Water-energy nexus-based scenario analysis for sustainable development of Mumbai

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Abstract

The urban water-energy nexus sits at the intersection of the global phenomena of water scarcity, energy transitions and urbanisation. Research found that end use dominates the water-energy nexus and that this component plays an important role in urban dynamics, but focussed on the Global North. We investigate the nexus of Mumbai and its long-term resource demand. Our tool is a novel system dynamics model representing the urban water-energy nexus and takes into account characteristics such as intermittent water supply and the presence of slums. We devised scenarios around the Sustainable Development Goals and the Swachh Bharat Mission. The model shows that both can be achieved while saving on future water system infrastructure investments compared to business-as-usual. We find that also in Mumbai end use dominates the nexus. Representing end-use interactions increases expected water demand. This work indicates that globally, sustainable development of infrastructure must consider the urban water-energy nexus.

Highlights

- A system dynamics model explores the water-energy nexus of Greater Mumbai out to 2050
- Including the effects of energy use on water use increases expected water consumption
- End use has the greatest share in the nexus, in line with Global North
- Meeting the SDGs requires better housing but could save on water infrastructure

Keywords

Water energy nexus; cities; end use; system dynamics; Mumbai; sustainable development goals

1. Introduction

The urban water-energy nexus has grown into a very active research field over the past decade. It sits at the intersection of three global phenomena. The first is urbanisation: more than half of all humans alive live in cities, up from a third in 1950, and the share is projected to increase to 66% by mid-century (American Association for the Advancement of Science, 2016). The second is a scarcity of sufficient water resources in many regions of the world (Greve et al., 2018). The third is consumption of energy resources in a way that affects the world's climate system, together with global efforts to limit climate change through transformations of the energy system (Grubler et al., 2014).

Water and energy systems are linked in several ways, and that set of interactions is commonly referred to as the water-energy nexus. Gleick (1994) collated research on the interactions in both directions: the energy requirements of water supply including pumping for large-scale conveyance schemes and desalination, and the water demands of energy supply including fuel processing and cooling of thermal power plants. However, this leaves out most of the urban part of the water-energy nexus: the energy demands of water distribution and treatment and wastewater collection and treatment, and most importantly, the end use.

Cities are centres of high concentration of demands for energy and water services. As such, they constitute an important raison d'etre for the wider energy and water systems, and their problems. The urban perspective on the water-energy nexus has been receiving increasing attention (Meng et al., 2019). Remarkably, studies agree that the end-use component dominates the water-energy nexus, mainly because of water heating (De Stercke et al., 2016). Research is now going into increasing end-use detail: digital coincident measurements of household-level water and energy use will further understanding, with important benefits for utilities and water and energy system operators (Stewart et al., 2018; Nguyen et al., 2019). However, studies cluster around cases in the Global North where highly populated urban areas experience severe droughts, such as California and Australia where energy-intensive desalination technology was deployed. Of the 14 studies summarised in the review of the household water-electricity nexus by Wang et al. (2019, Table 5), two apply to China, the others to OECD countries.

This bias is at odds with global urbanisation patterns: the urban population in the Global South is both the largest and the fastest growing (American Association for the Advancement of Science, 2016). One of the reasons is a lack of urban data in those regions due to high levels of informality, hampering improvements as it is difficult to track progress accurately (Klopp and Petretta, 2017). However, to achieve sustainable development at a global scale, we need to learn more about the dynamics of the urban water-energy nexus and about the challenges and opportunities that end-use interactions pose for the future of water and energy systems in cities in the Global South.

In the Global South, research in urban energy and water use, separately, has been active. In India e.g., Ekholm et al. (2010) examined fuel choice for cooking, and Chaturvedi et al. (2014) studied urban energy use and projected it out to the end of the century, while on the water side, Sadr et al. (2016) studied residential water use in Jaipur, and Shaban and Sharma (2007) in seven major cities. While providing insights and data to conceptualise the urban water-energy nexus, all end-use studies appear to rely on surveys rather than measurements..

Finally, most studies present the quantification of a snapshot in time and do not analyse how the urban nexus will evolve over time. It is important to know how interactions will play out over time, and some researchers have investigated that: Hussien et al. (2017) use a water-energy-food nexus model at a household level to estimate resource consumption under 5 scenarios, and De Stercke et al. (2018) show that not taking water-energy interactions into account can lead to excess capacity in London's water system.

In this study, we address the gaps in knowledge about the dynamics of the urban water-energy nexus in the Global South. Building on previous research (De Stercke et al., 2018), we develop a model of Mumbai's water-energy nexus and use it to estimate future energy and water use under different scenarios in an integrated way. Scenarios are alternative visions for the future and are employed extensively for 'what if' analysis. We chose Mumbai as a case study because of its salience as a world city and the associated research interest it has generated, its long-time presence of slums, its rapid urbanisation, and its complex struggles with water provision. The novelty lies in the characterisation of the city's water-energy nexus with a presence of slums and intermittent operation of water supply, which is informed by the insights and data gathered from interviews with local stakeholders

In order to make the research directly relevant, we have based the scenarios on global and locals goals, such as the United Nations' Sustainable Development Goals (SDGs) which require that everyone have access to sanitation, clean water, and modern energy sources by 2030 (UN-DESA, 2016), and the national Swachh Bharat ('clean India') Mission (SBM) which aims for open-defecation free (ODF) cities (Government of India, 2020). The former imply that slums should not exist anymore in 2030 according to their common definition of 'an area that combines, to various extents [...] (1) inadequate access to safe water; (2) inadequate access to sanitation and other infrastructure; (3) poor structural quality of housing; (4) overcrowding; and (5) insecure residential status' (UN-Habitat, 2004). SDG 6 on clean water and sanitation covers the first two components and SDG 11 the others. This transformation involves changes in energy and water use patterns, and the interactions between them will have an impact on overall system performance.

We have structured the paper such that it continues from here with an overview of the nexus conceptualisation in this study and how it maps to the key processes relevant for the dynamics of Mumbai. Then, an explanation of how these insights were translated into novel components of the system dynamics model follows in section 2. Scenario narratives and parameters, as well as an explanation of the sensitivity analysis approach, are described in section 3. Section 4 shows the model results in terms of urban metabolism, the water-energy nexus and infrastructure requirements. There, we also present the sensitivity analysis together with the interpretation of the scenario outcomes and a discussion on implications for policy. We relegated a comprehensive overview of the input data to appendix A and all model equations to appendix B.

2. Methods

To simulate the urban water-energy nexus of Mumbai, a conceptualisation of the key processes that comprise the system and its interdependences have to defined. Fig. 1 shows the nexus as conceived of in this study, with the terminology we employ. What we term the up-

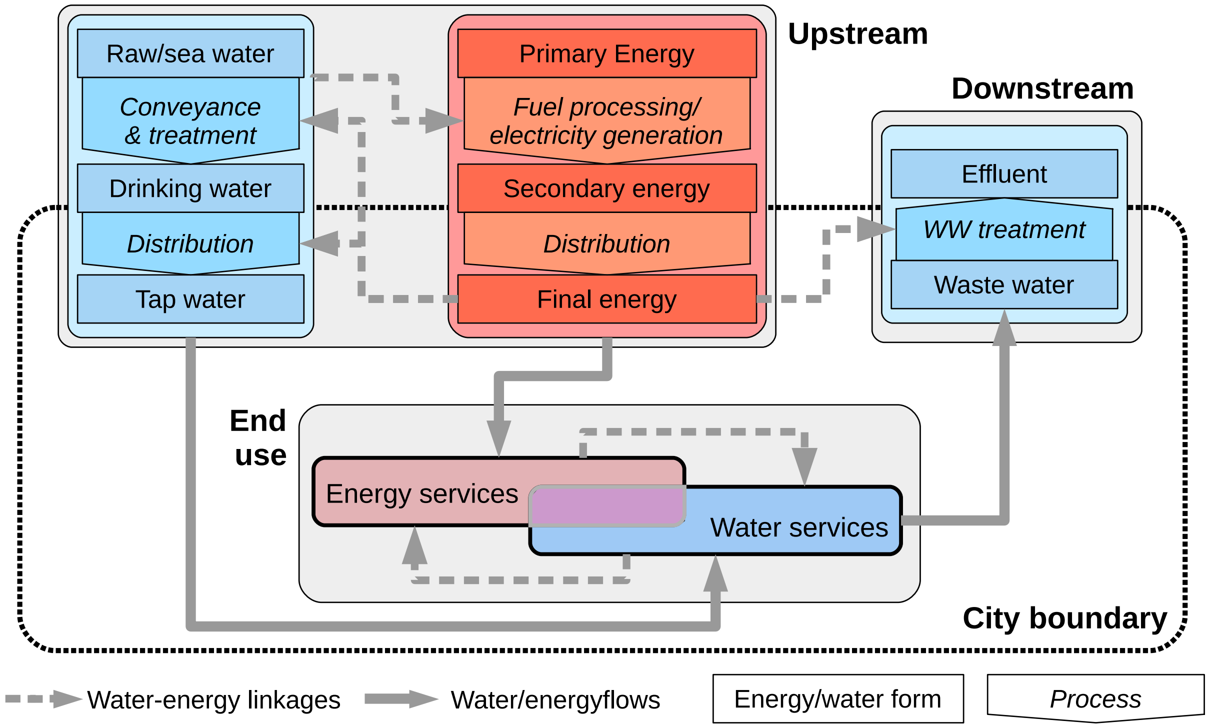


Figure 1: Diagram of the urban water-energy nexus. The city boundary includes all of end use, which has at its core a demand for energy and water services. These services are enabled by resource provision from the upstream water and energy supply chains, which cross the city boundary from their origins in the city's hinterland and beyond. Supply chains and end use of water and of energy require energy and water, respectively, and this is shown by dashed arrows. The downstream water system crosses the city boundary, beyond which used water is ceded back into the environment.

stream section of the urban water-energy nexus consists of water supply and treatment, and of the energy production chain including electricity generation. The downstream section consists of wastewater collection and treatment. The upstream and downstream sections cross the city boundary, where piped water and final energy deliver water and energy services at the end use. In this conception of end use it differs from Ramaswami et al.'s (2017) similar transboundary multi-sector framework.

