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# Clean energy and water: assessment of Mexico for improved water services and renewable energy

**Kelly T. Sanders · Carey W. King · Ashlynn S. Stillwell · Michael E. Webber**

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**Abstract** Vast natural resources and strained water supplies make Mexico a valuable geographic setting for studying the energy-water nexus. While Mexico has historically been a major oil producing country, it struggles with water stress, as much of its land area is experiencing or approaching physical water scarcity. Solving many of Mexico's water issues will require energy for extracting, transporting, and treating water where it is needed most. Yet such energy use is not always possible since many people are not connected to an electricity grid or other decentralized energy infrastructure. In addition, a continuation of the almost decade-long trend of declining oil production and exports might reduce revenues and available energy to fund and operate new water systems. Consequently, there is an opportunity to improve water services through use of distributed renewable energy technologies that do not directly require fossil resources or large-scale infrastructure. Various policies and technologies are relevant to the energy-water nexus on a decentralized scale, which are covered in this manuscript. We use an integrated technology policy framework to assess the efficacy of integrating renewable energy and water systems in Mexico via case studies of technologies affecting energy-water policy objectives and

K. T. Sanders · A. S. Stillwell
Department of Civil, Architectural, and Environmental Engineering,
The University of Texas at Austin, 301 E. Dean Keeton St. Stop C1786,
Austin, TX 78712, USA
e-mail: kellytwomeysanders@utexas.edu

A. S. Stillwell
e-mail: astillwell@utexas.edu

C. W. King
Center for International Energy and Environmental Policy, The University of Texas at Austin,
2275 Speedway Stop 9000, Austin, TX 78712, USA
e-mail: careyking@mail.utexas.edu

M. E. Webber (✉)
Department of Mechanical Engineering, The University of Texas at Austin,
204 E. Dean Keeton St. Stop C2200, Austin, TX 78712, USA
e-mail: webber@mail.utexas.edu
URL: http://www.webberenergygroup.com

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choices. Particularly, important factors for technology development include consideration of performance parameters, cultural acceptance, willingness to pay, and financing.

**Keywords** Distributed technologies · Energy · Mexico · Policy · Renewable energy · Water · Energy-water nexus

## 1 Introduction

Sufficient access to energy and water is vital to maintaining quality of life and economic prosperity. Together they enable such things as ample food, safe drinking water, electric power, and sanitation. Inadequate access to energy and water has already placed strain on many developed and growing economies around the world. While resource deficiencies might hinder economic growth, curb power production, and reduce agricultural productivity across any demographic, poor communities are particularly vulnerable to resource constraints.

A number of factors influence the ability to access drinking water and wastewater systems: remote villages can be difficult to connect to centralized water distribution networks; local water supplies can be contaminated and require energy-intensive treatment to make the water of sufficient quality for drinking; and resource over-exploitation can leave little to no local water available to supply growing populations. Solving many of these water supply challenges requires energy. Unfortunately, often the areas that lack access to water are the same areas that lack access to electricity. Thus, due to the nexus of energy and water, these energy constraints (which inhibit water treatment and distribution) mean some people do not have access to high-quality water. As a corollary, energy availability can enable water availability at the right quality and abundance.

Globally, over 2.5 billion incidences of waterborne diseases result in approximately 2.2 million deaths per year (Montgomery and Elimelech 2007). Diarrhea alone is attributed to 1.3 million deaths of children under the age of five and is the sixth largest cause of mortality (Fink et al. 2011). Increasing access to water and sanitation is considered one of the most effective means to reduce child mortality (Fink et al. 2011). However, despite prolonged national and international efforts to increase access to clean water and wastewater services, more than 1.1 billion people lack access to clean drinking water worldwide and as many as 2.6 billion people still lack adequate sanitation (Montgomery and Elimelech 2007).

Future energy and water resource constraints are likely to intensify, especially in poor communities that might have to simultaneously manage economic and population growth, climate change, and political instability. A deficiency in either resource can exacerbate the availability of the other, since water and energy are closely related. Consequently, a constraint in one resource imposes a constraint on the other; likewise, conservation of either resource yields cross-cutting savings. Therefore, the effective management or mismanagement of water or energy can potentially yield coupled savings or coupled resource costs.

Although the relationship between energy and water has received increasing attention in the literature, analyses are typically limited to a specific region and do not provide holistic means of evaluating potential energy and water management tools at the systems level. Developing holistic tools to evaluate the efficacy of potential sustainable energy and water policies is particularly relevant in developing countries and/or regions that are particularly susceptible to climate change. Here, we describe an analytical framework for assessing the potential outcomes and trade-offs of various policy and technology options that address increasing clean water and energy access in developing economies. We use this framework to assess potential technology and policy options for addressing energy-water nexus challenges facing Mexico, a country with increased water scarcity issues in context of growing population and declining fossil energy production. This study was part of a larger project, sponsored by the International Development Research Centre's Climate Change and Water Program, assessing similar issues in Argentina, Southern Africa, and Eastern Africa.

## 2 Background

With an estimated population of over 113 million people and diverse natural resources, Mexico is a nation with opportunities for improvements in terms of the energy-water nexus. Mexico is an energy-rich nation: in 2009, it was the seventh largest producer of oil (OECD/IEA 2011) and the 15th largest producer of natural gas (Simon 2003). At the same time, Mexico oil production has declined since 2004 (EIA 2010a), and it is a water-stressed nation: most of the land area is classified as experiencing or approaching physical water scarcity (Earthscan and IWMI 2007). In 2005, 90 % of the population had access to drinking water—measured as persons with piped water to their property or access to a public source—leaving over 11 million without such access (Tortajada 2006). Furthermore, 78 % of population had access to sanitation—measured as persons connected to a sewer or septic tank system and those discharging directly to a river, lake, or ravine—leaving over 22 million without such access (Tortajada 2006). Inadequate or non-existent water and sanitation systems are usually found in rural areas, but some urban areas also lack sufficient water infrastructure. Solving much of Mexico's water issues requires energy for extracting, transporting, and treating water where it is needed most. Yet such energy use is not always possible since more than 3 million people still lack access to electricity, usually in remote regions that are difficult to connect to the grid (Cancino-Solorzano et al. 2010).

