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Managing the Water-Energy Nexus within a Climate Change Context—Lessons from the Experience of Cuenca, Ecuador

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Abstract: The impact of climate change dynamics has a multiplicative effect when the interlinkages between water and energy are considered. This also applies to climate change co-benefits that derive from adaptation and mitigation initiatives implemented at the urban level and that address the water-energy nexus. A better understanding of the water-energy nexus is a precondition for integrated resource planning that optimizes the use of scarce resources. Against this background, the paper assesses the potential impact of water-energy saving technologies (WEST) on the water-energy nexus of Cuenca, Ecuador, focusing on how vulnerability to climate change may affect the water metabolic cycle of the urban area. Water-energy saving technologies such as rainwater harvesting, solar water heaters, and micro water turbines, reduce water-related energy consumption and mitigate greenhouse gases emissions; thereby illustrating the potential to generate climate change mitigation and adaptation co-benefits. The paper relies on primary data collected through interviews and a survey as well as secondary data in order to assess the extent to which water-energy saving technologies influence the water-energy nexus in Cuenca's urban water metabolic cycle. Within the context of climate change, the paper develops a business-as-usual scenario and assesses how this is modified by the implementation of water-energy saving technologies.

Keywords: water-energy nexus; climate change adaptation and mitigation; climate change co-benefits

1. Introduction: The Urban Water-Energy Nexus and Co-Benefits of Water-Energy Saving Technologies

An urban nexus highlights the intertwined connections of various systems and sectors within a particular urban space. The water-energy nexus explores the intertwined linkage between the two sectors in the sense that the supply of one depends on the availability of the other [1]. The water-energy nexus occurs when humans use water to generate energy, and also when energy is consumed to access water resources. The nexus reveals substantial trade-offs and opportunity costs associated with the ways water and energy are used. A better understanding of the water-energy nexus is essential for better resource planning that fosters the optimization of the use of scarce resources [2]. The level and nature of such interactions between the two sectors are multi-directional and showcase a high degree of interconnectedness between different urban systems. The urban impact on water resources and the resultant water scarcity is a high priority risk, which, coupled with climate change represents a catastrophic potential hazard. Optimizing the synergies of the water-energy nexus becomes an important premise for sustainable urban development world-wide. Such optimization requires an in-depth understanding of the complex and pervasive connections between energy and water in urban areas, and calls for integrated and coordinated approaches that promote synergistic pathways between standalone water and energy systems [3–5] (Figure 1).
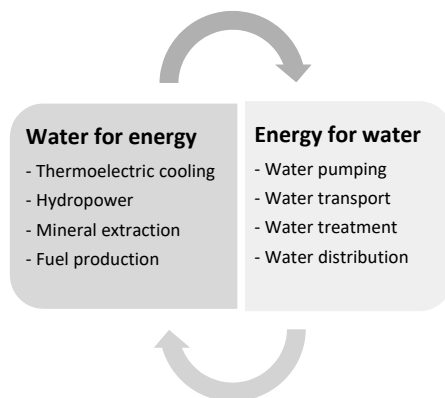
Figure 1. Interlinkages between water and energy sectors.

The urban water metabolic cycle has two components: the water flows in various stages of the water metabolic cycle and the energy input these various stages of water cycle demand for different processes such as extracting, pumping, treating, and storing [6–10]. For the purpose of this study, the volume of water and wastewater flowing through the various stages in the water cycle is considered. This is accompanied with the analysis of the energy consumed for each process. The generation of this energy has an environmental footprint, which can be expressed as greenhouse gases (GHG) emissions in the form of equivalent carbon dioxide emissions (CO_2e). This paper used the CO_2e emissions of the energy generation process as an indicator of the sustainability of the process in line with the climate change mitigation and adaptation framework utilized by Demuzere et al. [11]. The prime focus of the study is on the water flows, associated energy consumptions, and the related GHG emissions from the water sector. These indicators are also utilized to gauge the adaptation and mitigation benefits the implemented water-energy saving technologies (WEST) could potentially contribute to the water-energy nexus in the urban water cycle.

WEST represent the technological measures taken to conserve water and energy resources or make their consumption more sustainable in the face of two kinds of future uncertainties: gradual changes (e.g., climate change) and system shocks (e.g., natural disasters and energy price spikes) [12]. Regarding climate change dynamics, which are the focus of this study, knowledge of adaptation and mitigation co-benefits are valuable for urban planners to develop integrated climate policy making and planning practices [13]. Water management is at the heart of the concerns arising from climate change. While some places face water scarcity due to lack of precipitation and drying rivers, other areas are endangered by flooding and rising sea levels. In this study, the urban metabolic water cycle, its consequent energy consumption and equivalent carbon dioxide emissions (CO_2e) in the various stages of the water cycle are analysed within a climate change framework. Simultaneously, this study also emphasises the importance of adaptation and mitigation synergies. Water-energy saving technologies (WEST) reduce water-related energy consumption and mitigate GHG emissions, and therefore should be considered as important tools that symbolize the adaptation and mitigation co-benefits in the water sector. For example, while rainwater harvesting reduces storm water run-off (by capturing and storing rainwater), it also lowers the energy consumption of the water system (local collection and consumption of rainwater removes the need for treatment and pumping to households) [14,15]. This dual benefit of rainwater harvesting makes it a 'no regret strategy', which means that this strategy is useful for most places around the globe with different contexts and problems (suitable for drought problems as well as places prone to flooding).

The study focused on three selected WEST, that is rainwater harvesting [8,14,15], micro-hydropower turbines (water turbines) [16–18] and solar-water heaters [19]. Based on the literature, the implementation of WEST has multiple benefits which may include:

(1)   GHG emission reduction. Similar to the benefits of green urban infrastructure as mentioned by Demuzere et al. [11], WEST reduce the energy consumed to treat and transport water across

the various stages of the urban water cycle. Depending on the energy generation process, CO_2e emissions related to the use of conventional fossil fuel are mitigated.

(2) Water losses to sewage. Due to impermeable urban roads and buildings, rainwater fails to recharge groundwater but instead adds to the water to be managed by the downstream areas creating long-term stresses on groundwater levels upstream, and flooding issues downstream [15]. WEST help retain a high quality of rainwater in on-site storage tanks, ensuring less water to sewage.