Our given problem is that of a city's future in terms of its water and energy systems which are linked in various ways and on various levels, and the context in which they are managed and used. We use System Dynamics (SD) as a method as indicated by Kelly et al. (2013) for system understanding of urban-scale dynamic processes. SD was developed in the early 1960s by Forrester (1961) as a 'perspective and a set of conceptual tools that enable us to understand the structure and dynamics of complex systems' (Sterman, 2000). It has been applied to a wide range of problems, and despite its age and its origins in times of - by today's standards - very limited computing power it is still very popular today. SD modelling software is widely accessible and facilitates learning and understanding of complex systems even by those with little technical background (Kelly et al., 2013).

Several researchers have used SD to model aspects of the urban water-energy nexus. For example, Wang and Davies (2018) model urban water management and planning around end-use simulations, Sahin et al. (2016) study the effect of a pricing policy on desalination capacity and operation, and Hussien et al. (2017) model household water and energy demand as the end-use component of the nexus.

An SD model covering the entire urban water-energy nexus exists: De Stercke et al. (2018) developed it and applied it to London. However, some aspects specific to Mumbai are not represented in the original version, such as the presence of slums and mechanisms to cope with intermittent water supply. We expand the existing model with those elements, and describe it in this section. The model features all aspects in which the De Stercke et al. (2018) model is novel, most importantly the representation of the end-use component in the urban water-energy nexus with its symmetric interactions. Appendix B contains all model equations.

For a clear understanding, we begin this section by introducing the case study, as some of its qualitative aspects directly informed the model development.

We constructed the model with Vensim PLE but used the Python package PySD (Houghton and Siegel, 2015) in combination with the R package RPython (Bellosta, 2015) for all of the analysis, which we performed in R (R Core Team, 2018).

2.1. Case study description

Mumbai is the capital of the Indian state of Maharashtra, and its metropolitan region is the largest in India and one of the largest in the world. In this paper, we close our system boundary in around Greater Mumbai, which is composed of the districts of Mumbai (also known as the Island City) and the Mumbai Suburbs. The latter consist of the area between the Island City, and Thane and Mirandar; and it excludes Navi Mumbai. Mumbai has been a centre for financial and commercial services since Independence in 1947 when the main industrial activity of Mumbai changed away from cotton (Pacione, 2006). Since then, the population of Greater Mumbai has grown from fewer than 200 thousand to over 12 million in 2011, when the latest census was held.

The Brihanmumbai (Greater Mumbai, formerly Bombay) Municipal Corporation (BMC), also known as the Municipal Corporation of Greater Mumbai (MCGM) has nurtured Mumbai to grow into a 'world class' city, but this trajectory has its hurdles. Half of the mumbaikars live in slums and lack or have poor access to sufficient and clean water, to clean cooking fuels, to sanitation, or to long-term housing stability. The city is among the densest in the world. Its operation is enabled by a highly effective public transport system that millions commute on each day: in 2005, it accounted for 82% of all passenger-kilometres in Mumbai's metropolitan region (Reddy and Balachandra, 2012).

Electricity use per capita in urban India is low (less than 2 GJ per person per year or 1.5 kWh per person per day) and projected to grow over tenfold in the twenty-first century (Chaturvedi et al., 2014). Mumbai is no exception. Although formal access to electricity in slums may not be complete, mumbaikars enjoy a constant electricity supply in that Greater Mumbai, alone in Maharashtra, is immune from load shedding (More et al., 2007). Gas is the other main energy carrier in Mumbai's residential sector. Although some areas receive piped gas, most households rely on LPG in cylinders. Because gas is mainly used for cooking, the projected increase in use over the course of the century is small (Chaturvedi et al., 2014).

Rapid development over the past decades has challenged Mumbai's water system. Intense rain occasionally overburdens the drainage system and leads to flooding, and through water overconsumption in some areas the system could not satisfy all demand under continuous operation. To compensate, the BMC rations water use by intermittently providing water to different districts. However, in response it induces coping mechanisms among consumers that thwart centralised attempts at stabilising the situation (Galaitsi et al., 2016). The water system is hence embedded in a complex economic, political, social and technical context. Publications on these issues highlight the gravity of the situation with titles such as 'municipal disconnect' (Anand, 2012), 'water wars' (Graham et al., 2013), 'pipe politics, contested waters' (Björkman, 2015), 'landscapes of disaster' (Gandy, 2008) and 'PRESSURE' (sic.) (Anand, 2011), and illustrate the systemic nature of the problem, without a single culprit. It is clear from these texts and from anecdotal evidence that knowledge about the water system is fragmented and distributed. The resulting scarcity of reliable data is common to fast-growing cities in Africa and Asia (Klopp and Petretta, 2017).

In Mumbai, the water problem appears to be one of distribution rather than centralised supply. There is little decentralised supply from groundwater, because of salinity (Bambale, 2012) and also because historically there has been no need for it as Mumbai's administrators began the development of far-away surface water as sources from the mid-19th century; in Chennai, another coastal city suffering water-related problems, this was not the case (Sule, 2004). There, groundwater from private wells supplements piped water and is often the main source by volume (Srinivasan et al., 2010).

Mumbai is a rapidly changing city, still experiencing population growth while already being one of the world's most crowded places. Under the Government of India Swachh Bharat missions and under the global Sustainable Development Agenda, some of the desirable changes are prescribed. Others will be the manifestation of internal dynamics under external influences, all of which are not controlled by anyone. The myriad factors and mechanisms that we hypothesise to play a role are diverse in nature. We want to bring these into account as we investigate water and energy use until 2050 while also representing the interactions between water and energy systems. System dynamics, the method we use, was devised exactly for this kind of problems of high complexity. We devised scenarios to represent the factors of influence, on the system we describe, of which the endogenisation is beyond the scope of this study.

2.2. System Dynamics model development

2.2.1. Mumbai model structure

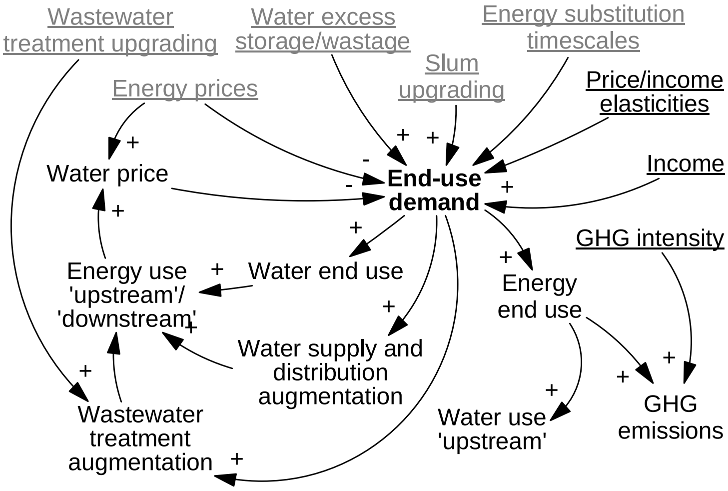


Figure 2: Modelling approach as a high-level causal loop diagram (CLD). Exogenous model variable types are underlined, of which scenarios determine those in grey. Intermittent water supply is represented by the excess storage or wastage of water. Polarities (+/-) indicate whether an increase in one variable leads to an increase (+) or a decrease (-) in another variable.

The model structure centres around the end-use demand module that De Stercke et al. (2018) developed. This module determines consumption of resources by individual end use - e.g. hot water, space heating, exclusive water uses - in response to resource prices and income and timescales for substitution among energy carriers. The latter are electricity and gas in this implementation. The end-use model incorporates water and energy interactions in end use: price- or income-induced changes in energy use affect water use, and vice versa.

The schematic of the structure, presented as a causal loop diagram (Fig. 2), indicates exogenous variable types by showing them underlined. A subset depends on the scenario formulation (section 3.3) and their names are shown in grey.

The demand for resources determines their consumption, which in turn translates into changes in water system capacity, both on the supply and on the waste water side. We consider the energy supply system to be exogenous to the chosen urban boundary and therefore we do not model it explicitly. Increasing energy intensity is associated with expansion of the water system and the scenario-dependent degree of wastewater treatment, which in turn affects the water price and therefore water consumption.