### 2.1 Oil revenues

Although Mexico's economy has been largely dependent on revenues from fossil fuel extraction, the nation's energy demand is beginning to be limited by the economics of its known reserves. Mexican oil production fell to 3 million barrels per day (MMBBLD) in 2009 from its peak of 3.9 MMBBLD in 2004 (EIA 2010a). The International Energy Outlook 2010 predicts a decreasing trend in crude production in the upcoming years and forecasts that the country might become a net importer of oil by 2015 (EIA 2010b). Even today, despite its role as a large oil exporter, Mexico is a net importer of refined petroleum products (EIA 2010b). Considering the large dependence of the Mexican economy and federal government on oil revenues, this shift will likely be detrimental to the fiscal health of the country since the oil produced by Pemex, the state owned oil company, generates over 15 % of total Mexican import revenues, and the taxes and payments from Pemex account for 40 % of the country's governmental revenues (EIA 2010b).

The drop in Mexican government revenues from energy sales and exports is important to consider because it will make internal financing of water infrastructure more difficult. Even in times of oil abundance, frequent episodes of drought and flooding have made water management across the country difficult. Although the annual renewable supply of freshwater in Mexico is generally sufficient to support the population based on per capita water needs, the supply is unequally distributed. While the Northern and Central Regions are relatively dry with 28 % of the total water, they also represent 92 % of Mexico's irrigated land and the majority of Mexican industries. In many areas where groundwater is used extensively, water extractions often exceed renewable supplies leading to unsustainable depletion. Aquifer depletion in water-scarce regions has increased significantly in the past few decades.

## 2.2 Agricultural water management

Agriculture is a large component to Mexican water resources management and policy. Seventy-one percent of Mexican land devoted to crop production in 2002 was rainfed. Accordingly, irrigation water for agriculture is important for economic well-being. But this irrigation water use can also be harmful in terms of water quantity and quality. In total, 60 % of Mexico's water consumption is for irrigation, 90 % of which is done in dry or semi-arid regions (Shah et al. 2004). Although irrigated crops only represent 29 % of total agricultural area, these irrigated crops account for 55 % of total agricultural production and 70 % of total agricultural exports (OECD 2006). The average efficiency of agricultural water use is as low as 43 % since water and electricity subsidies incentivize water exploitation, and consequently, irrigators have very little economic incentive to monitor the proper operation of their irrigation systems (OECD 2006; Shah et al. 2004). Water pollution is mainly caused by irrigation through chemical runoff, but livestock effluent is becoming an increasing factor (OECD 2006).

Agricultural water concessions account for three-fourths (by volume) of total concessions (i.e., legal rights to withdraw water as granted by the National Water Commission). In the Northern and Central regions, concessions often amount to over half of water availability, whereas little water is assigned to concessions in the South. Of these agricultural water concessions, two-thirds are tied to surface water and one-third to groundwater (OECD 2006). Concessions are not well enforced, and often exceed the allotted volume permitted. Over-extraction is often committed by smaller concession holders, though scale is usually correlated with agricultural activity since scattered, small-scale users are harder to police than large users. Often the administrative burden of enforcing concessions and collecting payments is large and costly. Applications to obtain new concessions, therefore, are often backlogged over multiple years, which promote illegal extraction of water by those who need it (Shah et al. 2004).

Agriculture policies have had both positive and negative effects on national water resources. Market price support for agricultural commodities instituted in the 1990s managed resource exploitation in comparison with prior schemes that fostered over-production (OECD 2006). However, the majority of land is owned by the community, which leads to the "tragedy of the commons"[1] with resource exploitation: since no individual is held responsible, it is difficult to implement resource management policies or reprimand bad behavior (Hardin 1968). Water use subsidies, as exemption from fees or subsidies for the energy needed for irrigation, also encourage over-use or misuse of water. Although subsidies were implemented to alleviate poverty in agricultural communities, water subsidies tend to be concentrated in the economically rich north, so such policies have been

[1] The "tragedy of the commons" refers to a concept of environmental risk induced by shared (or common) land for which there is no single property owner or regulatory authority to oversee its sustainable management. The idea was published by Garrett Hardin in *Science*, December 13, 1968.

ineffective. In 2003, an important policy was enacted to remove farmers' exemption for water charges, which was intended to reduce water waste and misuse (OECD 2006). However, the lack of data does not enable a full evaluation of agricultural policies' impact on increasing equitable access water resources since that year.

## 2.3 Urban water management

Urban water management presents a different set of challenges compared to rural locations. Seventy-seven percent of the Mexican population lives in urban areas, the largest of which is Mexico City—the nation's capital and political, cultural, educational, and financial center. Mexico City, with 20.5 million people, is the third largest city in the world (CIA 2011). Mexico City also has a large percentage of people living below the poverty line with 18 % of its population classified as very low socioeconomic status and 67 % as low-medium (Tortajada 2006). Thus, providing clean, affordable water and energy to this population is extremely important.

