River Water Treatment in Chennai: Producing Drinking Water by Reverse Osmosis and Biocrude Oil by Hydrothermal Liquefaction
(Technical Paper)

Evaluating the Role of Government in Establishing Sustainable Energy Infrastructure in Massachusetts
(STS Paper)

A Thesis Prospectus
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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Prospectus

Introduction:

Nine million people worldwide died prematurely in 2015 due to health effects associated with pollution (WHO, 2019). Approximately 90 percent of these deaths were due to contaminated air or drinking water (Sifferlin, 2017). As the global population continues to climb, and the effects of climate change become more evident, water scarcity and hazardous air quality are emerging public health crises. Globally, over two billion people in developing countries use a drinking water source contaminated with feces, spreading deadly enteric diseases (WHO, 2019). India, the second most populated country, has extreme pollution in 70 percent of its drinking water sources and greatly needs water treatment plants (Banerji, 2018). While developed countries like the United States fare much better in regards to water scarcity, the industrialized infrastructure presents a host of other environmental issues. The nation's natural gas pipelines, some over 100 years old, are past their prime and are leaking methane (CH_4) directly into the atmosphere (Kelly, 2017). CH_4, a strong greenhouse gas (GHG), is more than 25 times more potent than carbon dioxide (CO_2) at trapping heat in the atmosphere (EPA, 2021). Additionally, CH_4 reacts with nitrogen oxides (NO_x) to catalyze ozone (O_3) formation, which causes cardiopulmonary and respiratory diseases, including cancer (UCS, 2014). As science continues to develop regarding the impacts of natural gas and its disadvantages, local and state governments are left scrambling while trying to solve the issues caused by this decaying energy infrastructure.

Chennai, India currently faces extreme water scarcity due to abnormal rain patterns and the pollution of local water sources. Chennai depends on rain during the monsoon season to supply the city with clean water, but recently this source has become increasingly unreliable. Three large rivers running through Chennai were historically used as sources of clean water to the area, but now the rivers are heavily polluted with sewage and heavy metals and are incapable of sustaining life (Agoramoorthy, 2014 & Elangovan and Dharmendirakumar, 2013). Chennai lacks water treatment facilities, causing 30 percent of the municipal drinking water to fail standard quality tests (TOI, 2019). As a result, much of the city relies on bottled water or privately owned water trucks for drinking. During periods of drought, however, prices increase significantly and not everyone can afford the luxury of clean water. Our technical project will aim to design a water treatment plant on Chennai's biggest river, the Cooum. This water treatment plant will use the Cooum River as its water source, as opposed to rainfall, to provide a reliable and cheap source of drinking water to the 11 million people in Chennai (Chennai Population, 2021).

Boston, Massachusetts has been the source of groundbreaking research on the leakage of CH_4 from the city's natural gas pipelines. As of 2012, much of the pipelines running underneath Massachusetts were constructed of cast iron and installed over 100 years ago (*History*, 2013 and Kelly, 2017). These lines have deteriorated over time, and have an average lifespan of 90 years (Gallagher et al., 2015). In other words, the pipes are in desperate need of repairs. Studies produced by Boston University and Harvard University have shown that there were thousands of leaks in Boston alone, some of which produced CH_4 concentrations up to 14 times the baseline (Phillips et al., 2012 and McKain et al., 2015). Because of the detrimental environmental and human health effects of CH_4, significant pressure was placed on the local and state governments to develop a plan to protect citizens. Around the same time, researchers were discovering that natural gas proved to be more destructive to the atmosphere than initially thought, prompting the widespread move away from natural gas as an energy source (UCS, 2014). Currently, the Massachusetts state government is intertwined in a battle between protecting its citizens in the present and preserving its citizens' futures. In my STS research paper, I will use the situation in Massachusetts as a case study to investigate the role that government entities play in mediating the environmental impacts of decaying energy infrastructure in the United States.

Technical Topic (Capstone):

In the city of Chennai, India, the Cooum River holds high levels of contamination in the form of sewage, biological matter, industrial waste, nutrients, and heavy metals (Gowri et al., 2007). This area of India also faces high levels of water scarcity. Our goal is to design a reverse osmosis (RO) water treatment plant that sources water from the Cooum river as an alternative source of drinking water for Chennai to relieve some of this water scarcity. Water will be directly pumped from the Cooum River, and will go through various stages of pretreatment before RO treatment. These pretreatment steps will include sedimentation of large solids, a macro-filter, and a microfilter. This water will then be pumped through the RO membrane. The permeate water leaving RO will be disinfected and leave the system as potable water.