In the next two sections, we explain why and how we integrated the two main aspects in which Mumbai's water-energy nexus differs from cities in the Global North: the presence of slums, and intermittent water supply operation. We then present our new implementation of the waste water system, and income effects on service and resource demand.

2.2.2. *Slums*

On the order of half of the population of Greater Mumbai live in slums. Their access to water and energy services is constrained not only because of financial reasons but also because of a lack of provision. The latter can exacerbate the first, as poor households need to augment their supply from water vendors who charge a higher price. This important difference necessitates a differential characterisation of non-slum users and slum users in the model, instead of representing all by only one average user.

Mumbai has always aimed to lift mumbaikars out of slum living conditions, and there have always been policies to eliminate them through various mechanisms, such as slum upgrading or rehabilitation, and resettlement. There have not been simple solutions to this problem as every fix had unintended side-effects (Patel, 1996). Whatever the mechanism, it is necessary to improve a building stock, and that is how the model converts the slum population into non-slum population in the model.

This happens through the construction of 'decent housing', a term the vagueness of which shows our impartiality to the exact mechanism of slum eradication as slum dynamics are beyond the scope of this study. Fig. 3 shows the implementation in the stock-and-flow diagram (SFD). Decent housing is expressed in numbers of people. The decent housing construction begun at any time is expressed in people per year and is equal to the total slum population divided by the time available until 2030, the SDG time horizon, and multiplied by an urgency factor which depends on the scenario. The average construction time also depends on the scenario and introduces a realistic delay. Construction completion reduces the slum population, in addition to the superposition of a decrease in line with the observed 2001-2011 decrease.

The consumption of electricity, gas and water of slums are determined separately from the non-slum population segment. In the model, their per capita values increase with a scaling factor which grows at a fixed rate of 1% per year. In keeping the relative demands fixed, we avoid the complexity of slum dynamics. The justification lies in the shrinking contribution of resource consumption by slums, and the fact that per capita consumption is lower at the outset.

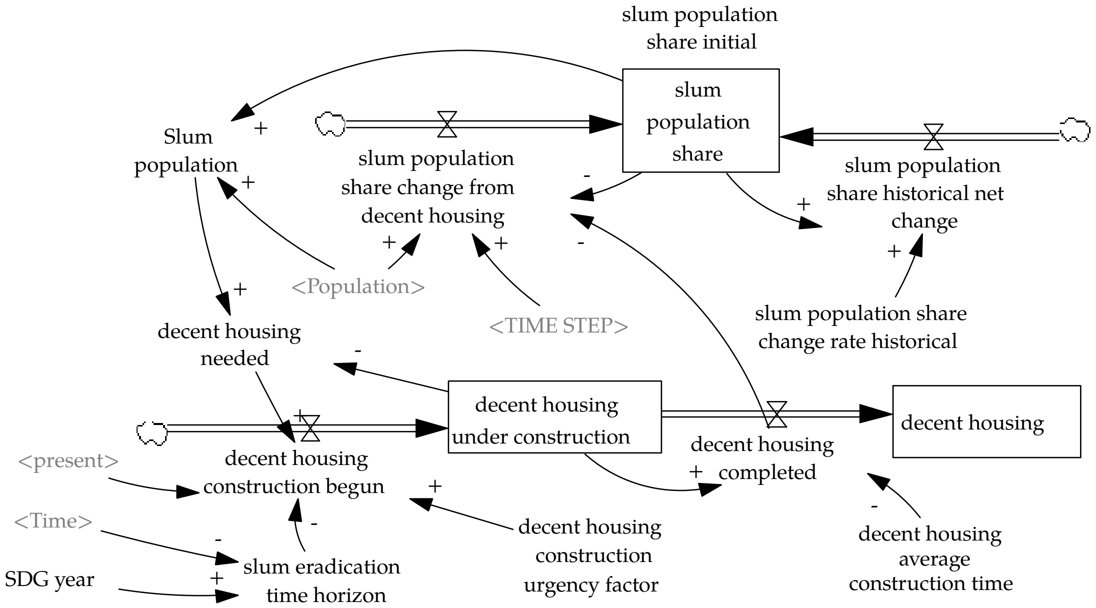


Figure 3: Stock-and-flow diagram structure of the slum dynamics. The bottom two-stock ageing chain is fed by an inflow of decent housing construction projects, based on how much is needed to lift people out of slum conditions and how much time there is left before the SDGs need to be met, combined with a dimensionless urgency factor which depends on the scenario narrative. This inflow accumulates into a stock of decent housing under construction which is depleted as these projects are completed with an average construction time. Simultaneously, the share of the population living in slums decreases, in addition to a decrease in line with historical observations. We refer to appendix B for the functional relationships among the variables.

2.2.3. Intermittent water supply

Most piped water connections in Mumbai, such as private connections or standpipes, are only pressurised for a few hours a day, depending on the area and according to predetermined schedules. Consumers transform this into a virtual continuous water supply by storing sufficient water until the next supply period with a margin, in case demand is higher than expected or the next supply period will be erroneous. Modelling the complex dynamics of an intermittent water supply is beyond the scope of this study; instead we model the symptoms, with factors of importance depending on the scenarios.

A symptom which is salient in media reports because of its visibility but, according to the water department, insignificant in terms of volume for water supply (Argade, 2016) is provision with tanker trucks. Also, a portion of the trucks are filled with municipal water, which therefore merely constitutes a redistribution of piped water. Hence, we do not model tanker trucks.

We model two symptoms:

- an inflated demand because of contingency storage, both among slum and non-slum users. We assume that the daily volume which is not used, is wasted as users replace it daily with fresh water.
- electricity consumption by the end user for pumping the water to the elevated storage

tanks, as the system pressure is low even during supply windows.

For slums, we neglect the latter because water is mainly transported by hand. The slum water wastage is a static volume per capita per day.

In the model, non-slum water consumption necessitates electricity the quantity of which we determine from an average pumping head. This in turn is the product of an average storey height and a number of storeys. We chose to formulate the number of storeys as a function of the Floor Space Index (FSI) because of its prominence in debates about Mumbai's development and slum upgrading. FSI is the ratio of floor space to lot size; for a given FSI, the more floors a building has, the more open space there should be in the lot. New developments are sprouting up all over the city, and are higher than before with greater FSI allowed under the Mumbai Development Plan 2034 (Kumar and Babar, 2018). We model this with an exponential growth. The SFD component is shown in Fig. 4. This electricity consumption component depends on water consumption, and is therefore not subject to changes in total electricity consumption induced by changes in price, income, or water use for a shared service. Changes are also applied to the reference electricity demand in the economic, elasticity based component, as in Fig. 7.

We model water wastage with an exponential decrease, with a historical rate before the year 2019, and a future rate which depends on the scenario. Fig. 4 shows this on the right.

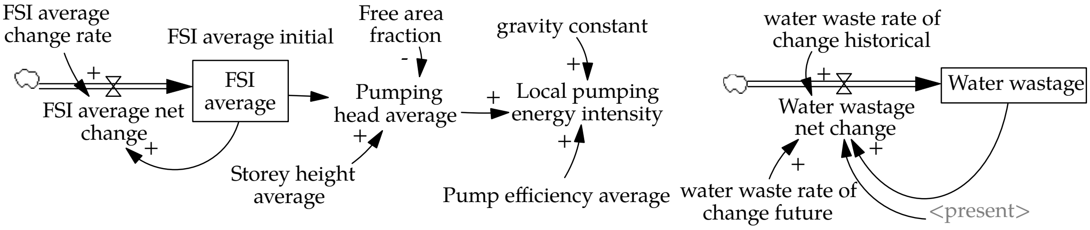


Figure 4: Stock-and-flow diagram structure of symptoms of intermittent water supply: local pumping requirements depending on building height (left) and water wastage due to contingency storage (right). The pumping energy intensity depends on the average head, which depends on the average storey height and the average number of floors. The latter depends on the FSI and the fraction of free area on a plot. Appendix B contains all functional relationships.

2.2.4. Wastewater

In the model by De Stercke et al. (2018) water supply includes the wastewater system. This simplification assume that all users that are supplied with water have wastewater services, and that the degree to which wastewater is treated is sufficient throughout. We split wastewater collection and treatment out from the water system, in order to capture the effects on electricity consumption due to wider coverage and improved treatment.

Sewerage coverage. We assume the non-slum segment of the population to have complete access to sewerage while it is only partial for slums. The share of slums sewered increases with a simple first-order tracking, to the asymptote of 100%. We then convert this into a share of all water demand which passes through sewerage. Fig. 5 shows the SFD implementation.