In 2000, over 95 % of the population of Mexico City had access to drinking water, either to a household or via a common community pipeline. The percentage of the population with water access in Mexico City is higher than that of the State of Mexico at approximately 84 % (Adler 2011). Unfortunately, an estimated eight million people in Mexico City do not have reliable access to the centralized water supply, and those that do receive tap water from the city question its quality (Tortajada 1998, 2006). Thus, Mexico is the world's second largest consumer of bottled water (Tortajada 2006). While access to this bottled water supply is better than having no clean water, interruptions in service typically occur in the poorest neighborhoods, where the cost of bottled water can significantly reduce discretionary income that could potentially be invested otherwise (Haggarty et al. 2001).

Leaks play an important role in Mexico City's water management, as water shortages are frequent. On average, a 10 % deficit in water supply exists in Mexico City, which is exacerbated by high leakage rates estimated at 35 % or more (Ibarguengoitia 2010). These leakages represent 1,300 L/capita/d—enough to supply 4 million people, or half of residents without a reliable supply. For those with intermittent or no water service, this water waste from high leakage rates creates unnecessary hardships as most people that lack access to the centralized water network are forced to spend an average of 6 to 25 % of their daily income on 100-L water containers delivered by trucks. These people are typically the poorest, yet pay 500 % more for water than those that receive the city's water (Tortajada 2006). In addition to social equity issues of water purchases, buying water from petroleum-consuming trucks represents an energy-intensive, costly, and inefficient method of delivering freshwater.

Water delivered within Mexico City's centralized water system is also extremely energy intensive and costly. Although the city was built on a huge groundwater aquifer, population growth and climate change have altered the hydrology of the region, forcing water planners to look far outside the boundaries of the city to meet its needs (Adler 2011; Lankao 2010; Tortajada 2006). Currently, the groundwater resources beneath the city can only meet 70 % of the metropolitan area's supply. Pumping of the aquifers is estimated to be two to three times the natural recharge rate [45–54 $m^3$/s average annual withdrawal rate compared to 20 $m^3$/s recharge rate[2] (Tortajada 2006)] and has caused subsidence—now 0.4 m/year—in

[2] Extraction rates over 0.4 times refill rates are considered extreme by United Nations (Ibarguengoitia 2010).

the area since 1925. The remaining demand now is met by surface water reservoirs outside the periphery of the city in the Lerma-Balsas and Cutzamala River basins, which contribute 21 and 9 % of Mexico City's demand, respectively. Water coming from the Cutzamala is pumped over long distances of up to 154 km, to elevations of over 980 m from the Cutzamala River to Mexico City, using 102 pumping stations, 17 tunnels, and 7.5 km of canals. (Tortajada 2006). It is estimated that this system consumes 1.79 billion kWh per year,[3] which comes at a cost of $62.5 million dollars, annually (not including treatment and personnel). Energy consumption for such water delivery systems is likely to increase in the future as increasingly distant water supplies are needed to fulfill growing demands (Tortajada 2006).

Ironically, while Mexico City suffers from a deficient water supply, flooding still occurs during the rainy season (Ibarguengoitia 2010). And, as climate change has been associated with more intense droughts, it might also lead to more frequent flooding (Ibarguengoitia 2010). Depending on the season, 20–70 % of wastewater might be rain, which overwhelms the city's feeble and relatively small sewer system. The city's storm runoff is often more than the amount of surface water available for its supply. Despite significant investments to combat flooding for the past 400 years, floods still plague the area, and drainage and sewer infrastructure are ineffective (Ibarguengoitia 2010). For example, in 2010, a major channel carrying wastewater effluent and excess rainwater from the city collapsed, displacing thousands of people and causing widespread concern over mosquito-borne diseases and other illnesses caused by the stagnant wastewater (Adler 2011). Groundwater recharge and rainwater harvesting are two possible approaches to sustainable flood management.

Although Mexico City's centralized supply-driven approach to water supply has not been successful, recent policy shifts toward decentralization of urban water management in Mexico City have been equally ineffective. Poor water quality, high levels of unaccounted for water (via high leakage rates), marked social inequity in terms of water access, and enormous water waste are problems that have plagued Mexico City (Tortajada 2006). Yet little liability can be assigned to the mismanagement of water resources, and the various stakeholders are not incentivized to fix infrastructure (Espinosa 2002). With many stakeholders in many regions involved in water supply to the Mexico City Metropolitan area, water system accountability and efficiency are rare (Haggarty et al. 2001). Although current water deliveries are insufficient to meet the city's water demand, new proposals to increase drinking water supplies via interbasin transfers are extremely energy intensive and costly, which exacerbate inaction. Wastewater management is also very poor, with only one-third of wastewater in the Distrito Federal (Federal District, DF) receiving treatment before discharge to water bodies (Ibarguengoitia 2010). Projected increases in drought and flooding due to climate change will likely exacerbate current water management challenges (MacDonald et al. 2008; Figueres et al. 2003).

Decreasing fossil energy reserves (and revenues) in the face of increased water management challenges provide a difficult context for addressing water quantity and quality issues. In the absence of energy (or fiscal) and environmental (e.g., carbon) restraints, treating and moving water of any quality over any distance is conceivable. However, Mexico, like much of the world, is financially and resource constrained. Thus, a variety of policy and technology changes must be incorporated in order to ensure a clean and abundant water supply that can sustain a growing population while preserving the environment.

[3] To put this amount in perspective, it is similar to the total amount of electricity consumed by Puebla, a nearby state of 8.3 million residents.