(3) Evaporative cooling of buildings. According to Schmidt [15], water harvested from water saving measures can be used to cool buildings. Water is the cheapest and most effective method to cool a building without any energy invested in air cooling devices such as air conditioners. This usage of harvested water has large implications for the energy sector. Less energy required to cool buildings implies lower stress on the water-energy nexus.

(4) On-site local water supply. WEST can potentially help with reclaiming and reusing water resources multiple times cascading from higher to lower quality [11]. Storm-water or rainwater becomes a resource increasing local sustenance, reducing the reliance on water from centralized water grid systems.

WEST are expected to influence the water-energy nexus in multiple positive ways, making the urban water metabolic cycle more sustainable and resource efficient. In this regard, WEST may reduce the water and energy demand on the conventional water grid infrastructure, diminishing the water losses and run-offs to sewage after use and increase the recycling and re-using abilities of different grades of water. In addition, they reduce the carbon footprint (GHG emissions) of the urban water cycle.

2. Theoretical Background

It is important to understand the impact that different WEST could have on the water-energy nexus in the urban water metabolic cycle and various methodological approaches have been used in the literature for this purpose. Using the water flows of the hydrological metabolic cycle, Valek et al. [14] calculate the impacts of reducing leakages, pricing reforms and rainwater harvesting on the water consumed by the system, yielding a water saving percentage on an annual basis. A similar approach was used by Chacha [8] but in his study, the focus was only on rainwater harvesting as a water saving measure. Taking rainwater harvesting as an example, the technology fulfils two purposes as it reduces the storm water runoff to the wastewater drainages and it is also useful to fulfil some fraction of the residential or industrial water demand; thereby, reducing water demand from the water grids of the city. A crucial indicator that comes out of these two studies is the annual precipitation levels used to calculate the potential amount of rainwater that can be captured by the water saving technology. This indicator was also used in this study to understand the potential of water savings by rainwater harvesting. For the analysis of the WEST influence on the water-energy nexus, the annual water saving percentage should be calculated. The energy demand for the WEST hypothetical scenarios can be measured by calculating the energy consumed by the implemented WEST and the energy needed for the remaining percentage of the water cycle delivered by the conventional grid as per the Business As Usual (BAU) scenario. Hence, in essence, the WEST reduce the water demand from the conventional grid of the water system in the urban context. This reduction of water demand creates a diversification of the water supply sources and has an implication on the energy required for treatment and distribution of water to residences and industries. The effect on the water flow of the wastewater treatment facilities is also an important factor which should be quantified. In addition, WEST also help to reduce the energy demand from the conventional energy grid, energy demand that arises from the water metabolic cycle [16–18].

Studying these water and energy demands within the water metabolic cycle in an urban context, the analysis of climate change-related effects to the water metabolic cycle, and additionally, the impact and feasibility of WEST on the urban water systems are three complicated research fields, as illustrated by the numerous research done in each field separately. The problem, though, lies in integrating these three fields to derive meaningful practical outcomes. To solve this problem, various researchers

have come up with holistic frameworks in recent times. For example, Sapkota et al. [7] in a paper on hybrid water supply systems, utilize a generalized framework which is supported by "models and tools including water balance modelling, contaminant balance modelling, multi-criteria decision analysis (MCDA), and future change analysis". In another study [6], the models used the volume of water/wastewater, energy consumed of each process, chemicals used in each process, and transportation distances as the inputs for each process of water system and generated the outputs of water-borne emissions, air-borne emissions, and solid waste. Chacha [8] utilizes the urban water metabolism analysis breaking the hydrological cycle into four components—freshwater availability, potable water production, domestic water consumption, and sewerage. Reference [8] analyses the implementation of the Integrated Urban Water Management (IUWM) methodology by conducting feasibility analysis of rainwater harvesting in Cuenca, Ecuador. The IUWM methodology includes the study of water flows (quantity and quality), managing water sources (such as rainwater, wastewater, storm water drainage, and runoff pollution), preventing water-borne diseases, and reducing the risks of water-related hazards, while ensuring the sustainability of the water resources for future generations [8]. One limitation of the IUWM methodology is that it does not integrate linkages of the water sector with the energy and other sectors in search of potential synergies. In contrast, there is an existing body of literature that deals with the methodological steps needed to carry out the assessment of technological solutions like solar water heater systems and hydroelectricity generation systems [19,20] that are not holistic enough to derive investment strategies for local urban authorities. Another limitation of the abovementioned approaches includes a lack of analysis of climate change-related effects.

In relation to these limitations, the literature review process pointed to the water supply and demand investment options assessment framework ('Planning for Resilient Water Systems' framework), shown in Figure 2 below. This framework focuses on key performance criteria such as affordability, waterway health criteria, maximum level of GHG emissions, cost to society, and externalities to assess the performance of new measures [21]. The framework strongly integrates climate change-related shocks and influences. However, scenario development is not incorporated in the framework.
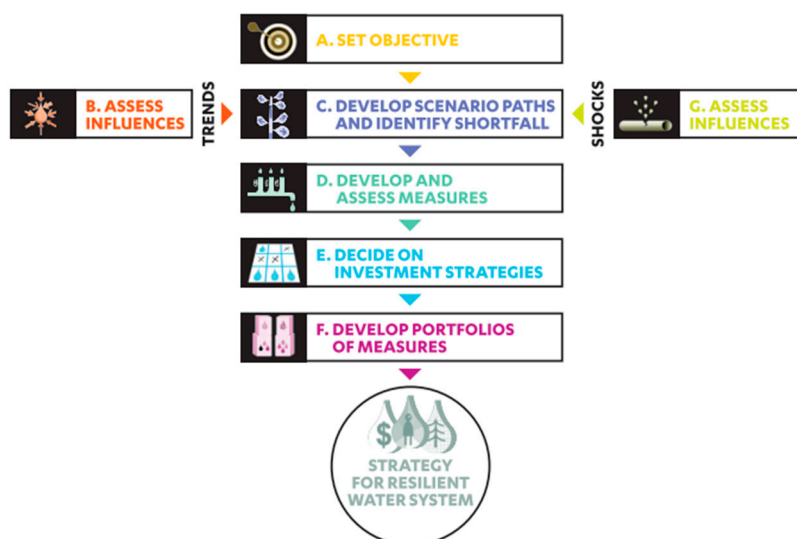
Figure 2. 'Planning for Resilient Water Systems' Assessment Framework [21].