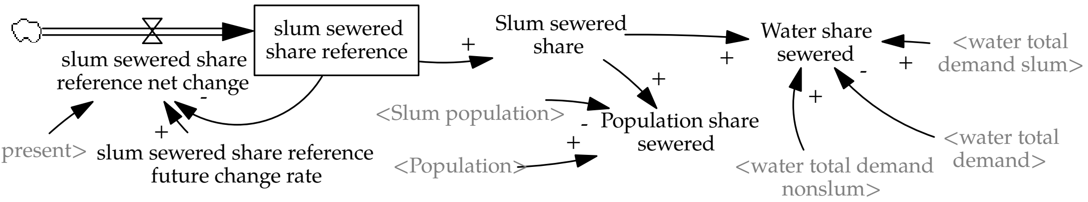


Figure 5: Stock-and-flow diagram structure determining the share of the population provided with sewerage services, and the volume that the sewer system captures. From the share of the slum population which has a sewer connection, both the share of population with a sewer connection as well as the fraction of water demand which goes into sewerage are calculated.

Wastewater treatment. Given the current sewerage coverage, there is enough wastewater treatment capacity in Mumbai's system. Most of this is primary treatment, after which the wastewater is sent to marine outfalls, mainly situated on the Arabian Sea side. To improve conditions for aquatic life (SDG 15) among other motives, wastewater needs to undergo at least secondary treatment. We model wastewater treatment as three ageing chains which represent primary, secondary and tertiary treatment, each with its own energy intensity. Fig. 6 shows the SFD component. In the model, there is upgrading from primary to secondary treatment, and from secondary to tertiary, with rates depending on the scenario. The model adds secondary wastewater treatment capacity when total water demand, which we assume equal to the discharge into sewers, plus a percentage margin, exceeds the current capacity. We note that we neglect stormwater in this study.

2.2.5. Income effects

Whereas the model by De Stercke et al. (2018) contains only a price response with an elasticity calibrated on price and decreasing demand trajectories, we include income as a factor for two reasons: (1) a lack of consistent data on consumption and prices spanning consecutive years because of several providers and the presence of poorly monitored slums, which inhibits calibration; and (2) an increase in consumption of electricity and gas, e.g. as projected by Chaturvedi et al. (2014).

We therefore add to the model a resource consumption change due to income effects, for electricity and gas, while we do not for water consumption because of the supply constraint. In the model, we implement this with an annual income growth rate and an income elasticity. In the SFD, we include this change as one of the flows which adjust the reference consumption value. Fig. 7 shows this. The [*resource*] *demand change from price* is calculated from a simple constant elasticity model (Mankiw, 2014):

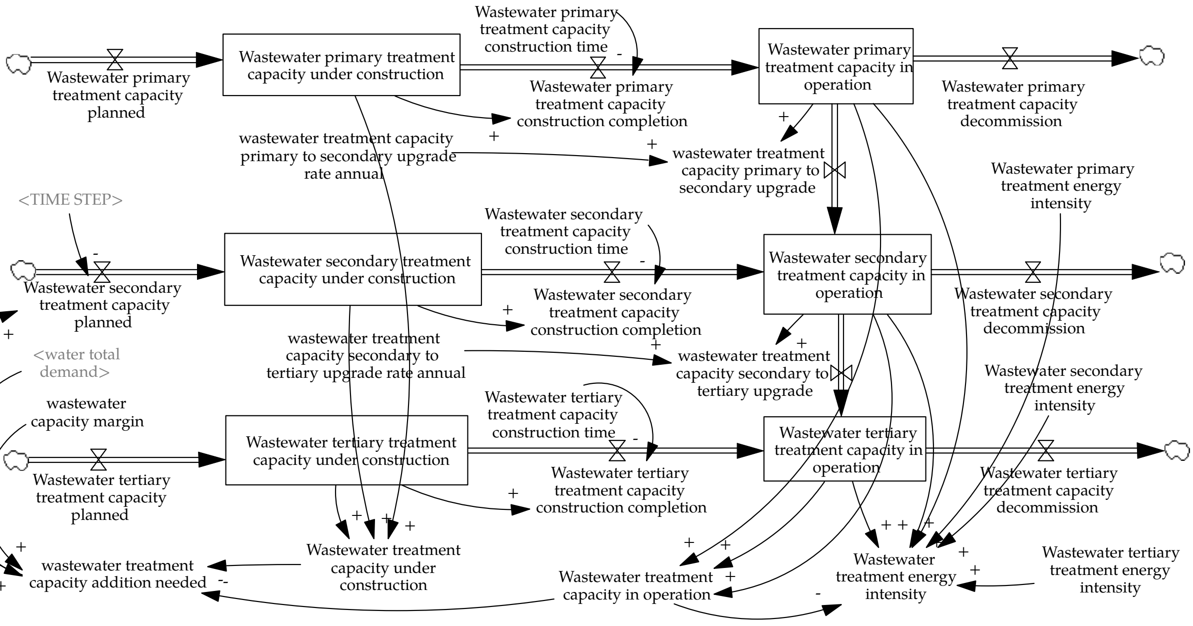


Figure 6: Stock-and-flow diagram structure of wastewater treatment. The three ageing chains, displayed horizontally, model wastewater treatment capacity planning, construction and operation. Capacity belongs to one of the three chains according to its highest degree of treatment. Vertically (in the diagram), capacity in operation can move from one chain into the other through upgrading. New secondary capacity is planned (inflow of the second ageing chain) as necessary according to total water demand and current capacity in operation and under construction.

$$\frac{\Delta Q}{Q} = \epsilon \frac{\Delta p}{p} \tag{1}$$

where Q is the resource consumption per capita, ϵ is the price elasticity of demand, and p is the price per unit (De Stercke et al., 2018).

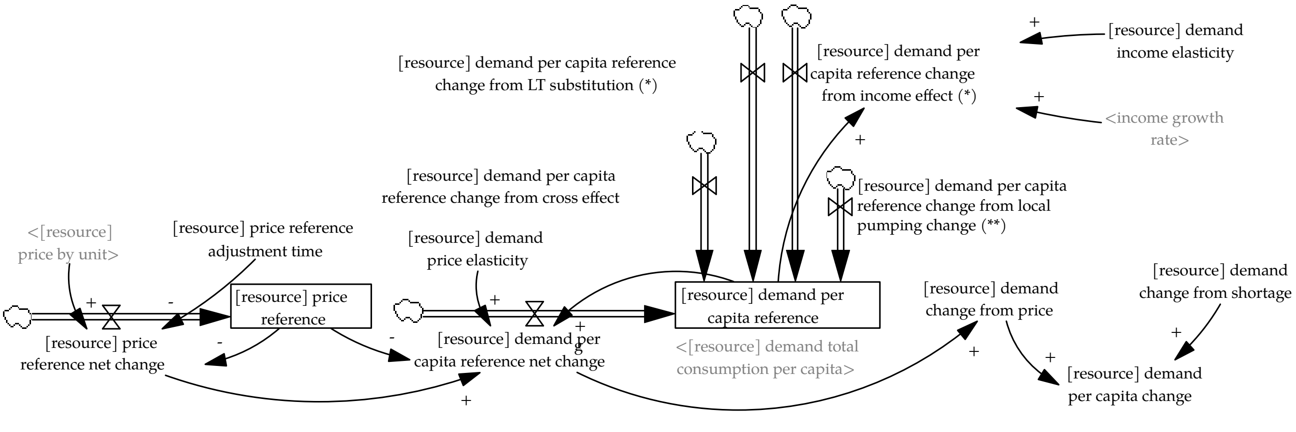


Figure 7: Stock-and-flow diagram structure of the resource consumption model for price and income elasticity. The parts marked with one asterisk (*) are only present for electricity and gas. The variable marked with two asterisks (**) is only present for electricity. The two stocks hold the reference values of price and resource demand, against which the changes in each are expressed to obtain the relative changes as in equation 1. A change in income level is one of the factors which influence the reference demand level (the vertically depicted flows) without interfering with the price-induced changes.

3. Experimental setup

3.1. Data

We rely on various sources for the data in the model, from peer-reviewed and grey literature as well as data that we collected from the MGCM Water Department on field visits to Mumbai in 2016. We only mention key sources here, and deferred exhaustive documentation to appendix A. The Censuses of India of 2001 and 2011 provided demographic data (Office of the Registrar General & Census Commissioner, India, 2001, 2011). We derived total water consumption from Bambale (2012) while Shaban and Sharma (2007) inspired the shares for different uses. Round 68 of the National Sample Survey (2011-2012) (National Sample Survey Organisation, 2014) allowed us to estimate per capita electricity and LPG use, for slum and non-slum users.

3.2. Effect of end-use interactions

The model enables us to investigate the effect of water-energy interactions in end use by activating or deactivating them using binary toggle variables. These determine whether e.g. a change in water consumption for appliances prompts a change in energy consumption for appliances. Although the model normally includes such interactions, we can study the counterfactual of their absence to highlight their effect.

3.3. Scenarios

Despite Mumbai's size and density, it is still growing in population and consumption. National-level ambitions apply to the city: Mumbai plays a crucial role in achieving the Sustainable Development Goals by 2030, many sanitation-related goals fall under the Swachh Bharat (Clean India) Abhiyan or Mission, and it can provide part of the Nationally Determined Contributions (NDCs) to reducing global greenhouse gas emissions. However, even though they affect cities, these goals have not been translated into numerical benchmarks for cities such as Mumbai. Data limitations at a subnational level are one problem which makes it difficult to identify trends (Lucci and Lynch, 2016). We therefore devise three scenarios, the narrative of each of which incorporates elements of a plausible future. We project these narratives onto the model by choosing variable values in line with them. The parameters that differ between scenarios are few and some that depend on national-level rather than local policy, such as decarbonisation rate of electricity, are identical across scenarios. Brief descriptions of the scenarios follow, and Table 1 lists the specific parameter values which are different among scenarios.