### 2.4 Climate

Because of Mexico's latitude, climate change is anticipated to exacerbate water scarcity in many regions of Mexico due to increased drought. Models and observed trends agree on a trend toward higher precipitation at high northern latitudes (50°–80°N, northern Canada), lower precipitation in low northern latitudes (0°–30°N, Mexico to equator), but with no conclusive trend for mid-latitudes encompassing the majority of the United States and southern Canada (Zhang et al. 2007). Additionally, under high greenhouse gas emissions scenarios, most climate models tend to show increased values for drought indicators (more consecutive dry days and/or more soil moisture anomalies) in southwestern United States and Mexico [see Figure 3-10 and Table 3-3 (IPCC 2012)]. Thus, the Intergovernmental Panel on Climate Change (IPCC) expresses *medium confidence* that droughts will intensify in the twenty-first century in Central North America, Central America, and Mexico with over 90 % of Global Climate Models anticipating drier future conditions for many portions of Mexico (IPCC 2012).

With higher temperatures and less precipitation expected for northern Mexico, this region could increasingly struggle to produce agricultural products and supply water to municipalities in an already arid region of the world (Stahle et al. 2009). The drought persisting over the years of 2009 and 2010 marked one of the most severe in terms of water scarcity over the past century; during some months, as many as 5 million people lacked sufficient access to water (Adler 2011). Prior work (MacDonald et al. 2008) suggests that because of anticipated ongoing warming from global climate change, the latest North American drought could be signaling a transition to a state of persistent aridity and more prolonged droughts. Although it is widely accepted that climate change is expected to exacerbate existing water scarcity issues in Mexico (Wilder et al. 2012; MacDonald et al. 2008; Stahle et al. 2009), implementing more robust water management strategies is necessary to address *current as well as future* resource concerns (i.e., population growth, inadequate clean water and wastewater infrastructure, urbanization, unsustainable agricultural practices, etc.). Thus, we focus on increasing clean water and renewable energy infrastructure as means to placate existing water resource constraints (while decreasing dependence on fossil fuel reserves) rather than evaluating the efficacy of technology and policy choices as specific adaptive responses to climate change.[4] Our analysis considers suitable technologies and policies for utilizing renewable energy for increasing clean water access, but does not focus on macroeconomic or international trade implications. However, in most cases, technologies that offer resilience to existing water scarcity concerns (i.e., maintaining access to clean water and sanitation in the event of a failure of centralized infrastructure) will also add resilience to failed or inconsistent water services in the context of climate change.

## 3 Methodology

The purpose of this manuscript is to present a framework for achieving a variety of policy objectives to address water resource constraints in countries that have water services and

[4] For example, although improved information gathering systems such as information and communication technologies (ICT) are touted in terms of their potential role as effective adaptive responses to climate change (Wilder et al. 2012), we only discuss ICT systems in terms of addressing existing water management challenges.

infrastructure that are either of low quality of not fully distributed to all citizens. While the technology and policy options outlined are particularly relevant in growing economies, the matrix (Table 1) yields insight into general policy objectives that would benefit growing and developed economies alike. Here, we present case studies based in Mexico, but the general framework can be extended to other regions that experience similar resource constraints.

We use Mexico as a case study since it is a country that is faced with a full spectrum of water management and energy resource challenges. Geographically, Mexico is one of the most diverse countries of the world, spanning desert, coastal, mountainous, and lush ecosystems. The climate is such that it can experience extreme flooding and drought, in the same locale, within the same year. Regions such as Mexico City are so densely populated that sanitation and supply become the primary public health burden, while citizens in rural areas lack access to a safe water supply, electricity, and sanitation infrastructure altogether. While the energy industry suffers from declining oil and natural gas production, agricultural and industrial sectors cannot ensure the water required to sustain their economic well-being, exacerbating Mexican citizens' access to water and energy resources. At the same time, strong solar, wind, geothermal, and hydroelectric resources offer the potential for Mexico to become a leading producer of renewable energy globally (Cancino-Solorzano et al. 2010). Strategies to effectively manage the breadth of issues facing water and energy planners in Mexico offer useful insights into a wide spectrum of challenges facing growing economies around the world.

Although different countries have varying goals defined regarding energy, water, and carbon management, we define five broad policy objectives as an organizing framework for evaluating various technology and policy choices including water security, energy security, water quality, carbon management, and renewable energy. Here, water security and energy security refer to the reliable access to clean water or energy, respectively, by means of an increased supply, increased efficiency, or increased conservation. Increased water quality refers to the effective mitigation of anthropogenic impacts that degrade the ambient natural aquatic environment through pollution (i.e., thermal, nutrient, total dissolved solids, etc.), while carbon management refers to the reduction in anthropogenic carbon emissions. Renewable energy relates to the generation of energy from solar (sunlight, wind, waves, biomass), gravitational (tides and falling water), and geothermal resources (King et al. 2013).

Each technology listed in the left-most column of Table 1 is assigned a corresponding symbol to signify the efficacy of each technology on achieving each policy objective, and the efficacy of policies that might encourage the adoption of each of those technology options. For detailed definitions of the policy objectives and policy choices listed in Table 1, see King et al. (2013). In Table 1, an up arrow (↑) indicates that the technology helps to achieve the policy objective, a down arrow (↓) indicates that the technology hinders achievement of the policy objective, a level arrow (↔) indicates that the technology has choices and trade-offs that make its effect upon the policy objective site specific or unclear, and dashes (–) indicate that the technology has no appreciable impact on the policy objective. In situations where a technology can be used for widely varying purposes, multiple arrows indicate the outcome can be different depending upon the application. The ● symbol indicates policy choices that can be effective in increasing or decreasing use of a technology, and the ○ symbol indicates policy choices that are only moderately effective (King et al. 2013).