The methodological approach proposed in this paper is potentially particularly useful for local governments world-wide which face a scarcity of financial resources and technical expertise. Other studies have focused on the interrelationship between the water and energy sectors at the urban level and in particular on the technologies and interventions that have the potential to improve the sustainable management of scarce natural resources [16–18,22,23]. Firstly, a major gap identified in these studies is the lack of integration of the various approaches taken to study the dynamics of

multiple water-energy interlinkages. While there are frameworks like Sapkota's [7] and IUWM that focus on the analysis of the water sector performance levels and assessing measures within the water sector, these clearly exhibit a lack of integration of climate change-related risk assessment. Secondly, while the 'Planning for Resilient Water Systems' framework addresses climate change-related shocks and trends in developing investment strategies of potential measures, there has been a lack of literature looking at the implementation of the different steps of the framework in an urban case study. This paper aims to address the two research gaps by combining the abovementioned approaches to assess the benefits of alternative strategies.

Another important aspect covered by the paper is the role that institutional arrangements may play in the implementation of green innovations and WEST in particular. Looking at the role of different actors from the public, private and community sectors is essential to assess the concrete possibility or a transition towards a more sustainable management of scarce natural resources. Local governments have a strategic role in facilitating the adoption of WEST for example by providing incentives as well as adopting regulatory frameworks. As emphasised by Li et al. [24] in a comparative study of the implementation of solar water heater technologies, different framing strategies, policy instruments and implementation mechanisms can have profound effects on the level diffusion of green technologies. From a slightly different perspective, Berardi [25] sheds light on the role of different stakeholders, with different interests and priorities, in dealing with and overcoming the barriers related to the adoption of energy-saving technologies. This type of analysis may explain the low level of adoption and provide useful insights into how to strengthen the facilitating factors that may foster the implementation of green innovations. Other studies similarly discuss how effective policies and incentives by the public sectors [26] as well as the role of political leadership, institutional reform and social change [27] are critical to the promotion of green innovations.

The applied approach used in this study combines aspects of different frameworks available in the literature in order to develop a practical methodology for decision makers at the local level to evaluate potential climate change threats to the urban water cycle, assess the resilience of the water cycle, and explore the impact and feasibility of potential solutions to improve the resilience of the water systems. Against this background, the objectives of the paper are to analyse the water-energy nexus of Cuenca's urban water metabolic cycle and in particular to carry out a rapid assessment of the future benefits of different water-energy saving technologies within the context of climate change, including the analysis of the institutional arrangements that may foster their implementation.

3. Materials and Methods

The study has been conducted in the city of Cuenca, Ecuador. Having a wide range of climatic variation with the coastal regions, the mountainous Andes region, and the Amazon rainforest region, Ecuador is characterized by an abundance of water resources with numerous rivers arising from the Andean glaciers and high precipitation for the most part of the year. However, changes in the climate of the Earth in the past 50 years have resulted in a myriad of repercussions that pose risks to Ecuador's availability of natural resources. Due to this, the national government has been proactive in attempting to nullify and prevent the threats that climate change poses to the country. The National Climate Change Plan (2015–2018) is one such effort setting the national climate change strategy and objectives up to 2025 [23]. In recent years, Ecuador has recorded sustained increases in temperature, changes in the frequency and intensity of extreme events (e.g., droughts, floods, and frosts), changes in the hydrological regime and retreat of glaciers, according to the National Institute of Meteorology and Hydrology [23]. Between 1960 and 2006, the average annual temperature has increased while the fluctuation between the maximum and minimum temperature has also risen [23].

The Cuenca metropolitan area is the third largest city in Ecuador with a total area of 3665.32 km^2 [22] and a total population of 505,585 in 2010. However, the urban centre amidst this large cantonal area was a mere 66.71 km^2 in 2010 [20]. Despite the small percentage of the area of urban Cuenca, approximately 330,000 inhabitants lived in the city of Cuenca in 2010 [8]. Cuenca is a typical

mountainous city high up in the Andes with an altitude between 2350 and 2550 meters above sea level [19]. Cuenca is known for the abundance of water supplies which come from four rivers (i.e., Tomebamba, Machangara, Yanuncay and Tarqui) and is the centre of Ecuador's energy transition from fossil fuels to hydroelectricity. However, an increased energy investment in water treatment plants before and after its usage increases the need to study the water-energy nexus of the urban water cycle and its repercussions. With Cuenca relying heavily on its abundant water resources from the Andean glaciers for water and energy, it is pertinent to ensure that this interdependency of water and energy cycles is resilient in the face of uncertain future scenarios.

It is important for Ecuador and its cities to prepare for the unforeseen impacts that climate change might have on its water resources like the Andean glaciers, precipitation, rivers and ground water levels. This applies to cities more generally, regardless of their geographical location. The relevance of this study is to contribute to an enhanced understanding of integrated urban water models at the urban level and the deep impact of the urban water cycle in all sectors of cities. This thesis presents a study of an urban water cycle case study of Cuenca which is renowned in Latin America for its superior water management practices and water abundance in general. However, by looking at a case where hydroelectricity is the most important source of energy, a blueprint can be developed that can be emulated by other cities around the globe which rely on a less sustainable energy generation model. The lessons that can be gained from studying the case of Cuenca are important beyond Ecuador as the challenges of how to manage scarce resources are common to urban areas world-wide.

The challenge lies in creating a balance between the detailed, complex mechanism required to bring together the various aspects of different frameworks and tools mentioned in the previous section, and a framework that is practically usable by local authorities with limited time, financial resources and competencies. Thus, it is also necessary to emphasize that the objective of the paper is not to carry out a fully-fledged life cycle environmental impact assessment of the WEST considered. This research paper looks to contribute to the existing literature by showcasing the methodology to utilize tools (like Life Cycle Assessment) and frameworks (like IUWM) at various steps of the 'Planning for Resilient Water Systems' framework, highlighting the granular complications of the implementation process, while building a step-by-step methodology easy to be implemented in practice by local authorities. In achieving this, the methodological approach taken in this research provides a ground level perspective of how interconnections and synergies with the energy sector can be studied in practice while embedded within a holistic top-level framework.