3.3.1. Business-as-usual (BAU)

This is the standard scenario, in which current trends are persisting without the necessary corrections to meet the SDGs. Development continues and it is not a priority to improve away

Variable (unit)	BAU	SDG	WAT
heating electricitygas substitution time (year)	40	20	40
hotwater electricitygas substitution time (year)	40	20	40
gas price by unit change rate future (year^{-1})	0.026	0.052	0.026
water waste rate of change future (year^{-1})	-0.02	-0.1	-0.1
slum sewered share reference future change rate (year^{-1})	0	0.05	0.2
wastewater treatment capacity primary to secondary upgrade rate annual (year^{-1})	0.05	0.1	0.2
wastewater treatment capacity secondary to tertiary upgrade rate annual (year^{-1})	0	0.01	0.02
decent housing construction urgency factor (-)	0.5	1	0.5
decent housing average construction time (year)	3	1	3

Table 1: Scenario parameter values

the slums. This translates into a low urgency factor for decent housing construction, and a long construction time, which together with a constant share of slums being sewered, symbolise a systemic reluctance to better the lives of slum dwellers.

A lack of strong environmental policies means that there is no tax on carbon, keeping gas prices low, and also that electricity-for-gas substitution is slower, with time constants twice that of the progressive *SDG* scenario. This corresponds to a continuation of using gas as a cooking fuel. The degree to which wastewater is treated improves with a move towards secondary treatment, but the conversion is slower than in the other scenarios, and there is no development of tertiary treatment over the model timeline.

The water department is not able to keep up with development and the transition from an intermittent to a continuous water supply is slow, so residents abandon excess storage and the water wastage resulting from it at a slower pace than in the other scenarios.

3.3.2. SDG compliance (SDG)

In this scenario, Mumbai meets the SDGs. In the context of the water-energy nexus, this means that everyone has access to safe drinking water, sanitation, decent housing and modern energy carriers. The latter should be used efficiently and derive from renewable resources as much as possible. A main corollary is that no-one lives in slums by 2030. For the water system, this comes down to full sewerage and no water rationing through intermittent supply operation. For the energy system, it means that there is an electrification of heating and cooking. Progress towards SDG 14, which protects aquatic life, requires wastewater treatment to be mainly secondary rather than primary. There is also a conversion to tertiary treatment, though slower than that from primary to secondary treatment.

In terms of scenario-specific parameters (Table 1), the absolute values of the rates of change are higher than in the *BAU* scenario, causing all processes moving towards meeting the SDGs to be faster: increase in gas prices, electricity-for-gas substitution, decrease in water wastage through excess private water storage, slum sewerage provision, wastewater treatment improvement, and upgrading of slums. The combination of these settings reduce non-compliance with the Sustainable Development Agenda to negligible levels.

3.3.3. *Water as a priority (WAT)*

The Water-as-a-priority (*WAT*) scenario narrative is intermediate between the *BAU* and the *SDG* scenarios. Here, the emphasis is on providing water services above all, while slums may persist throughout 2030 according to non-water related elements of their definition, such as overcrowding and quality of housing. This scenario is in line with the finding by Lucci and Lynch (2016) that water access is easier to accomplish than improved housing and improved toilet access.

Parameter values not related to water are equal to those of the *BAU* scenario (Table 1). The decrease in excess water storage and wastage is as fast as in the *SDG* scenario, while sanitation provision growth and improvement in wastewater treatment are more ambitious.

3.4. *Sensitivity Analysis*

We perform a local and qualitative sensitivity analysis on the model. This can give us two types of insights. On the one hand, it can show us to what extent uncertainty on a parameter influences the model results. On the other hand, it can also lead us to the discovery of useful systemic levers to engender desirable outcomes in the real world. Our approach follows Kotir et al. (2016) and is to find the variations of the values of model outputs for the year 2050, in response to a 10% variation in both directions of each of the model parameters, one at a time: once increasing it by 10%, once decreasing it by 10%. The model output variables we chose as indicators are the total demands of the three resources, the water distribution leakage, the population and the water supply capacity augmentation.

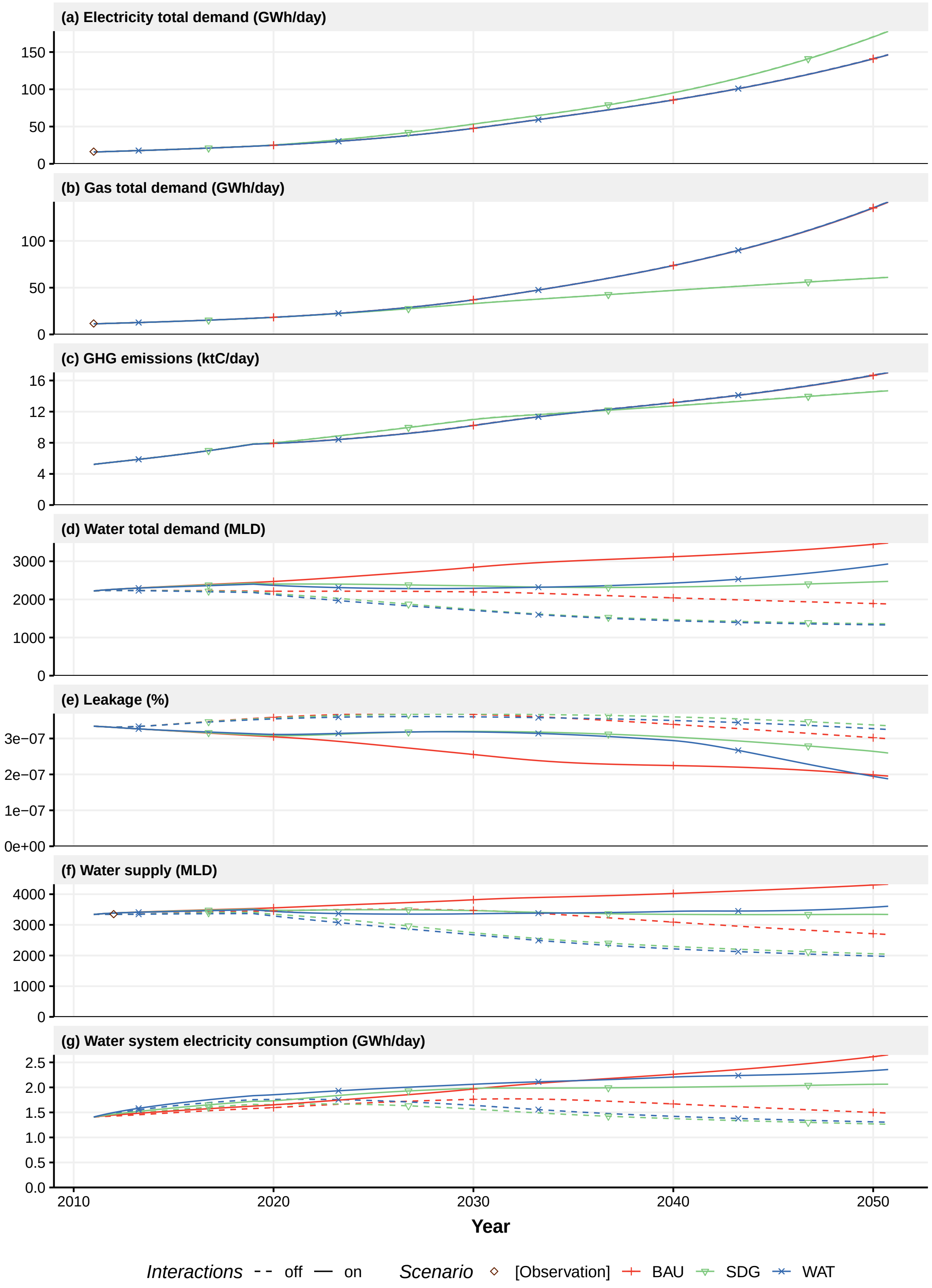
4. Results and discussion

The model results yield a number of valuable insights, both with regard to the water-energy nexus, and in terms of the lessons for policy from the model application.

This sections combines results with discussion. We have organised it into subsections by key message.

4.1. *End-use interactions increase water use*

The interactions between water and energy end use play a significant role in Mumbai and have an important effect on water consumption by consumers as well as upstream and downstream in the water system. Fig. 8 shows the trajectories over the period 2011-2050 for several variables that are related to the metabolism of Mumbai. Each of these is linked to one of the


(a) Electricity total demand (GWh/day)

(b) Gas total demand (GWh/day)

(c) GHG emissions (ktC/day)

(d) Water total demand (MLD)

(e) Leakage (%)

(f) Water supply (MLD)

(g) Water system electricity consumption (GWh/day)

Figure 8: Resource use and other indicators, by scenario, including observations. The line type indicates whether water-energy interactions or linkages at the end use are enabled ('on') or disabled ('off'). MLD = million litres per day.

scenarios, and to whether the interactions in end use are switched on or off in the model. Fig. 8 also shows those data points that we collected before modelling. Enabling the interactions lifts the entire envelope of water demand across scenarios (Fig. 8d): in any given year, the greatest water demand without interactions is lower than the lowest water demand with interactions enabled. This is because of the increase in both gas as well as electricity use (Fig. 8a-b). The effect of the interactions on water consumption is opposite to that observed with a similar model in London (De Stercke et al., 2018) as in that case total energy consumption fell over time.