It is important to note that a technology that achieves one policy objective might be detrimental to achieving another objective (King et al. 2013). For example, the widespread deployment of distributed rainwater collection barrels to provide potable water might

**Table 1** A list of technology and policy tools that can be used in combination to achieve certain policy objectives for securing clean water access in developing or remote rural economies

| Technologies | Policy objectives | | | | | Policy choices that can influence use of technologies | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Water security | Energy security | Water quality | Carbon Mgmt. | Renewable Energy | Public relations and community engagement | Mandate/ regulation | Right pricing | Subsidy | Financing (micro and macro) |
| *Distributed energy-water technologies and systems applicable for region* | | | | | | | | | | |
| No/low-flow plumbing fixtures | ↑ | ↑ | – | ↑ | – | ○ | ● | ○ | ● | |
| Energy-efficient appliances | ↑ | ↑ | – | ↑ | – | ○ | ● | ○ | ● | |
| Distributed rainwater collection (non-potable uses) | ↑ | ↓ | ↑ | ↓ | – | ○ | ● | ● | ● | ○ |
| Solar hot water heating | ↑ | ↑ | ↑ | ↑ | ↑ | ○ | ● | ● | ● | ○ |
| Solar distillation of saline water sources | ↑ | ↑ | ↔ | ↑ | ↑ | ○ | | | ● | ○ |
| Geothermal heat pumps | ↑ | ↑ | ↔ to ↑ | ↑ | ↑ | ○ | ● | ● | ● | ○ |
| Groundwater pumping (coupled to renewable electric sources) | ↔ | ↓ | – | ↓ | – | | ● | ● | ● | ○ |
| Residential/building-scale solar photovoltaic | ↑ | ↑ | – | ↑ | ↑ | | ● | ● | ● | ○ |
| Residential/building-scale and community owned wind power | ↑ | ↑ | – | ↑ | ↑ | | ● | ● | ● | ○ |
| Desalination by distributed renewable electricity or heat | ↑ | ↓ | ↔ | ↑ | ↑ | | | ● | ● | ○ |
| Municipal waste and wastewater to energy | ↑ | ↑ | – | ↑ | ↑ | | ● | ● | | |
| Combined heat and power (connected to local biomass combustion) | ↑ | ↑ | – | ↑ | ↔ | | ● | ○ | ● | ○ |

**Table 1** continued

| Technologies | Policy objectives | | | | | Policy choices that can influence use of technologies | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Water security | Energy security | Water quality | Carbon Mgmt. | Renewable Energy | Public relations and community engagement | Mandate/ regulation | Right pricing | Subsidy | Financing (micro and macro) |
| Hydropower | ↑ | ↑ | ↓ | ↑ | ↑ | | ● | ○ | | |
| Irrigated agriculture | ↓ | ↓ | ↓ | ↔ | – | | ● | ● | ● | |
| Information and communication technologies (ICT) | ↑ | ↑ | ↑ | ↑ | ↑ | ● | ○ | ● | | |
| Gray water and reclaimed water use | ↑ | ↔ | – | – | – | | ● | ● | ○^ | ○^ |

○^ Gray water use applicable for residential and commercial buildings most applicable for help from subsidies and financing

○ Somewhat effective

● Effective

increase water security in areas that lack a dependable, centralized water delivery and treatment system. However, installing point-of-use treatment technologies to treat water to standards acceptable for drinking would result in an overall increase in energy use for water treatment. (If this energy is provided by fossil fuel sources, the increased energy consumption would likely result in an increase in carbon emissions as well.) Thus, this matrix is useful in evaluating trade-offs regarding energy and water services, particularly in developing countries.

## 4 Assessment of Mexico

Several examples of technology and policies in Table 1 are evaluated that achieve one or more of the five energy and water policy objectives—water security, energy security, water quality, carbon management, and renewable energy.

### 4.1 No/low-flow plumbing fixtures

As early as 1989, the governing body of Mexico City set forth an initiative that resulted in a 2-year replacement of over 350,000 toilets averaging 16 L per flush by toilets requiring only 6 L per flush. Estimates suggest that the water saved by these low-flow installments saved the city the water required to meet the needs of 250,000 residents. More recently, during the 2009 drought, the government outlined a plan to replace 4.7 million shower fixtures and 1.7 million toilets with more water-efficient technologies. These replacements were projected to save the city 420,000 L of water per minute in comparison with 2009 baseline consumption. In some cases, the low-flow appliances were offered free of cost (Policy Choice: subsidy) to the consumer with the trade in of the original fixture. The program was supported by the introduction of green labeling to signify certified products meeting the requirements of "low-flow" technologies (i.e., less than 3.8 L/min and 5 L per flush for shower heads and toilets, respectively) (Adler 2011). Using less water also means that less energy (and embedded carbon) is used to carry water to and from the point of use.

### 4.2 Energy-efficient appliances

The Mexican Energy Ministry oversees a program intended to replace air conditioners and refrigerators of age 10 years or older with a more energy-efficient machine. This initiative is supported by allocating vouchers that cover the costs of replacing the older appliance (including transportation, collection, and the destruction costs; Policy Choice: subsidy) or direct financing of a new appliance (Policy Choice: financing). In 2009, this program was estimated to save nearly 300 GWh per year (Rosas-Flores et al. 2011). Water and/or energy savings vary depending on the type of appliance replaced.

### 4.3 Distributed rainwater collection

In the past few years, decentralized rainwater harvesting (DRH) systems have offered a means of both supplementing strained water sources in times of drought and reducing pumping demand during times of flood. Since 2009, a non-profit called Isla Urbana has been installing distributed rainwater harvesting systems to bring non-potable water to families in Mexico City that would not otherwise have access to an affordable water supply. One of the successes with Isla Urbana's rainwater harvesting installations has been its attention to educating the local workforce to install the systems, using local materials, and teaching families about the merits and upkeep of their systems (Policy Choice: public relations, community engagement). Integrating cultural considerations into the deployment of a new technology has proven critical to its success.