The multi-step methodological approach followed by the study and applied to the Cuenca case is based on the framework developed by Mukheibir and Mitchell [21]. To assess the economic feasibility and impact of the water-energy saving technologies (WEST) on the water metabolic cycle of Cuenca and its water-energy interlinkages, indicators such as affordability, cost to society, monetary savings by government, and externalities in the form of GHG emissions reduction have been derived and analysed based on the following four key steps (Figure 3):

(1) Evaluation of the current Business-As-Usual Scenario (BAU) scenario, developing the supply-demand requirement of the urban settlement for the time frame 2015–2030.

(2) Influences and scenario paths derivation to assess the climate change risks posed to the water sector of Cuenca.

(3) Development of forecast projections for the selected water-energy saving technologies. The forecast projections map the water and energy supply-demand requirement of Cuenca for the time frame 2015–2030.

(4) Comparison of the forecast projections with the Business-As-Usual scenario to yield the water saving potential, the energy saving potential, the GHG emissions reduction potential, and the monetary savings for society that would help conclude whether a given WEST is feasible and beneficial for Cuenca.

Figure 3. Methodological steps.

To collect information on the efficiency and suitability of implementing WEST initiatives in the context of Cuenca, primary data were collected along with the review of secondary sources. This information was essential to develop the hypothetical scenario needed for understanding the potential impact WEST could have in achieving sustainable urban water management in the urban water cycle of Cuenca. A Business-as-Usual (BAU) scenario was developed based on the analysis of the three different variables: residential water flows (variable 1), energy demand (variable 2), and GHG emissions (variable 3). Projections were then made to evaluate the BAU scenario over the time frame 2015–2030. Table 1 below specifies the variables and related indicators used in the study.

Table 1. Variables and indicators considered by the study.

Variables	Indicators	Description
1. Residential water flows	1.1 Potable water produced [8,14,28] 1.2 Residential water consumption [8,12,14,28] 1.3 No. of Residences [8,9,29] 1.4 Supply costs [14,28,30,31] 1.5 Supply revenue [12,28,29] 1.6 Water Quality [10,31]	1.1 Volume of drinking water produced for distribution by ETAPA 1.2 Volume of water used and paid for by the residences 1.3 Number of houses in urban Cuenca 1.4 Total costs borne by ETAPA to maintain water systems to and from the residences in urban Cuenca 1.5 Revenue generated by ETAPA from water bills paid by residences in urban Cuenca 1.6 Water Quality Index (WQI) is utilised to monitor the quality of water at the start and end of urban water metabolic cycle
2. Energy demand	2.1 Energy consumption [9,10] 2.2 Energy costs [10,14,32] 2.3 Energy fuel type [9,10,14]	2.1 Energy input required by the various stages - potable water production, water distribution, and wastewater treatment 2.2 Costs that arise due to the energy consumption 2.3 Form of energy utilised—e.g., electricity
3. Greenhouse gases emissions	3.1 Emission factor [33] 3.2 Energy consumption [9,10,14,30]	3.1 Brander et al. (2011) define emission factor as the GHG emissions from energy production process that are calculated for each country based on the mix of energy production processes 3.2 Energy input required by the various stages - potable water production, water distribution, and wastewater treatment
4. Water-Energy Saving Technologies ● Rainwater harvesting ● Green roofs ● Solar water heaters ● Water turbines	4.1 Installation costs [8,10,14,23,28,34] 4.2 Water saving potential [8–10,14,21] 4.3 Energy saving potential [8–10,14,21] 4.4 GHG emissions reduction potential [10,11,14,21] 4.5 Monetary savings [8,10,14,21] 4.6 Climate change threats [10,11,14,21] 4.7 Suitability [8,10,11,14,28]	4.1 Total cost estimate for the installation and operation of WEST 4.2 Amount of residential water demand reduced on the water grid per unit time due to WEST 4.3 Amount of energy demand reduced on the energy grid per unit time due to WEST 4.4 Amount of GHG emissions reduced per unit time by the WEST implementation 4.5 Total monetary savings for the government that WEST scenario generates as compared to BAU scenario 4.6 Indicator used in questionnaire and interviews to gather experts' opinions on hazards/threats to Cuenca's water sector due to climate change in near future 4.7 Indicator used in questionnaire and interviews to gather experts' opinion to shortlist WEST for Cuenca's context that best address the climate change threats (4.6)

ETAPA (Empresa de Telecomunicaciones, Agua Potable, Alcantarillado y saneamiento de Cuenca) is the public utilities company owned and operated by the city of Cuenca; GHG (greenhouse gases emissions); WEST (Water-Energy Saving Technologies).

Three forecasts have been developed, one each for rainwater harvesting, solar water heaters and water turbines, using Microsoft Excel software. These have been compared to the BAU scenario. This procedure has yielded results on four indicators to assess the performance of each WEST: water-saving potential, energy-saving potential, GHG emissions reduction potential, and monetary savings. This analysis has been carried out to assess the potential of the considered WEST initiatives to improve Cuenca's water sector and its interlinkages with the energy sectors, with the ultimate objective of making it more resilient in light of climate change dynamics.

A total of 33 experts from different public, private and non-governmental organizations were interviewed to collect primary data (University of Cuenca, Universidad del Azuay, Public Works

and Drinking Water company, Planning department of Cuenca, Public company for potable water and sewage management, city counsellors, Environmental management department of Cuenca, non-governmental organizations). The selection of the experts to be interviewed was achieved through purposive and snowball sampling. The experts were selected due to their relevant knowledge and professional role in the urban water metabolic cycle of Cuenca. The experts interviewed the provided information about the variables analysed in the study so to triangulate and validate the information accessed through secondary sources. Furthermore, they were asked to provide their opinion on the broader institutional arrangements of Cuenca water and energy sectors and on the feasibility of implementation of the selected WEST. Interviews were conducted in Spanish and later transcribed to English. The transcripts are available upon request.

There were two rounds of interviews:

(1)   The first round of interviews were conducted at the early stage of data collection and were aimed at understanding the current water systems and the management practices in Cuenca and the climate change potential threats and the water-energy saving technological (WEST) solutions that would best fit the context of Cuenca.

(2)   The second round of interviews were conducted at the later stage of projection forecasts development. During these interviews, experts were asked about information needed to implement the selected WEST solutions in Cuenca on a residential level. Information was also obtained on the social, economic and environmental effects of implementing the shortlisted WEST solutions in Cuenca.