As greater water demand requires greater supply, the interactions increase water supply as well (Fig. 8f). However, this effect is weaker than in the case of water demand (Fig. 8d). The unit cost of water supply is progressive, and therefore they also have the effect of making water more precious which results in lowering the economic level of leakage (Fig. 8e). Because of this mitigation, the interactions increase the electricity consumption of the upstream and downstream water system (Fig. 8g).

Having shown the effect of the end-use interactions, in what we discuss next we only consider the results with interactions enabled.

4.2. *End use dominates the water-energy nexus*

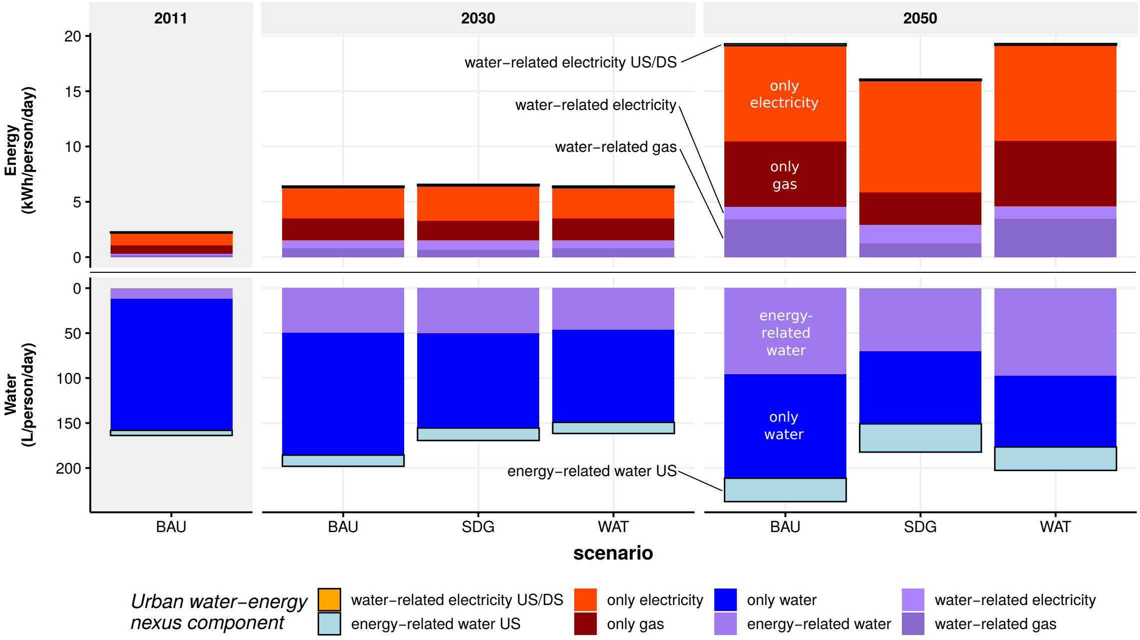


Figure 9: Nexus over time and scenarios for residential sector, per capita. The top graphs, with an upward positive axis, show energy consumption, broken down into electricity related to the water supply or wastewater system, gas/electricity consumption in end use related to water (e.g. for water heating), and gas/electricity consumption in end use unrelated to water (e.g. for lighting). The bottom graphs, with a downward positive axis, show water consumption, broken down into water use for electricity generation, water consumption in end use related to energy (e.g. hot water for showering), and water consumption in end use unrelated to energy (e.g. for drinking).

Component (% of end-use cons.)	2011	2030 BAU	2030 SDG	2030 WAT	2050 BAU	2050 SDG	2050 WAT
water-related electricity US/DS	4.6	2.1	2.0	2.2	0.8	0.8	0.7
only electricity	51.3	44.6	48.6	44.6	45.2	63.4	45.1
only gas	33.7	31.2	27.6	31.2	31.0	18.2	31.0
only energy	85.0	75.8	76.2	75.8	76.2	81.6	76.1
water-related electricity	7.0	11.7	13.3	11.7	5.8	10.5	5.8
water-related gas	8.0	12.5	10.6	12.5	18.0	7.9	18.0
water-related energy	15.0	24.2	23.9	24.2	23.8	18.4	23.8
energy-related water US	3.6	6.7	8.9	8.3	12.3	20.8	14.7
only water	92.4	73.1	67.8	68.9	54.7	53.2	45.0
energy-related water	7.6	26.9	32.2	31.1	45.3	46.8	55.0

Table 2: Nexus components expressed relative to end-use consumption, in percent, for 2011, 2030 and 2050; and by scenario.

We bring together all aspects of Mumbai's water-energy nexus in Fig. 9. It shows the resource consumption per capita of water, gas and electricity, as well as the water or energy use in the upstream and downstream components of the urban water-energy nexus (as defined by Fig. 1). The resource consumption distinguishes whether it is connected in the end-use part of the nexus ('water-related' or 'energy-related') or not ('only'). Water wastage due to excess storage is included in 'only water'.

As a complement to Fig. 9, Table 2 shows resource use by nexus component relative to end-use consumption. Both show clearly that in Mumbai, and across scenarios, end use dominates the water-energy nexus: of all energy-related water and water-related energy, more is consumed or used in end use (7.6% and 15% in 2011) than upstream or downstream (3.6% and 4.6% in 2011). This is in line with findings for cities in the Global North, as mentioned in the Introduction.

4.3. *Business-as-usual will add challenges*

Delaying efforts for the Swachh Bharat Mission and towards the SDGs carries with it other challenges. While it potentially reduces investments related to the construction of decent housing for current slum dwellers and related to upgrading wastewater treatment, a business-as-usual approach will require great infrastructure expansion in terms of upstream and downstream capacity in the water system. This is confirmed by the model results when we compare investments in terms of capacity for various types of urban infrastructure for the different scenarios: Fig. 10 shows, aggregated by decade, the creation of infrastructure in each of the scenarios. The units for each type correspond to their representation in the model.

An increase in energy use drives the increase in water demand which in turn necessitates system expansion. A relatively large share of future energy use is gas, either piped or from LPG cylinders. Because electricity supply can decarbonise but gas cannot, greenhouse gas emissions are higher than in the *SDG* scenario after the mid-2030s (Fig. 8c). This adds challenges related to global warming, especially in the context of requirements for emissions of greenhouse gases