As of June 2011, 521 systems, serving nearly 3,720 people, have been installed. Although these systems cannot supply the entirety of a family's annual water demand, one system can supply, on average, about one-half of a family's water needs. The organization estimates that 50 % of Mexico City's residential water demand can be met by rainwater harvesting systems if implemented on a large scale (IslaUrbana 2011). This water volume equals that currently pumped into the city through interbasin transfers. Although the literature indicates that using DRH reduces energy use when gravity-fed water is used for non-potable purposes, it can actually increase energy use when the water must be treated and/or pressurized at the point of use to potable standards (Retamal et al. 2009).

### 4.4 Solar hot water heating

Solar Water Heaters (SWHs) are renewable energy technologies that use available solar heat to warm a working fluid, which heats water in a heat exchanger and stores excess heat in a thermal store (Mallett 2007). The introduction of SWH installations at residences in Mexico City had not been successfully integrated into the culture until 2007 when the Mexican Energy Commission released its *Programme to Promote Solar Water Heating* (PROCALSOL), which intends to triple the country's installed surface area of solar collectors by 2012 (Policy Choice: public relations). Although attempts had been made for over 30 years to markedly increase the deployment of solar hot water heaters, this policy was the first to successfully integrate the efforts of both private and public stakeholders across disparate disciplines such as manufacturing, finance, and government, to increase the rate of technology transfer to the public (Policy Choice: finance) (BMZ 2011). Also, critical was a partnership with the German entity, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), who provided technical and regulatory advice to the Mexican government.

Despite stakeholder investment, there were a number of issues that contributed to the public's resistance to SWH prior to the advent of PROCALSOL. First, there were no standards for renewable energy technologies such as SWH, making it very difficult for consumers to select a good system that would work for their particular needs. Systems were typically built by foreign companies, but sold by local distributors that had very little knowledge about the installation or operation of the systems. This unfamiliarity with the technology typically resulted in faulty installations by the buyer, in which case the technology did not operate according to its specifications. Bad installations were typically not remediated since sellers were only present at the point of sale and offered no follow-up with the customer (Mallett 2007).

After the implementation of PROCALSOL, however, a number of these issues were mollified, which has significantly increased the uptake of the SWH technology and reduced the use of natural gas and petroleum for water heating—thus adding energy resiliency by adapting to use a local renewable resource. Public awareness campaigns have been launched to inform the public about the economic, environmental, and technological benefits of the systems (Policy Choice: public relations, community engagement). Training and certification programs, in tandem with rigid quality standards complimented with handbooks, training materials, and websites to inform buyers, sellers, and installers, created an environment to foster high-quality installations (Policy Choice: regulation for standards). Overall, these efforts have significantly increased public awareness and utilization of the solar heating technologies (BMZ 2011).

## 4.5 Groundwater pumping and irrigated agriculture

Unsustainable groundwater depletion has led to many depleted aquifers, especially in the highly irrigated northern region of the country. Water and electricity subsidies, intended to help poor farmers, incentivize water (and energy) exploitation (OECD 2006; Shah et al. 2004). In many regions of Mexico, groundwater aquifers are being depleted faster than they can be naturally recharged. This groundwater mining can lower the water table, which increases the amount of energy required to pump water from the aquifer. In some cases, it will cause aquifer depletion. In 1975, 32 of 202 measured aquifers were considered over-exploited; the number increased to over 100 by 2005. This total is likely understated, since 451 aquifers are not monitored (OECD 2006), making identification of resource depletion or contamination challenging. Groundwater depletions are highest in the northern regions, which contain the majority of Mexico's industries, but only 20 % of its precipitation (Shah et al. 2004).

Ironically, subsidies (Policy Choice: subsidies) for water-efficient irrigation technologies often result in a net increase in water use at the river basin level as optimal water application causes agricultural expansion at maximum water consumption via evapotranspiration, without any return flow to surface water supplies or groundwater aquifers (Ward and Pulido-Velazquez 2008). Mexico can decrease the over-exploitation of groundwater aquifers through regulations (Policy Choice: regulation) that prohibit the expansion of pumping and proper scientific data collection and information dissemination (Policy Choice: public relations, community engagement).

## 4.6 Information and communication technologies

The amount of water granted by means of water concessions is not always available for use when needed. This disparity occurs partially because water rights are often rented from landowners over a year in advance, before it is known how much water will be available. Better information can more effectively allocate water on a real-time and seasonal basis (Policy Choice: community engagement to make existing regulation more effective). Water quotas are allocated to landowners based on normal water use and can be rented to farmers at a price that reflects the profitability of their crop and the availability of water for delivery. Thus, when shortages exist, those farmers with high-valued crops are usually given precedent over the water since they have paid expensive costs for insurance on water rights in the case that the original quotas cannot be distributed. Farmers who cannot pay the cost for insurance do not receive their anticipated volume of water determined by normal use quotas in times of low water availability (Skees and Leiva 2005).