Hydrothermal liquefaction (HTL) will be a secondary process that uses the biomass from the river to produce an energy rich bio-crude oil as a byproduct. HTL operates at moderate temperatures, typically 200-400°C, and high pressures of 10-25 MPa (Gollakota & Kishore, 2018). At these conditions we expect to generate a biocrude oil sludge, an aqueous wastewater stream, and a gas stream (Chen et al., 2020). We would like to join these processes together in a centralized system by using the sludge streams produced in pretreatment of water as a feed for HTL and recycling the dirty water produced in HTL into our water treatment process. A simple process flow diagram can be seen in Figure 1, with a more in-depth illustration for HTL in Figure 2. The final products of this project will be clean drinking water and bio-crude oil.

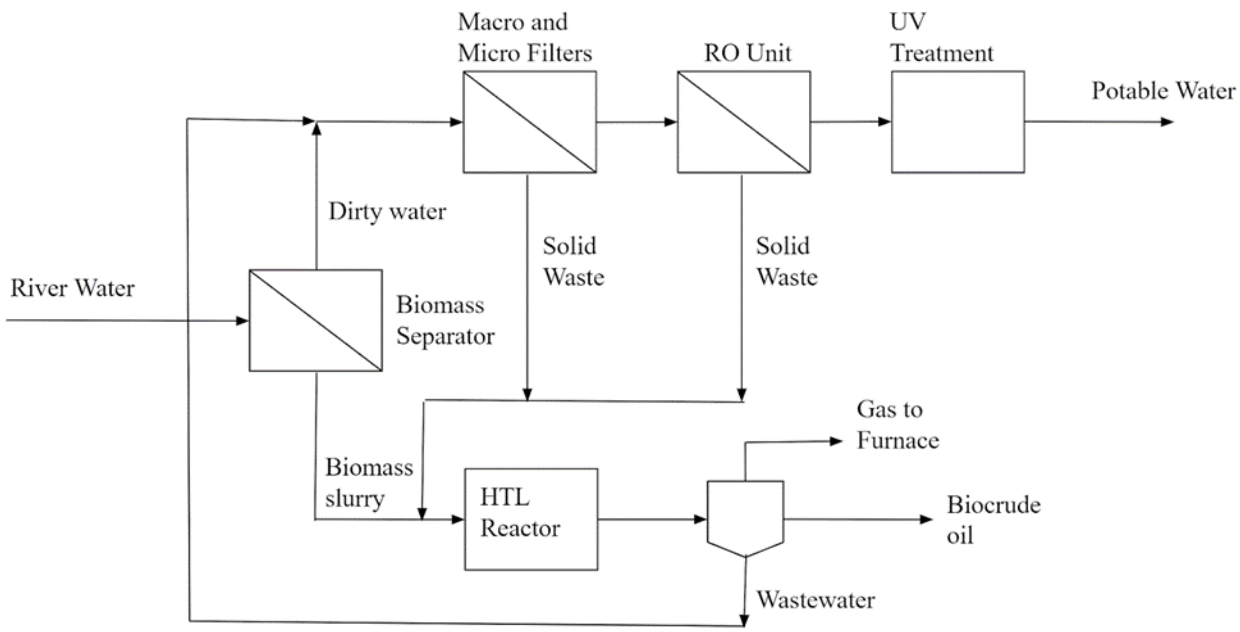

Figure 1: Overall Process Flow Diagram

Chennai gets the majority of its drinking water from the monsoon season, however when this season is short or does not provide enough rain, the city faces serious water scarcity. This is what occurred during the 2019 water crisis of Chennai (Frayer, 2019). The proposed design is worth pursuing as it addresses the problems of water scarcity in Chennai, as well as uses the pollution, specifically the excess of biomass, in the Cooum river as a profitable resource. RO will be used as a promising filtration technology to produce the potable water product. Additionally, HTL is a very new technology that has never been scaled up to larger than in-lab processes. However, industrially sized designs have been proposed, such as the design seen in Figure 2 (Snowden-Swan et al., 2016). Scaling up HTL and connecting it with the RO process streams will be a significant challenge of this design project.