4. Results

The first part of the section introduces Cuenca's context [35,36] and discusses its current water metabolic cycle (processes that form part of the water metabolic cycle: pre-treatment, distribution, sewage). The current water system constitutes the BAU scenario and describes in detail residential water flows, energy demand and GHG emissions. The second part of the section deals with the effects of the selected WEST (i.e., rainwater harvesting, solar water heaters, and water turbines) on the water metabolic cycle and water-energy nexus in Cuenca.

4.1. Cuenca Water Metabolic Cycle and the Business-as-Usual (BAU) Scenario

This section analyses the current water management practices in Cuenca, looking at the impact of these practices on associated energy costs and GHG emissions that can be expected until 2030 as per the BAU scenario.

4.1.1. Residential Water Flows Analysis

Based on various data from the last three decades, a prediction for Cuenca's growth until 2030 is developed. This includes the urban population from 1992 to 2013 as well as the number of households and total urban area. Furthermore, expert interviews with representatives of the municipality highlighted steady urban sprawl with predominant low-rise buildings. The interviews and secondary sources also lead to the assumption that the average household size will remain at about 3.85 [8,20,22,25]. Similarly, the study also developed a forecast until 2030 regarding the water metabolic cycle of urban Cuenca using the following indicators for the variable of water flow: potable water produced (in m^3/year), total water consumed (in m^3/year), residential water consumed (indicator 1.2 in m^3/year). The variable 'energy demand' is calculated by the indicator energy consumption (in kWh) calculated from the monthly electricity bills obtained at the Tixan and Cebollar treatment plants. The variable 'energy demand' is also closely related to the variable 'energy costs' (in USD).

Based on the primary data collected, the amount of potable water lost due to leakages in pipes was estimated to be approximately 25%–30%. As Chacha [8] notes, leakages and unsuitable fares result in economic losses of around USD 2 million per month. Residential water consumption was found by Malo-Larrea [37] to be approximately 80%–82% of the total water consumed through the years 1992 to 2013 with little fluctuation. This value of 80% has been utilized to co-relate the two indicators and generate values for residential water consumption forecast until 2030 in the data analysis. The rate of cost of production of potable water was calculated by Chacha [8] to be USD1.29 per m^3. This was utilized to estimate the supply costs of USD34.4 million in 2015. In 2015, the revenue generated, calculated from residential water bills and secondary data, amounted to USD28 million yielding an economic loss of USD6.4 million in 2015.

4.1.2. Energy Demands and Energy Costs Analysis

In 2017, the municipality had energy costs of USD1.3 million for potable water production, distribution and treatment, which coupled with the total volume of energy consumed of 12,997,556 kWh, results in an average unit energy cost of 9.9 kWh/USD. These energy costs related to the water metabolic cycle represent a crucial aspect of the water-energy interlinkage. For Cuenca's water metabolic cycle, similar calculations were repeated to forecast the energy costs until 2030. In Cuenca, the energy demand for the water supply calculation based on potable water produced yields an energy demand of 0.26 kWh/m^3 for the year 2017. This relatively low energy demand of Cuenca's water management system can be explained in the light of firstly the use of gravitational force for much of the production and distribution processes resulting in minimized use of electric pumps for transportation of water, and secondly, the biological technologies utilised to treat potable water and wastewater that require low-energy input, thereby minimizing the energy footprint of the water management system.

4.1.3. Greenhouse Gases Emissions Analysis

GHG emissions were analysed to calculate the environmental costs of the water metabolic cycle. For example, for the year 2017, the energy consumption by the water management processes was equal to 12,997,556 kWh. Therefore, the GHG emissions due to water management processes for the year 2017 were calculated by multiplying the energy consumed with the selected 0.270 kg CO_2e/kWh emissions factor to yield 3,504,141 kg CO_2e in GHG emissions. However, it should be considered that the local energy mix was 100% hydroelectric and Cuenca's example was a blueprint that the Ecuadorian government wanted to implement in the rest of the country. Therefore, Cuenca's local emissions factor (100% hydroelectricity) yielded 0 kg CO_2e per kWh. This effectively put the GHG emissions finding to a zero-value which contributed to Cuenca's case study being unique and an exemplary model to be imitated elsewhere. For assessing the GHG emissions reduction potential, Ecuador's national emissions factor of 0.270 kg CO_2e/kWh was utilized to evaluate the WEST in the performance having a reducing effect on the GHG emissions of the urban water cycle studied.

To summarize the findings in Cuenca's BAU scenario, the indicators of three variables residential water flows, energy demand and GHG emissions have been calculated on an annual basis and are presented in Table 2 below. Based on the data available, residential water flows was highlighted using the indicators potable water produced, residential water consumed, and total water consumed. Energy demand was calculated using the indicators of energy consumption and energy costs. Lastly, the GHG emissions were determined by the indicators' emissions factor, which revealed different values for Ecuador national-level and Cuenca's local level energy mix, and the energy consumption.

Table 2. Business-as-usual (BAU) scenario.

Year	Potable Water Produced (m^3)	Total Water Consumed (m^3)	Residential Water Consumed (m^3)	Energy Consumption from Water Management (in kWh)	Energy Cost (in USD)	GHG Emissions (in kg CO$_2$) as Per Ecuador's National Energy Mix
2015	39,983,333	33,372,105	26,697,684	10,560,455	1,067,807	2,847,099
2016	40,560,727	34,252,099	27,401,679	10,712,957	1,083,227	2,888,213
2017	49,210,534	35,132,093	28,105,674	12,997,556	1,314,231	3,504,141
2018	50,978,409	36,012,087	28,809,669	13,464,490	1,361,444	3,630,026
2019	52,746,284	36,892,080	29,513,664	13,931,423	1,408,658	3,755,912
2020	54,514,159	37,772,074	30,217,659	14,398,357	1,455,871	3,881,797
2021	56,282,034	38,652,068	30,921,654	14,865,291	1,503,085	4,007,682
2022	58,049,909	39,532,061	31,625,649	15,332,224	1,550,298	4,133,568
2023	59,817,784	40,412,055	32,329,644	15,799,158	1,597,511	4,259,453
2024	61,585,660	41,292,049	33,033,639	16,266,092	1,644,725	4,385,338
2025	63,353,535	42,172,043	33,737,634	16,733,026	1,691,938	4,511,224
2026	65,121,410	43,052,036	34,441,629	17,199,959	1,739,152	4,637,109
2027	66,889,285	43,932,030	35,145,624	17,666,893	1,786,365	4,762,994
2028	68,657,160	44,812,024	35,849,619	18,133,827	1,833,578	4,888,880
2029	70,425,035	45,692,017	36,553,614	18,600,760	1,880,792	5,014,765
2030	72,192,910	46,572,011	37,257,609	19,067,694	1,928,005	5,140,650

4.2. Water-Energy Saving Technologies (WEST) Measures

This section analyses the impact of the introduction of the selected water-energy saving technologies (WEST) on Cuenca's water metabolic cycle and the water-energy nexus in terms of water flows, energy costs and GHG emissions. The implementation of rainwater harvesting, solar water heaters and water turbines are compared to the BAU scenario outlined in the previous section.