Remote sensing technologies have improved water management, especially in highly irrigated, arid regions, such as those in Northwest Mexico (Skees and Leiva 2005). Remote wireless information communication technologies (ICT) and remote control technologies enable water managers to have accurate knowledge of water distribution to each of dozens of irrigation modules within each irrigation district. Also, groundwater wells can be operated remotely. Implementing on-site ICT and measurement and control devices on wells could increase the ability of the Comisión Nacional del Agua (National Water Commission, CNA), the Sociedades de Responsabilidad, and irrigation districts to monitor, control, and govern water withdrawals in efforts to slow the decline of water tables. More generally, ICTs enable up-to-date information needed to base actions for adaptation to short-term (drought) and long-term (climate change) trends. PLEIADeS (Participatory multi-Level EO-assisted tools for Irrigation water management and Agricultural Decision Support) is an example that has been proposed as a tool to improve water management in Mexico's Sonora River Valley (PLEIADeS 2011). It would provide real-time data on farm-level water consumption that could be used for irrigation efficiency and aquifer stabilization. Another program SIRIUS (Sustainable Irrigation water management and River basin governance) is focusing on the Rio Yaqui and Rio Mayo irrigation districts.

### 4.7 Solar photovoltaic and wind electricity

Mexico has enormous solar potential, receiving an average of 5 kWh per square meter per day of insolation. In 2006, 17,633 kW of photovoltaic modules were installed for rural electrification, communications, and water pumping. By 2013, 25 MW from photovoltaic modules are expected to be online (14 GWh/year) (Cancino-Solorzano et al. 2010). (To put this in perspective, Mexico consumed 212,000 GWh of electricity in 2010 (EIA 2012).) Currently, the largest installations are in San Juanico (Baja California) and Agua Prieta Sonora (Cancino-Solorzano et al. 2010).

In addition to solar PV, concentrating solar power (CSP) is a form of solar-powered electricity generation that uses mirrors or lenses to concentrate solar energy on small regions to create sufficient heat to drive thermoelectric steam cycles. Although Mexico has strong potential for CSP technologies from a resource adequacy perspective (Trieb et al. 2009), it has drawbacks such as high costs and intermittency issues. Developing countries generally lack the regulatory framework to incentivize investments in CSP over other forms of electricity. However, with robust policy creation, it is possible that levers such as feed-in tariffs might make CSP a viable strategy for electricity generation in developing countries (Kulichenko and Wirth 2012).

The country also has vast wind resources. The Isthmus of Tehuantepec has among the best wind resources in the world, and several analyses indicate nationwide wind energy generation potential of more than 40 GW [which is comparable to 65 % of Mexico's total installed capacity in 2010 (EIA 2012)]. The year 2007 marked the inauguration of the first large-scale wind farm (La Venta II with 83 MW) in Mexico. By the end of 2012, projections suggest that the country will have over 2 GW of wind power installations, nearly triple the total installations present in 2010 (Cheeseman 2012). Although most of this capacity is in large-scale wind farms, building-scale wind turbines are an attractive option for more densely populated urban centers.

Wind installations and distributed solar photovoltaic technologies are especially promising in rural regions that might be too expensive to connect to the grid or centralized water network. For example, the state of Baja California Sur (BCS) is the least populated state in Mexico with slightly over 1 million people. Population density is the lowest in the nation with over 2,400 settlements, only 17 of which are urban (Bermudez-Contreras et al. 2008). Unlike the rest of Mexico, BCS does not have ample gas and oil resources and is not connected to the national grid. Gasoline, diesel, and liquefied petroleum gas arrive by sea.

The majority of Mexico's renewable energy generation to date has been due to the fact that it has become a popular host country for Clean Development Mechanism (CDM)[5] projects, not due to Mexico's own policymaking (Policy Choice: subsidy, *although not a*

[5] Clean Development Mechanism (CDM) projects are activities that (Annex I) countries that have signed the Kyoto Protocol can fund in developing nations (non-Annex I) to offset carbon emissions in their home country. These activities are intended to allow Annex I countries to meet their reduction targets at a lower

*subsidy funded internally within Mexico*). As of April 2011, Mexico has 249 CDM projects of varying scope, completed or under development (Dechezlepretre et al. 2009). The average CDM project size in Mexico is 70–80 kt $CO_2$ equivalent ($CO_2$e)/year, and the median CDM project size is approximately 20 kt $CO_2$e/year (Dechezlepretre et al. 2009). In total, current CDM projects in Mexico have the potential to offset nearly 19 Mt-$CO_2$ per year and add 5.1 GW of renewable electricity generating capacity (UNFCCC 2011). (In 2010, Mexico had 62 GW of total installed capacity (EIA 2010b).)

### 4.8 Desalination by distributed renewable energy or heat

Solar-powered desalination offers an alternative to costly water imports. Desalination is growing in Mexico, especially in water-scarce tourist regions such as the BCS. A total of 67 desalination systems are in operation in the BCS, alone, both state managed and private, with 13 more under construction. Of the 67 operating systems, 54 desalinate brackish water and 13 desalinate seawater using mostly reverse osmosis technology (four use multi-stage flash) with all systems using conventional sources of power. Despite the current reliance on conventional sources of power, some desalination facilities have worked to harness solar power. The first efforts to integrate solar power and desalination focused primarily on thermal desalination, with past projects in Puerto Chale in the 1970s, La Paz and Las Barrancas in 1980, and El Pardito in 1993. Current solar desalination projects utilize reverse osmosis technology, using solar PV arrays with battery banks to treat seawater. These current solar desalination installations can produce 19 $m^3$/day (Bermudez-Contreras et al. 2008). Reported benefits of solar desalination in BCS include providing electricity and clean water to communities without access to electricity or primary fuel resources or water networks. Economics (Policy Choice: right pricing and financing), reverse osmosis membrane maintenance, energy recovery, and energy storage are concerns that limit implementation and performance of solar desalination systems (Bermudez-Contreras et al. 2008).