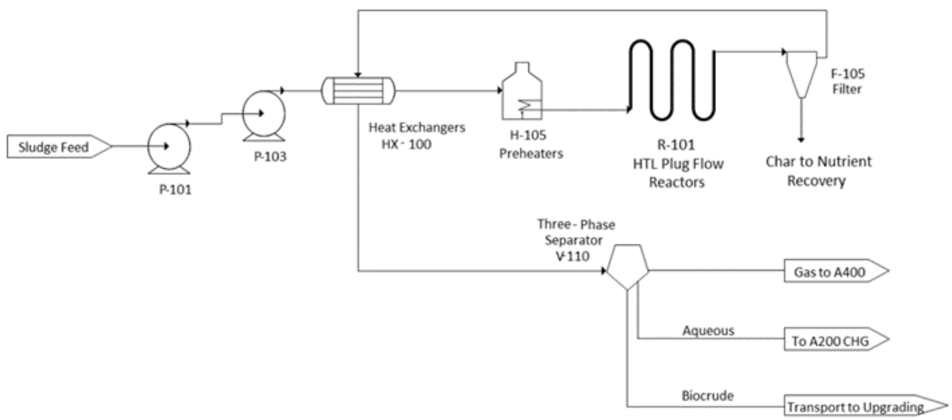

Figure 2: Hydrothermal Liquefaction Process Flow Diagram

The final report will contain complete material and energy balances, the design of major equipment including reactor and membrane filtration designs, an estimation of costs and returns and a discussion of the environmental and social impacts. Information regarding the flow rates of pollutants in the Cooum River will be obtained from sources that analyze the river for its contents in order to understand the components of the feed stream (Gowri et al., 2007). The two-semester technical project will be done amongst a group of five individuals. Calculations will be done using shared Excel spreadsheets, dividing calculations amongst group members as needed. Every calculation will be checked by at least two team members before publishing. Where appropriate, Aspen Plus will be used to simulate certain processes to obtain stream data and thermodynamic properties in the process. The group will meet at least once a week to discuss progress, findings, and future calculations.

STS Topic (STS Research Paper):

Climate change is fueled partially by GHG emissions. GHG are gases that contribute to the greenhouse effect by absorbing radiation from the sun, trapping heat in the Earth's atmosphere. CO_2 makes up the majority of anthropogenic GHG emissions. However, CH_4 is also heavily produced and has more than 80 times the warming power of CO_2 over its first 20 years in the atmosphere (EDF, 2021). Due to CH_4's warming potential, limiting its anthropogenic production is a major focus of environmental scientists and engineers.

In 2020, natural gas accounted for 34 percent of the United States' primary energy consumption, and was second only to petroleum (EIA, 2021c). Natural gas has prevailed in recent history as a more favorable power source than coal and petroleum because it's cheaper, cleaner burning, and more efficient (EIA, 2021b). Natural gas combustion emits 50 to 60 percent less CO_2 than a typical new coal plant, and 15 to 20 percent less GHG than gasoline when burned in a vehicle (UCS, 2014). Because natural gas is such a widespread energy source, it is transported throughout the entire country in underground pipelines. The vast majority of these pipelines are cast iron pipes that were installed prior to the 1960s (EIA, 2021a). In the northeast, pipelines are frequently over 100 years old (Kelly, 2017). These cast iron mains have lifespans of 90 years on average (Gallagher et al., 2015). As we enter the mid 2020s, most of the natural gas system is approaching the end of its lifetime. Due to the nature of cast iron, the pipes have corroded over time, weakening the walls and eventually causing leaks of natural gas into the ground and, subsequently, the atmosphere (Gallagher et al., 2015). Natural gas is almost entirely made of CH_4 (EIA, 2021a). As mentioned previously, CH_4 is a potent GHG and causes significant environmental and health consequences.