4.2.1. Rainwater Harvesting (RWH)

Firstly, the annual precipitation levels in Cuenca were studied from 1998 to 2012 and 2014 to 2017. This annual precipitation data was utilized to understand the generation potential of potable water by the rainwater harvesting (RWH) in Cuenca. The annual precipitation in Cuenca averaged around 1017 mm per m^2 and this value was used in the development of the rainwater harvesting scenario. The average roof area of households in Cuenca was estimated at 82.51 m^2, the average cost of installation of above ground tank per household was USD1551 and the average monthly household water bill was sourced to be USD24 [8]. As per the BAU scenario, water management processes yield economic losses to the public utilities company owned and operated by the city of Cuenca on the order of approximately USD9.8 million every year. These losses, as entailed by Chacha [8], were a result of unsuitably low prices charged for water to Cuenca's inhabitants as well as water losses in the distribution network due to leakages of approximately 25%–30%. In the rainwater harvesting scenario, it was assumed that the WEST would be able to operate with 80% efficiency to develop a conservative and realistic projection. It was found that rainwater harvesting could reduce the water demand from the water grid by 22% on average from 2018 to 2030. The energy savings (kWh) were utilized to calculate the reduction in GHG emissions which yielded a saving of 12.5 million kg CO$_2$e emissions in the 13 year time period.

Rainwater harvesting technology was not found to be a recommendable installation in Cuenca in the current context due to high implementation costs and negative return on investment. The investment costs for the rainwater harvesting project hovered at approximately USD229 million. Additionally, the savings from reduced production and distribution costs of water was nullified by the loss of water bill revenue for ETAPA (Empresa de Telecomunicaciones, Agua Potable, Alcantarillado y saneamiento de Cuenca) from Cuenca's residences yielding USD11.8 million further losses due to the project implementation in the given time period. For the energy-saving potential, rainwater harvesting reduced energy demand by 3.6 million kWh per year. Furthermore, an annual reduction of 960,000 kg CO$_2$e for a water management process that generated 3.5 million kg CO$_2$e in 2017 equates to an approximate 27% reduction in GHG emissions annually. If the reduced GHG emissions are weighed in terms of monetary benefits, rainwater harvesting might become a practical solution. However, the main reason for the unfeasible outcome for rainwater harvesting was found to be the fact that rainwater harvesting does not reduce the volume of wastewater to be treated at the wastewater treatment plant.

It should be noted that the rainwater harvesting scenario was developed considering precipitation data over an annual period to study the economic and environmental impact of the technology. Furthermore, to include the effects of climate change on the precipitation patterns in Cuenca, two scenarios of 20% above and 20% below par precipitation were also incorporated in the data analysis. However, the results were not sensitive to the increase or decrease of the annual rainfall. An important finding of the expert interview revealed that changes in the precipitation patterns of Cuenca were likely to result in a shorter raining season with increased intensity (resulting in flash floods) and longer periods of dry season (resulting in water reserve depletion). These changes were not reflected in the forecasts of this study due to two main reasons: 1) the projections were generated to analyse short-term (10–15 years) impacts and benefits whilst significant changes in precipitation patterns would take place over a longer term, and 2) the economic feasibility calculations did not include the potential economic losses to Cuenca's economy due to the flooding and drought events.

4.2.2. Solar Water Heaters (SWT)

The scenario for solar water heaters (SWT) was based on the assumptions of installation costs per household of USD800, hot water storage capacity (200–250 litres), and hot water temperature (60–65 degrees Celsius). Furthermore, the cost of installation of a propane gas tank system per house (USD600), subsidized cost per gas tank (USD1.60), actual cost per gas tank (USD12.25), number of gas tanks required per month for a family of four persons, and size of a propane gas tank (15 kg of propane) were the indicators gathered to develop the baseline propane gas tanks scenario to compare the solar water heaters performance with. Other information obtained from secondary sources were: conversion of kilograms of propane gas to gallons (volume) and then, gallons of propane to Btu or kWh as in the case of this research study. Lastly, the GHG emissions factor for propane gas tanks was sourced from two different sources [19], and the value of 0.2548 kg CO_2/kWh [19] was selected for two reasons: 1) the paper had detailed emissions factors for different applications and this value was provided for domestic water heating applications, 2) it was the higher of the two obtained values—this was accepted to counter the lack of considering methane and nitrous oxide greenhouse gases emissions in the calculation due to the lack of data available.

The first step was to calculate the unsubsidized economic cost of utilizing propane gas tanks for the population of urban Cuenca. This was measured by multiplying the number of gas tanks consumed by the average household in Cuenca to the actual cost of gas tank with number of residences in urban Cuenca. The next step was to calculate the cost of implementing the solar water heater systems using the installation cost per household and the number of residences in urban Cuenca. The next step in the building of the forecast was to calculate the energy savings (in kWh) due to the solar water heaters with electric power backup. It was calculated that each gas tank contains 15 kg of propane gas. Fifteen kg of propane was converted to 7.8 gallons of propane (volume) which yielded the energy provided equating to 209.3 kWh for each gas tank. This value of energy was utilized to measure the total amount of energy saved per year for urban Cuenca (in kWh) referring to the amount of energy converted from traditional fossil fuel sources to renewable energy sources (main power: solar and backup power: hydroelectricity). The amount of energy saved for Cuenca per year averaged 559,000,000 kWh for the period under consideration. These energy savings were then utilized to calculate the GHG emissions reduction (in kg CO_2) using the emission factor of 0.2548 kg CO_2/kWh [19] which yielded an impact of reducing around 142,000,000 kg CO_2 per year in GHG emissions.

