water end uses consumption, water-related energy consumption, and associated carbon emissions production due to different water conservation measures. The developed model addresses the impact of a certain water conservation measure and related user behaviour change; baseline monthly water consumption; water consumption distribution; characteristics of the building (e.g. water heating energy source, heater efficiency, pumping energy source, pump efficiency); energy and carbon intensity of the water and wastewater urban services; energy source(s) for water-related energy; energy supplier(s) and monthly energy mix(es) on the water, water-related energy and GHG emissions savings.

Using the method, one can assess water, water-related energy and GHG emissions reductions in diverse and geographically variable buildings. We applied the method to two types of non-residential buildings (university building and hotel) with roughly 300 users, located in 5 different cities (Gondomar, Aveiro, Cascais, Beja and Portimão) of the Mediterranean climate zone, assuming retrofit of the WCs of the university building and of the hotel guestrooms. The results demonstrate that substantial reduction in water, energy and emissions can be achieved (50% for the WCs and 56% for the guestrooms, which corresponds to annual savings of 250 m^3 of water, 335 kWh of energy and 57 kg of carbon emissions for the university building in comparison with the 2.0–6.1 thousand m^3 of water, 1.3–3.7 MWh of energy and 1.7–9.5 kg of CO_2 for the hotel). However, in the university building 66% of the water, energy and emissions savings are due to flushing toilets retrofit, whilst in the hotel 67% of the water savings and 97–98% of the energy and emissions savings result from the retrofit of hot water use devices (showers and washbasin taps), particularly showers (78–80% of the energy and emissions savings). This demonstrates that heterogeneity among uses in different types of buildings results in absolute and relative water, energy and emissions savings significantly different. In this regard, for management purposes ranking prioritization of interventions for each type of building/users has high influence on the optimization of the water, energy and carbon emissions savings.

In addition to adopting the correct values for each specific case, the influence of using an adequate time scale for the analysis is demonstrated and discussed. The seasonality in terms of both the water consumption and the energy mix may result in over or underestimating the real benefits in terms of emissions reduction from water efficient measures in buildings. In the case of the university buildings, an overestimation on the carbon emissions was observed for the month of August comparing the results of conducting the analysis on an annual basis instead of on a monthly basis (relative differences of 198%). For hotels the differences are even higher, but more importantly they are reversed, with overestimation on the carbon emissions in January and underestimation in August (relative differences between − 62% and 233%). The higher water consumption during the summer months leads to higher water savings in the months where the fraction of non-renewable sources in the energy mix is higher. Consequently, the emission reduction during the summer months is enhanced twice when performing the analysis in a monthly time scale compared to performing the analysis using annual average values.

Lastly, the application of the methodological approach to different scenarios demonstrates the need for accurate data to feed the model with. In this regard, studies on the effective water savings from water conservation measures taking into account the corresponding user behaviour changes and studies on the monthly pattern and distribution of water consumption in different types of buildings, particularly non-residential, are in need.

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