With this knowledge in mind, several researchers have undergone the process of investigating natural gas leaks from the pipelines around several major cities. The original studies with the most significant findings, took place in Boston, Massachusetts. Multiple analyses conducted by Boston University and Harvard University, among others, found that there were over 3,000 individual leaks in Boston as of 2012 (Phillips et al., 2012 and McKain et al., 2015). The publication of these findings prompted government officials to make a serious effort to protect the citizens of Massachusetts and develop a plan to fix the pipelines. The result was the creation of the Gas System Enhancement Program (GSEP). The GSEP is a multiyear, multibillion dollar project to completely replace the majority of the natural gas lines in Massachusetts (Shankman, 2021). As the program progressed and billions of dollars were spent, climate scientists produced new research on the emissions of natural gas. The drilling, collection, and transportation of natural gas contributes to 29 percent of total CH_4 emissions in the U.S. (EIA, 2021b). Additionally, these operations have destroyed the habitats for many animal populations and contaminated water sources throughout the country (EIA, 2021b). In an effort to lower total carbon emissions, experts have pushed for a move away from natural gas, and the government of Massachusetts has set a goal to end natural gas use by 2050 (Shankman, 2021). This goal conflicts majorly with the GSEP, and scientists and politicians are stuck trying to balance the importance of protecting the public's health now and preserving the economy and environment for their future.

Methodology:

To assess the relationship between environmental researchers and government agencies within Massachusetts, I will utilize the theory of co-production. Co-production is a process of knowledge production through the collaboration of multiple relevant entities, and is typically used to characterize the societal understanding of the relationship between nature and society (Jasanoff, 2010). The theory of co-production has been developed through multiple industries, including public and business administration, science and technology studies, and sustainability science. In the field of sustainability science, early research incorporating co-production included the work of Gary Kofinas in 1998 (Miller & Wyborn, 2020). Kofinas set out to use co-production of socio-ecological systems as a basis to understand how the Alaskan government and Indigenous communities could effectively co-manage resources (Miller & Wyborn, 2020). The theories of Kofinas have been contested, as he believes that co-production is an aspirational goal rather than a de facto reality like other scholars. This view ignores the pre-existing co-production of knowledge that is inherent within a community and the inevitable politics of configuring knowledge and societies. In my research, I will adopt the view of Elinor Ostrom, whose research emphasized the de facto presence of co-production throughout society. This assumption acknowledges that knowledge production is not an isolated process and occurs contemporaneously with other technological and societal developments (Gummesson, 1987).

In order to effectively analyze the evolving infrastructure and environmental problems in Massachusetts, the fundamental concepts involved in co-production need to be established. The two "producers" in this scenario will be the various levels of government in Massachusetts and the sustainable science community (Miller & Wyborn, 2020). This will include city and state level government entities and any group of researchers or engineers whose work deals directly with natural gas and air quality. Each producer has several pre-established constraints that will direct the co-production process. The government is limited economically, and the creation of new policies takes excessive time due to bureaucratic red tape. The scientific community is also limited largely by time. Research is ever-evolving and must be peer reviewed, so new information frequently takes years to be published. These constraints limit the role of each producer and will be incorporated into future analysis. In this scenario, there is a singular, shared product: knowledge on how to create sustainable energy infrastructure to maintain current safety while protecting the environment for the future. Altogether, my analysis will focus specifically on how the government reacts to and interacts with the recent developments in environmental science.

Research Question: What role do local government entities play in mediating the detrimental environmental impacts of decaying energy infrastructure in Massachusetts as climate science rapidly advances?

To address my research question, I will use both policy and discourse analysis, as well as examine a historical case study. To begin, I will look back at several studies involving Boston, Massachusetts. These studies, performed by Harvard, Boston, and Duke University, will be analyzed to address the root cause of conflict between researchers and the government in regards to natural gas (Phillips et al., 2012 and McKain et al., 2015). Additionally, I will evaluate the government's initial response and later policies to understand the application of co-production in producing a safer, sustainable future. These findings will influence my analysis on the current discourse surrounding natural gas. More specifically, I will identify several primary sources addressing the newfound consequences of natural gas to outline the change in scientific opinion over the last decade (UCS, 2014 and EIA, 2021b). This information, in combination with opinions from political leaders found in local articles and reports, will be used to analyze the discourse currently taking place between scientists and policy makers in regards to the social, economic, and environmental impacts of replacing the natural gas pipelines versus abandoning the project and focusing on cleaner energy sources. In this analysis, I will also outline and briefly evaluate the possible solutions to this issue proposed as a result of co-production between science and government.