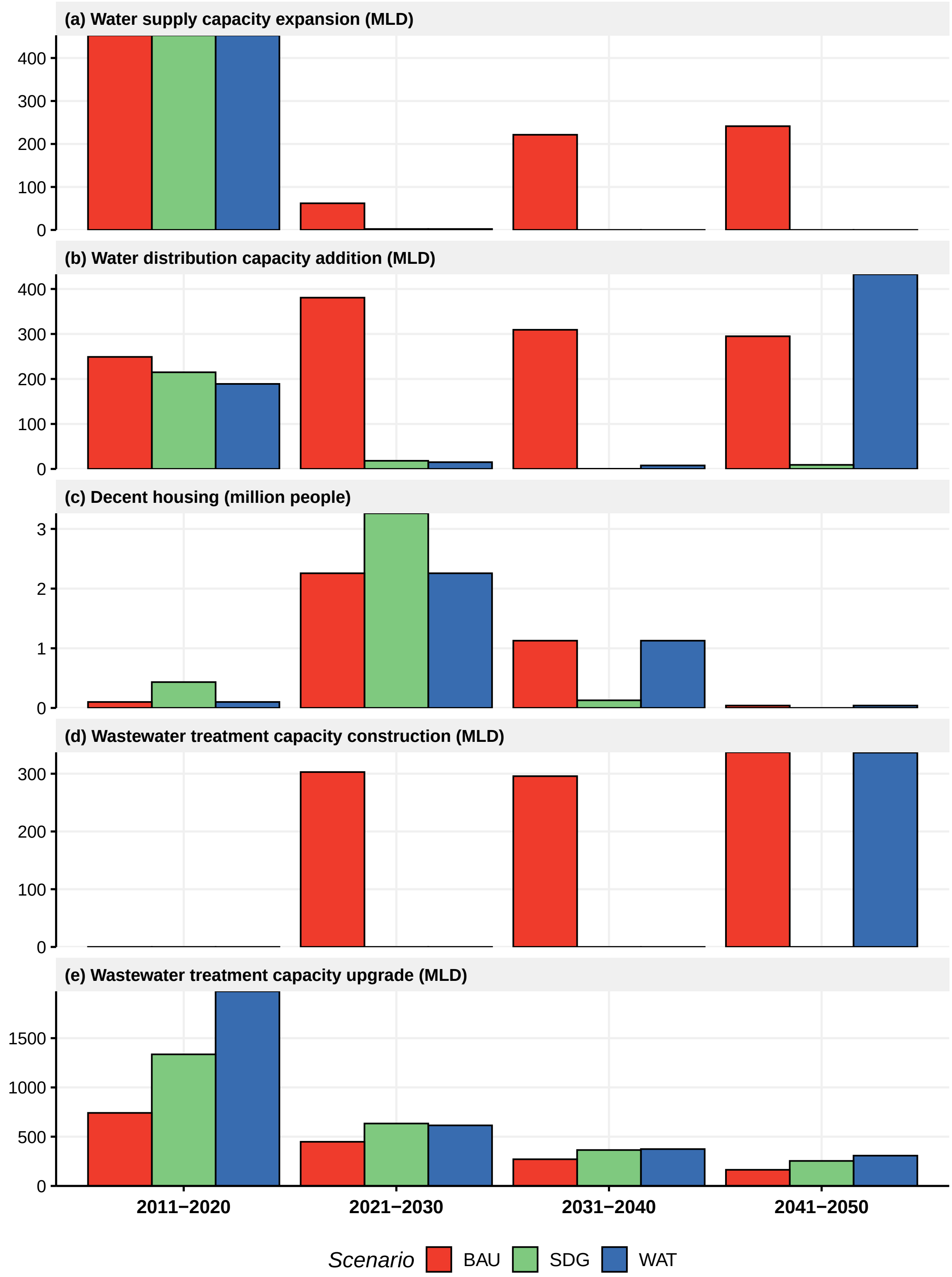


Figure 10: Relative infrastructure investments in terms of capacity, accumulated per decade, by scenario.

to go to zero and negative within this century in order to keep global warming below 1.5°C (Grubler et al., 2018).

4.4. 24/7 water for all is possible and multi-beneficial

Intermittent water supply is maintained through a complexity of interactions of various natures as Galaitsi et al. (2016) have illustrated, with several feedback loops operating concurrently. In order to transition towards continuous water supply, some of these must be broken, while others can help. An example of a loop that must be broken involves the belief that the poor are not willing to pay for reliable water and that hence prices cannot be raised to fund investments in water supply. By acknowledging that the poor have a willingness to pay for continuous and reliable water supply that is above the price of municipal water supply, prices can be raised to build capacity, human and technical, in the water system. Whilst our model does not represent the processes that are involved in such loops that must be broken, it does include a process in a feedback loop which can aid: that of excess water storage. Continuous water supply removes the need for this storage, thus lowering demand, while previously too high a level of demand was the reason for water supply to be rationed in the first place. This feedback is implicit in the two scenarios that restore continuous water supply from the current intermittent operation: the *SDG* scenario and, getting there faster, the *WAT* scenario.

Although moving from intermittent to continuous operation will increase leakage - many pipes will leak throughout the day rather than for just a few hours - the economic level of leakage actually increases (Fig. 8e) in the *SDG* and *WAT* scenarios. This introduces some leeway in the gradual transition to a 24/7 water supply. This is another illustration of a feedback loop which can aid the transition and is implicit in the model.

While reduced water demand decreases the energy use for local pumping, this effect is small as the savings from reduced water wastage are in the water-only part of consumption (Fig. 9) which is not heated, and the energy benefits are mainly on the upstream and downstream parts of the water system. Electricity consumption of the water system is significantly below that in the *BAU* scenario (Fig. 8g) after the mid-2030s. Before, it is greater mainly because of upgrades to wastewater treatment capacity (Fig. 10e) which make it more energy intensive.

The benefits of continuous water supply are pronounced in terms of the savings in infrastructure capacity investments for expanding water treatment, wastewater treatment, and water distribution (Fig. 10a, b, d).

4.5. How can Mumbai meet its targets?

In the *SDG* scenario, Mumbai is set to meet its targets regarding the SDGs that we considered and regarding the Swachh Bharat Mission. In this section, we highlight how Mumbai could take this trajectory by committing to a number of changes.

First of all, it is important to invest in slum upgrading as slum conditions are incompatible with the SDGs. This is the only infrastructure investment that we considered in which the *SDG* scenario significantly tops the other scenarios in the short term (Fig. 10c). Upgrading slums includes providing the people living there with decent housing, full wastewater services, and piped water supply access.

Second, the degree to which wastewater is treated must be at least secondary. The current capacity - most of which is primary treatment - needs to be upgraded, and new systems must be secondary treatment. However, compared to the *BAU* scenario, the infrastructure requirements for the latter are much lower as demand is lower.

Third, the water system must return to continuous operation which lowers water demand by taking away the excess storage requirement.

Fourth, an electricity-for-gas substitution allows for flexibility in decarbonising residential energy uses such as water heating and cooking. It brings down greenhouse gas emissions compared to the other scenarios. Grubler et al. (2018) suggest that both lower energy demand and faster electrification and decarbonisation are possible, hence there is reason to believe that in this aspect the *SDG* scenario is conservative and that emissions can fall much faster without compromising on other benefits. In addition, pressures to reduce end-use energy consumption can translate into further water consumption reductions through interactions that involve half of water demand in 2050 (Table 2).

Our analysis does not include a comparison of scenarios in terms of costs. However, a distinction is clear between the *BAU* and the *SDG* scenario in terms of who benefits from the infrastructure expansion proposed in this work. In the former case, these are largely vested interests and large-scale developers, whereas in the case of setting the SDGs as development targets, all citizens will benefit from a cleaner city, with less pressure on inland water resources.

4.6. Sensitivity analysis

To analyse the robustness of the model results, we conclude the work by performing a local sensitivity analysis (Fig. 11). Only those parameters to which at least one of the six indicators has a sensitivity – the ratio of the relative indicator change in response to the relative change in a parameter value – greater than 1 in absolute terms are displayed. The panel background of such parameter-indicator combinations is lightly coloured. We ordered the parameters and indicators according to maximum sensitivity.

We observe that sensitivities are of comparable orders of magnitude across scenarios, apart from those of the water supply capacity augmentation. Whereas the variation of several parameters can bring about a decrease in the indicator in the *BAU* and *WAT* scenarios, this is not the case in the *SDG* scenario. This is precisely because in the baseline, no augmentation is required

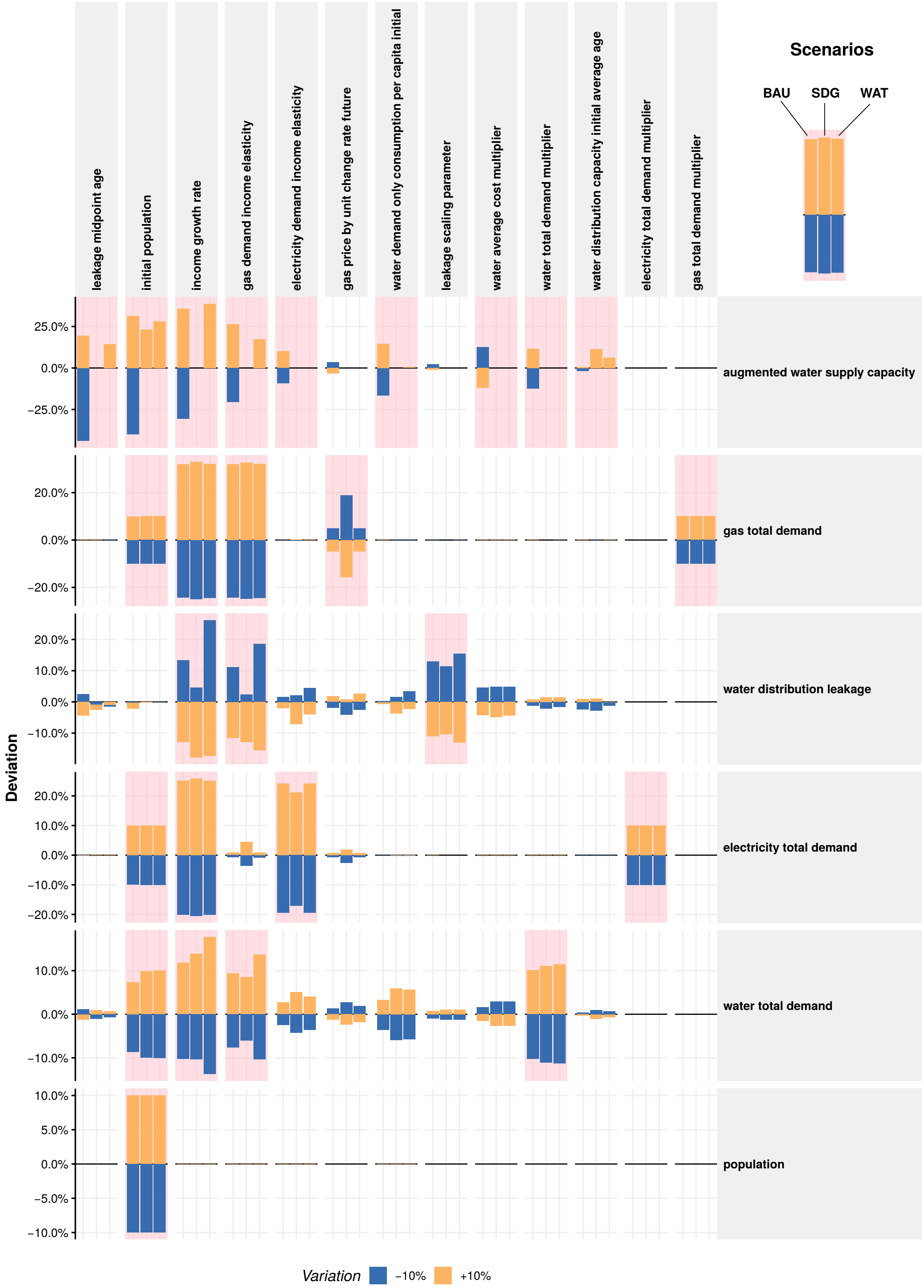


Figure 11: Sensitivity analysis results: relative change in indicator (rows) values to deviations of +10% and -10% in parameter (columns) values. The panels with a coloured background contain deviations of more than 10% in absolute value. Note that the y-scale varies from row to row. In each panel the horizontal axis represents the scenarios *BAU*, *SDG* and *WAT* respectively.

in the last decades, and therefore a reduction in demand will make no difference.