Solar water heaters with electrical backup power have a highly positive feasibility. Their implementation requires an investment of around USD78 million in the first year but would yield savings of USD613 million approximately over the considered time frame because of the transformation of domestic water heating system from propane gas to solar/hydroelectricity. The Net Present Value of the project was affirmed at approximately USD268 million with an Internal Rate of Return (IRR) of 52%. This is due to the large sum of money that Ecuador spends in importing propane gas from the international energy market. The Azuay province, of which Cuenca is the capital, is the hydroelectricity

centre of Ecuador. With numerous hydroelectric dams and an Ecuadorian vision of becoming 100% reliant on hydroelectricity for energy by 2050 [26], this solar water heater project could be a huge leap in the right direction to take Cuenca's residential energy demand and Ecuador's residential energy demand from imported fossil fuel-based energy to renewable energy sources like solar and hydroelectricity. Lastly, in terms of GHG emissions, Ecuador in total had a cumulative emissions total of 94.5 Mt of CO_2 in 2014 [27]. Although, the GHG savings of roughly 142 million kg CO_2 annually represents only 0.15% of the country's total emissions; however, it is important to note that urban Cuenca only represents about 2.5% of Ecuador's entire population and that hot water for domestic usage represents only a small percentage of sources of GHG emissions from a person on average.

4.2.3. Water Turbines (WT)

Cuenca has four rivers—Machangara (with a length of 30 km), Tarqui (with a length of 36 km), Tomebamba (with a length of 38 km), and Yanuncay (with a length of 36 km) [21]. These rivers provide more than sufficient water to meet the water needs of Cuenca. Azuay and Cuenca are well known in Ecuador as the centre for hydroelectricity generation. This is illustrated by the fact that 14% of Cuenca's economy comes from hydroelectric power generation [21]. The advantage of micro hydro-turbines as opposed to large hydroelectric dams is that these turbines are compact and can be installed easily along a flowing river without disrupting the ecosystem. Hydroelectric dams represent a more capital intensive and ecosystem disruptive technology that causes harm to downstream ecosystems due to creation of reservoirs and blocking the natural flow of water. Micro hydro-turbines were compact—approximately 1 m x 1.5 m x 1.5 m in dimension and could generate 5 kW of power that could operate 24 hours a day due to the river flows in Cuenca.

The installation cost of each water turbine inclusive of all operation and implementation costs would amount to USD40,000 per turbine. With this information in place, the first step to building the projection scenario was to calculate the residential electricity/energy demand. An average house in Cuenca utilizes 300 kWh per month. Even with operationally conservative calculations, one water turbine generated 100 kWh a day (with 20 hours working and 4 hours maintenance/down time). This information was crucial for calculation of the energy-saving potential in the study. Hence, one water turbine could sustain the energy requirement of 10 residences. The second step was to analyse the lengths of the four rivers running through Cuenca and measure the maximum number of water turbines (WT) that could be installed along the rivers of Cuenca. Water turbines could be installed at a recommended distance of 500 m from one another. Therefore, the lengths of the four rivers revealed that a maximum of 280 water turbines could be installed with the criteria specified by the expert in this field. For the prognoses, the installation of 100 water turbine over 5 years was assumed to develop a realistic forecast.

'Electricity generated by water turbines' was calculated by using the number of installed water turbines generating 100 kWh per day for 365 days for the annual total. Revenue generated by the electricity was calculated by utilizing the energy price of 9.9 kWh per USD. This yielded a total revenue of USD9.3 million from the project covering the implementation cost of USD5 million. The above two values were used to calculate a net USD4.2 million in undiscounted net operating profit from the water turbines project. The yearly electricity generation of 3.65 million kWh or 3.65 GWh was important for the context of Cuenca since the average residential electricity demand for the time period was calculated to be around 30 GWh. Hence, the electricity from water turbines represents a 12% coverage of Cuenca's residential electricity needs, helping measure the energy saving potential from this technology. Lastly, the cumulative GHG savings of 14.8 million kg CO_2 was an important take away from the forecast.

As mentioned earlier in Section 4.2.1, the effects of climate change were not observed in the time frame of the projections due to three reasons: (a) forecasts were developed for a short time frame (15 years), (b) due to the abundance of water in El Cajas National Park, the water management company does not see any foreseeable issue in maintaining the volumetric flow of the four rivers of Cuenca, (c)

an in-depth dedicated research on the technical details of installing the water turbines conducted for a longer time frame would be necessary to fully capture the effects of climate change on the success of the water turbine technology.

5. Discussion

The paper has presented what can be considered as a rapid assessment to prioritize WEST aimed at improving the sustainable management of scarce water resources. This approach can be potentially used by a wide range of local governments world-wide due to its limited financial and technical requirements. It can therefore be considered as part of a growing toolbox of rapid assessments that are fundamental to inform decision-making processes in relation to sustainability in general and to the water-energy nexus in particular. It should, however, be emphasized that the approach requires the existence of an appropriate institutional framework to support the implementation of the prioritized measures. This paper shows the need to include institutions and decision-making in the water–energy nexus. The feasibility of the prioritized options needs to be further assessed in relation, for example, to consumer behaviour to understand the level of cultural acceptance.

Regarding the existing institutional framework, in Ecuador, the Constitution of the Republic considers water and biodiversity as strategic sectors. This calls for the central government to regulate, control and manage these sectors under the principles of environmental sustainability, precaution, prevention and efficiency. In relation to the water and energy sector, the benefits of regulation associated with 'Plan de Accion REDD+' represent a high priority in Ecuador at both national and local level. Important efforts have been made to promote a change in the energy matrix based on the development of eight key hydroelectric projects. It is expected that, once completed, they will contribute significantly to the reduction of CO_2 emissions in the country. Furthermore, multiple government plans and policies have been launched with the aim to activate stakeholders at national and local levels, clearly defining targets and responsibilities of different actors from the public, private and community sectors. The assumption is that local governments, including in Cuenca, should devise policies and strategies for prioritising, sharing, and managing available resources, while taking into account local demands. This is one of the reasons why the methodology proposed by the paper is of extreme importance within the local context in Ecuador and beyond. Local governments should engage the various water users in discussing analyses, choices, and decisions related to water resources and also foster a culture of long-term planning that takes into account climate change dynamics and looks beyond short-term financial calculations.