Conclusion:

This paper will cover the design of a water treatment plant to alleviate problems due to water scarcity as well as an evaluation of the recent response to the degrading natural gas infrastructure in the U.S. The technical team will design a system to produce drinking water from a polluted river in India. This system will utilize RO and HTL to maximize the clean water produced. Bio-crude oil produced from HTL will be recycled within the facility for RO, reducing energy costs and contributing to the team's focus on sustainable engineering practices. The team will use ASPEN to calculate mass and energy flows for the system, with a focus on minimizing costs and maximizing the rate of production. This will allow the team to sell the water at a minimum to provide drinking water for more people and alleviate some of the water stress in Chennai, India.

The STS research paper will analyze the developments in Massachusetts as scientific opinion changes on natural gas and energy infrastructure become outdated. Using the framework of co-production, the role of the local and state governments will be recognized and evaluated in relation to recent scientific discoveries. To aid in analysis, studies, articles, and reports will be used to investigate the previous policy and discourse surrounding energy resources in Massachusetts. Using the historical trends, the current influence of co-production on the government's role in repairing energy infrastructure and protecting its citizens will be pinpointed. To further the discussion, select proposed solutions will be presented and the validity of each instance will be briefly evaluated. Altogether, the research paper will generate a comprehensive examination of the theory of co-production as applied in modern day sustainability science and policy in Massachusetts.

References

Agoramoorthy, G. (2014). Sacred Rivers: Their Spiritual Significance in Hindu Religion. Journal of Religion and Health, 54(3), 1080–1090. https://doi.org/10.1007/s10943-014-9934-z.

Banerji, A. (2018, July 5). *India's 'Worst Water Crisis in history' leaves millions thirsty*. Reuters. Retrieved February 1, 2022, from https://www.reuters.com/article/us-india-water-crisis/indias-worst-water-crisis-in-history-leaves-millions-thirsty-idUSKBN1JV01G

Chen, W.-T., Haque, Md. A., Lu, T., Aierzhati, A., & Reimonn, G. (2020). A perspective on hydrothermal processing of sewage sludge. Current Opinion in Environmental Science & Health, 14, 63–73. https://doi.org/10.1016/j.coesh.2020.02.008

Chennai Population. World Population. (2021). Retrieved November 18, 2021, from https://www.populationu.com/cities/chennai-population.

EDF. (2021). *Methane: A crucial opportunity in the climate fight*. Environmental Defense Fund. Retrieved February 1, 2022, from https://www.edf.org/climate/methane-crucial-opportunity-climate-fight

EIA. (2021a). Natural gas explained. Natural gas explained - U.S. Energy Information Administration (EIA). Retrieved February 1, 2022, from https://www.eia.gov/energyexplained/natural-gas/#:~:text=The%20largest%20component%20of%20natural,carbon%20dioxide%20and%20water%20vapor

EIA. (2021b). Natural gas and the environment. eia.gov. Retrieved February 1, 2022, from https://www.eia.gov/energyexplained/natural-gas/natural-gas-and-the-environment.php

EIA. (2021c). U.S. energy facts explained. U.S. Energy Information Administration (EIA). Retrieved February 1, 2022, from https://www.eia.gov/energyexplained/us-energy-facts/

Elangovan, N. S., & Dharmendirakumar, M. (2013, March 11). Assessment of groundwater quality along the Cooum River, Chennai, Tamil Nadu, India. Journal of Chemistry. Retrieved November 18, 2021, from https://www.hindawi.com/journals/jchem/2013/672372/.

Environmental Protection Agency. (2021, June 30). *Importance of methane*. EPA. Retrieved February 1, 2022, from https://www.epa.gov/gmi/importance-methane#:~:text=Methane%20is%20the%20second%20most,trapping%20heat%20in%20the%20atmosphere

Environmental Science & Technology Letters, 2(10), 286–291. https://doi.org/10.1021/acs.estlett.5b00213

Frayer, L. (2019, July 18). The Water Crisis In Chennai, India: Who's To Blame And How Do You Fix It?. NPR. Digging Wells, Skipping Showers: Life In A Water Crisis : Goats and Soda : NPR.