### 4.9 Municipal wastewater to energy

Despite the relative energy efficiency of centralized wastewater treatment over distributed systems, massive infrastructure investments can be a burden for installation of centralized wastewater treatment in areas without existing sanitation, like rural Mexico. In response, some communities install decentralized, distributed wastewater treatment technologies, such as septic tanks, package treatment systems, and membrane bioreactors (MBRs) (Makropoulos and Butler 2010). Package treatment systems perform many of the same operations as centralized treatment facilities on a smaller scale and could be suitable for some areas of Mexico. MBRs use membrane technology to facilitate digestion of organic contaminants in wastewater and separate solids from cleaner effluent in a compact unit operation. These small-scale wastewater treatment technologies are well suited for remote locations and areas where constructing sewer mains connecting to a centralized facility is economically infeasible, yet require electricity for operations.

Energy and nutrient recovery is possible on a distributed scale using heat recovery and microbial fuel cells (MFCs), among other technologies (Daigger 2009; Oh et al. 2010).

Footnote 5 continued
cost while transferring knowledge and technology to lesser-developed countries so that they might develop more sustainably.

Since wastewater contains low-grade heat, thermal energy can be recovered using a heat exchanger or heat pump and is up to 1.5 times as efficient in colder months than using outside air (Spencer et al. 2008). Use of MFCs generates electricity via oxidation–reduction reactions on a biofilm surface that simultaneously cleans wastewater and produces less sludge than similarly sized activated sludge treatment units, though operation and control of MFCs can be challenging (Oh et al. 2010). Source separation—separating various waste streams at the source of generation—is important for feasible energy and nutrient recovery with distributed wastewater treatment technologies (Daigger 2009). Implementing such sophisticated wastewater systems, however, can encounter cultural resistance due to lack of familiarity with the technology (Policy Choice: public relations and community engagement for training and education).

### 4.10 Hydropower

Mexico has approximately 11.4 GW of installed hydropower capacity [approximately 18 % of total installed capacity (EIA 2012)] that generated 39 and 26 TWh of hydroelectric power in 2008 and 2009, respectively (EIA 2010a). The Comisión Reguladora de Energía (Energy Regulatory Commission, CRE) estimates that hydroelectric generation could reach 80 TWh/year based on this potential capacity estimate; however, hydropower often encounters tough opposition (Policy Choice: public relations and community engagement). A large recent installment of 750 MW of hydropower in March 2007 attracted harsh criticism for economic, political, social, and environmental reasons (Cancino-Solorzano et al. 2010).

### 4.11 Gray water and reclaimed water

The application of municipal wastewater to irrigate cropland has been a widespread practice in Mexico for decades. In many cases, raw, untreated water is directly applied to fields. In the Mexico City Metropolitan area, approximately 70 % of all wastewater is discharged, without any form of treatment, to agricultural land (Siemens et al. 2008). Since wastewater contains high concentrations of nitrogen, phosphorus, and organic matter, many farmers actually oppose any treatment of wastewater that might compromise nutrient levels. However, irrigating dedicated food crops with raw wastewater can threaten public health and the environment through the exposure to pathogens (Qadir et al. 2010) and is a practice not generally accepted in most developed countries (Mendoza-Espinosa et al. 2004).

With adequate primary and secondary treatment, wastewater reclamation could be a good means of supplementing the water supply in water-stressed areas. The city of Ensenada is one of only a handful of cities in Mexico that treats the entirety of its wastewater. Approximately 2 % of this water was reused for purposes such as the irrigation of sports fields and public landscaping in 2002 (Mendoza-Espinosa et al. 2004). Many consider the artificial recharge of depleted groundwater aquifers another viable option to increase the water supply in water strained regions, especially once regulations are implemented to ensure adequate sanitation is observed (Carrera-Hernández and Gaskin 2009; Ibarguengoitia 2010). Potable reuse of reclaimed water, as in most of the world, is not currently an accepted practice in Mexico. In order to protect the health of farmers and consumers alike, more education and regulations need to be implemented in order to reduce the transmission of pathogens from wastewater to humans (Policy Choice: regulation).

## 5 Conclusions

Traditional energy resource production, such as petroleum, is declining in Mexico. Because the federal government depends upon oil revenues, lower oil production poses challenges for internal energy use as well as for financing of infrastructure projects, which is particularly relevant for water. Many of Mexico's future energy and water challenges can be addressed using a variety of technologies and policies, but the outcomes from the different options are often difficult to anticipate. This manuscript presents an analytical framework for assessing different options for managing and providing for water services, and we concluded that there are several technology and policy options that would be beneficial for Mexico's water needs. Some of these technologies include solar hot water heaters, renewable electricity systems tied to distributed water treatment and desalination systems, and information and communication technologies (ICT).

Consideration of performance parameters, cultural acceptance, willingness to pay, and financing can increase the likelihood of success for new technologies. Some successful programs have enabled renewable technologies to become more widely dispersed by policy choices to engage with communities (training, education) to increase cultural acceptance and use targeted subsidies both within and from outside Mexico (e.g., CDM) to overcome a low willingness to pay or lack of financing. For example, solar water heating in Mexico has overcome low levels of cultural acceptance via PROCALSOL efforts to integrate public and private groups. Solar PV and ICTs could follow a similar path as solar hot water heaters for successful deployment. Some technologies such as decentralized energy recovery from wastewater, however, might face strong cultural resistance due to unfamiliarity with the technology and need for more broad technical knowledge. Other subsidies and lack of regulatory enforcement pose current and future risks for management of Mexico's water resources (e.g., aquifer depletion in irrigated northern regions), but use of ICTs, possibly powered by distributed remote renewable energy, could better engage and inform both the irrigators and the regulators to better manage water resources.

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