The local government in Cuenca needs to work with the public utilities company ETAPA (Empresa de Telecomunicaciones, Agua Potable, Alcantarillado) and the academia to bolster efforts into conducting in-depth studies to verify the findings of this research especially for solar water heaters. The implementation of solar water heaters matches the objectives of a programme in Cuenca to encourage residents to transition from liquefied petroleum gas LPG tanks towards electricity-based devices. As confirmed by the experts consulted as part of the study, the potential of a replication of WEST all over Ecuador is significant. Therefore, further research studies and pilot projects should be encouraged to implement successful WEST applications and use these implementation models for replication across the country. Another advantage of WEST also confirmed by the experts interviewed is that these can promote local manufacturing activity since the technologies required to produce solar water heaters are available locally. It should however be pointed out that ETAPA was found to have a rather narrow sector-specific approach in their management of natural resources. The measurement of water and energy efficiency, and particularly the steps taken to improve the efficiency, were found to be low on the transdisciplinary and inter-sectoral scale. For example, ETAPA considered the increase in water demand in the future due to population increase, rising urbanisation and industrial demand manageable in view of the abundance of freshwater reserves in the El Cajas National Park, the Andean glacier and lagoon system that feeds freshwater to the four rivers flowing through Cuenca and the Azuay region. This assumption lacks scientific validation based on the analysis of future

precipitation patterns from meteorological and hydrological experts. Contrasting views on climate change and its associated risks are but natural due to the uncertainty. However, they should be discussed openly in the public domain and appropriate strategies should be in place to mitigate the potential risks and uncertainties. Furthermore, the lack of transdisciplinary and inter-sectoral approaches limits the innovativeness of the solutions implemented. For example, solar water heaters installed at the residential level in Cuenca would save enough money for the government due to the reduced importing needs for LPG from abroad which would be sufficient to fund and implement residential-level rainwater harvesting equipment for all residences of Cuenca. This would strengthen energy sector resilience and sustainability (solar energy) while simultaneously enabling a water sector innovation (harvesting rainwater) which could be too expensive as a stand-alone solution. Co-benefits can only be tapped into if integrated approaches are promoted.

6. Conclusions

This study has assessed the impact and feasibility of implementing three different WEST in urban Cuenca and the development of a projection forecast for the next 15 years for each scenario. While rainfall harvesting yielded an alternate mechanism which would remove the necessity to expand the production capacities of the four potable water treatment plants to meet the needs of Cuenca and would provide a useful tool for the city to be resilient in the face of severe water shortages, it was found to be unfeasible due to two main reasons. Firstly, the implementation costs amounted to USD194 million for the coverage of all the residences in urban Cuenca and the return on investment on the project was not able to recover the costs due to low water prices (which in turn were due to the abundance of water in the region). Secondly, approximately 93% of all energy consumed by the water management systems in Cuenca was found to be consumed in the wastewater treatment facility. This wastewater treatment would be required even if rainfall was collected and therefore, rainwater harvesting did not make much impact in energy or GHG savings in the prognosis. Overall, rainwater harvesting technology was found unfeasible for implementation in urban Cuenca. On the contrary, solar water heaters' implementation forecast showed positive results with a potential to save USD613 million over a 15-year time period. This forecast was found to be seamlessly suitable for the government to implement [34]. Solar water heaters represent a technology that would impeccably support the program and remove the necessity for propane gas tanks in Cuenca's residences permanently. Similarly, water turbines or micro hydro-turbines were also found to be complimentary to Ecuador's and Cuenca's policies on moving the energy mix towards hydroelectricity and the project yielded economic feasibility to be considered for immediate implementation. The potential of replication WEST all over Ecuador is large. Therefore, further research studies and pilot projects should be encouraged in cities like Cuenca to implement successful WEST applications and serve these models for replication across the country. With WEST, another advantage is that they can promote in-house manufacturing since technologies like solar water heaters are relatively easy to produce with a boost to the local economy and employment.

A study of Cuenca's water metabolic cycle represents a model example of a water management system where fresh water has been abundant and the water distribution network reaches over 95% of the inhabitants. Firstly, this study paves the way to assess the inequality between water-abundant and water-scarce cities of the world in terms of the water management systems utilized such as the sources of water tapped into, technologies used to treat and distribute water, consumption patterns of inhabitants. Moreover, the research study helps to emphasize the need to take drastic measures to adapt to and mitigate the threats posed by the changing climate.

This study focused on technologies that would not only be water-saving but also energy-saving, emphasizing a transition from fossil fuel to renewable technologies that have been on high priority in mitigation plans of countries across the globe. The methodology utilized in this study was suited to the holistic approach generally demanded by local governments in developing and transitional countries, presenting the results based on a few simple indicators (e.g., water quantity, energy demand, GHG savings, monetary savings) and conducting an initial-pilot economic feasibility study of renewable

technologies. Further detailed research on the performance and implementation of each water-energy saving technology, as well as surveys of consumer behaviour to understand the cultural acceptance of these technologies by residents of Cuenca, would be needed in the near future to move to the implementation phase.

The relevance of this study is to contribute to an enhanced understanding of integrated urban water models at the urban level and the deep impact of the urban water cycle in all sectors of cities. This paper presents a study of an urban water cycle case study of Cuenca which is renowned in Latin America for its superior water management practices and water abundance in general. However, by looking at a case where hydroelectricity is the most important source of energy, a blueprint can be developed that can be emulated by other cities around the globe which rely on a less sustainable energy generation model. The lessons that can be gained from studying the case of Cuenca are important beyond Ecuador as the challenges of how to manage scarce resources are common to urban areas world-wide.

The study, however, opens the doors to further research that addresses the limitations of this paper. This research represents the first step local decision makers can take to assessing the resilience of the local water systems and preparing for the climate change threats that are both short-term and long-term. However, due to the broad focus of the study, the LCA conducted on each WEST are fairly limited in scope. For example, the environmental footprint of producing, installing and operating these water-energy saving technologies (WEST) have not been integrated into the projection forecasts. While this study helps to consider various WEST solutions, and develop an initial proposal for shortlisted and more obviously impactful WEST solutions, further research into each selected solution needs to be conducted in order to fully assess benefits and costs

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