Gallagher, M. E., Down, A., Ackley, R. C., Zhao, K., Phillips, N., & Jackson, R. B. (2015). Natural gas pipeline replacement programs reduce methane leaks and improve consumer safety.

Gollakota, A. R. K., Kishore, N., & Gu, S. (2018). A review on hydrothermal liquefaction of biomass. Renewable and Sustainable Energy Reviews, 81, 1378–1392. https://doi.org/10.1016/j.rser.2017.05.178

Gowri, V. S., Ramachandran, S., Ramesh, R., Pramiladevi, I. R., & Krishnaveni, K. (2007). Application of GIS in the study of mass transport of pollutants by Adyar and Cooum Rivers in Chennai, Tamilnadu. Environmental Monitoring and Assessment, 138(1-3), 41–49. https://doi.org/ 10.1007/s10661-007-9789-9.

E. Gummesson The new marketing—developing long-term interactive relationships Long Range Plann., 20 (4) (1987), pp. 10-20

History. Natural Gas. (2013, September 20). Retrieved February 1, 2022, from http://naturalgas.org/overview/history/

Jasanoff, S. (2010). States of knowledge: The co-production of Science and Social Order. Routledge.

Kelly, J. (2017, October 25). *Look out below: Danger lurks underground from aging gas pipes*. USA Today. Retrieved February 1, 2022, from https://www.usatoday.com/story/news/nation/2014/09/23/gas-pipes-cast-iron-deaths-explosions-investigation/15783697/

McKain, K., Down, A., Raciti, S. M., Budney, J., Hutyra, L. R., Floerchinger, C., Herndon, S. C., Nehrkorn, T., Zahniser, M. S., Jackson, R. B., Phillips, N., & Wofsy, S. C. (2015). Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. Proceedings of the National Academy of Sciences, 112(7), 1941–1946. https://doi.org/10.1073/pnas.1416261112

Miller, C. A., & Wyborn, C. (2020). Co-production in Global Sustainability: Histories and theories. Environmental Science & Policy, 113, 88–95. https://doi.org/10.1016/j.envsci.2018.01.016

Phillips, N. G., Ackley, R., Crosson, E. R., Down, A., Hutyra, L. R., Brondfield, M., Karr, J. D., Zhao, K., & Jackson, R. B. (2012). Mapping urban pipeline leaks: Methane leaks across Boston. Environmental Pollution, 173, 1–4. https://doi.org/10.1016/j.envpol.2012.11.003

Shankman, S. (2021, October 4). As Massachusetts envisions a fossil fuel-free future, gas companies are quietly investing billions in pipelines - the Boston Globe. BostonGlobe.com. Retrieved February 1, 2022, from https://www.bostonglobe.com/2021/10/03/science/massachusetts-envisions-fossil-fuel-free-future-gas-companies-are-quietly-investing-billions-pipelines/

Sifferlin, A. (2017, October 19). *Pollution: Air and water pollution are killing millions of Americans*. Time. Retrieved February 1, 2022, from https://time.com/4989641/water-air-pollution-deaths/

Snowden-Swan, L. J., Zhu, Y., Jones, S. B., Elliott, D. C., Schmidt, A. J., Hallen, R. T., Billing, J. M., Hart, T. R., Fox, S. P., & Maupin, G. D. (2016). Hydrothermal Liquefaction and Upgrading of Municipal Wastewater Treatment Plant Sludge: A Preliminary Techno-Economic Analysis (PNNL--25464, 1258731; p. PNNL--25464, 1258731). https://doi.org/10.2172/1258731

TOI. (2019, November 20). Chennai: 30 percent water samples fail quality test: Chennai News - Times of India. The Times of India. Retrieved November 20, 2021, from https://timesofindia.indiatimes.com/city/chennai/30-water-samples-fail-quality-test/articleshow/72132907.cms.

UCS. (2014, June 19). *Environmental impacts of natural gas*. Union of Concerned Scientists. Retrieved February 1, 2022, from https://www.ucsusa.org/resources/environmental-impacts-natural-gas

World Health Organization. (2019, June 14). *Drinking Water*. World Health Organization. Retrieved February 1, 2022, from https://www.who.int/news-room/fact-sheets/detail/drinking-water