The income growth rate has an important effect on all indicators apart from population, across scenarios. The sensitivity of the water supply capacity augmentation is greater than unity for almost all parameters in Fig. 11. In line with expectations, the initial population has an important effect on total resource demand. The other parameters are mainly elasticities, prices and other demand determinants such as the multipliers.

These sensitivity analysis results are mostly unsurprising and not a cause for doubt about the model robustness. It is e.g. basic that a 10% difference in an annual rate, compounded over 40 years, translates into changes of well over 10%. However, the sensitivity analysis shows that water distribution leakage is sensitive to the parameters used in its simple formulation as a logistic function of average pipe age. This sensitivity propagates to the water supply capacity augmentation. A better, more robust model for leakage could be valuable in future work.

4.7. Limitations

The model represents all processes that we have found to be of relevance to the water-energy nexus of Mumbai. Some of these are very complex and have their own field of research, such as intermittent water supply and consumers' coping mechanisms, and the dynamics of slums. Our simplification of these processes through various assumptions carries with it some caveats regarding the results. In this section, we discuss the most important of these assumptions as well as their implications.

In the model, the end-use dynamics in response to price and income apply only to the non-slum population. We believe this was a necessary concession to keep the model manageable and to circumvent lack of data, and our justification includes the indications that the slum population is shrinking, and that energy and water use are lower in slums than the rest of the city.

By not representing finance other than instantaneously balancing costs and revenue of the water system, we implicitly assume that the financial motor which drives the changes we model is working well in the background. Although we assess infrastructure requirements in their simplest form, the project finance to make this happen is beyond the scope of this research: we trust that the money finds a way.

We formulated the scenario narratives and their parameters in relationship to each other rather than in absolute terms. They represent possible futures in response to emphases in policy and the degree to which policy is successful. Together, the scenarios span a range of possible futures. They also subsume some of the uncertainty regarding model parameters and stability of the processes that we model. As the results show, the behaviour of the modelled scenarios is consistent with their narratives, and the conclusions with regard to the end-use interactions are robust.

5. Conclusions

The urban water-energy nexus is getting the recognition that it deserves because of the challenges and opportunities it poses to cities, but there is a skew in research towards the Global North. We present a model for the residential water-energy nexus of Mumbai and its changes over time. We identified system dynamics to be an appropriate modelling method because of the nature and complexity of the multifarious situation, and adapted a model De Stercke et al. (2018) developed and applied to London, to suit Mumbai.

Both the characterisation of Mumbai's water-energy nexus and its evolution over time are novel elements in our study. Our scenario-based approach explores three possible futures that have roots in the ambitions regarding urban water encoded in the Sustainable Development Goals and the Swachh Bharat Mission.

We show that, despite lower energy use, the relative importance of the end use in the water-energy nexus of Mumbai is comparable to that in cities in the Global North. This could have significant implications for how sustainable development is achieved, as the scenario results show. In addition, we estimate relative infrastructure capacity requirements over time and between scenarios. The most socially and environmentally progressive scenario, the *SDG* scenario, has greater immediate requirements in terms of decent housing, but less for water supply.

The model inputs are partly estimates due to a lack of measurements and availability. Intermittent water supply and slum dynamics are two multidimensional and complex phenomena that we do not model in detail. Despite these limitations, the model conclusions are firm in light of what we know and in light of global and local ambitions: water use and energy use increase, and end-use interactions have a hand in this.

We use the model to show that for Mumbai, faster slum improvement, offering better living conditions for the citizens living in them, is instrumental in meeting the SDGs and in fulfilling the Swachh Bharat Mission. In addition, water supply must become continuous, decarbonised electricity must substitute for gas, and wastewater must be treated to a secondary degree. If these changes were implemented, costs related to the expansion of capacity in water supply and distribution, and wastewater treatment, as under the *BAU* scenario, could be avoided.

An analysis of sensitivities show that the greatest are related to the income growth rate and its influence on resource consumption, and that water distribution leakage is sensitive to the parameters in its simplified formulation. A better representation of leakage would benefit the model, but the effect on water system related quantities is limited.

We hope that this study opens a door towards further investigation of the water-energy nexus in cities in the Global South, which comprise an ever growing share of the world's population and resource use. Better data quality and availability would facilitate such a research avenue. In addition, a bias towards research on the largest cities limits our understanding of dynamics in smaller cities, which are more numerous and host, in aggregate, more people. The scaling of the water-energy nexus with city size is another interesting direction to pursue.

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7. References

References

American Association for the Advancement of Science. Rise of the City. *Science*, 352(6288): 906–907, May 2016. ISSN 0036-8075, 1095-9203. doi:10.1126/science.352.6288.906. URL `http://science.sciencemag.org/content/352/6288/906`.

Nikhil Anand. PRESSURE: The PoliTechnics of Water Supply in Mumbai. *Cultural Anthropology*, 26(4):542–564, November 2011. ISSN 08867356. doi:10.1111/j.1548-1360.2011.01111.x. URL `http://doi.wiley.com/10.1111/j.1548-1360.2011.01111.x`.

Nikhil Anand. Municipal disconnect: On abject water and its urban infrastructures. *Ethnography*, 13(4):487–509, December 2012. ISSN 1466-1381, 1741-2714. doi:10.1177/1466138111435743. URL `http://eth.sagepub.com/content/13/4/487`.

Shri. Shrikant Argade. Interviews with Deputy Hydraulic Engineer Planning and Control, MCGM, February 2016.

R. B. Bambale. Water Reforms - Mumbai, Maharashtra, November 2012. URL `http://test.icrier.org/pdf/Maharashtra_05nov12.pdf`.

BC Barah, Vandana Sipahimalani, and Purnamita Dhar. Urban water supply and sanitation. *Economic Instruments for Environment Sustainability, New Delhi: National Institute of Public Finance and Policy*, 1998.

Carlos J. Gil Bellosta. *rPython: Package Allowing R to Call Python*. 2015. URL `http://CRAN.R-project.org/package=rPython`. R package version 0.0-6.

Lisa Björkman. *Pipe Politics, Contested Waters: Embedded Infrastructures of Millennial Mumbai*. Duke University Press Books, Durham, October 2015. ISBN 978-0-8223-5969-2.

Vaibhav Chaturvedi, Jiyong Eom, Leon E. Clarke, and Priyadarshi R. Shukla. Long term building energy demand for India: Disaggregating end use energy services in an integrated assessment modeling framework. *Energy Policy*, 64:226–242, January 2014. ISSN 0301-4215. doi:10.1016/j.enpol.2012.11.021. URL `http://www.sciencedirect.com/science/article/pii/S030142151200986X`.

Aditya Chunekar, Sapekshya Varshney, and Shantanu Dixit. Residential electricity consumption in India: what do we know. *Prayas (Energy Group), Pune*, 4, 2016. URL `http://www.prayaspune.org/peg/publications/item/331.html`.

Simon De Stercke, Ana Mijic, and James Keirstead. A Review of Urban Water-energy Linkages in End-use: A Call for Joint Demand Studies. *British Journal of Environment and Climate Change*, 6(3):192–200, January 2016. ISSN 22314784. doi:10.9734/BJECC/2016/23725.

Simon De Stercke, Ana Mijic, Wouter Buytaert, and Vaibhav Chaturvedi. Modelling the dynamic interactions between London's water and energy systems from an end-use perspective. *Applied Energy*, 230:615–626, November 2018. ISSN 0306-2619. doi:10.1016/j.apenergy.2018.08.094.

Tommi Ekholm, Volker Krey, Shonali Pachauri, and Keywan Riahi. Determinants of household energy consumption in India. *Energy Policy*, 38(10):5696–5707, October 2010. ISSN 0301-4215.

doi:10.1016/j.enpol.2010.05.017. URL `http://www.sciencedirect.com/science/article/pii/S0301421510003885`.

Jay Forrester. *Industrial Dynamics*. Pegasus Communications, Waltham, MA, 1961.

S. E. Galaitsi, Robert Russell, Amahl Bishara, John L. Durant, Jennifer Bogle, and Annette Huber-Lee. Intermittent Domestic Water Supply: A Critical Review and Analysis of Causal-Consequential Pathways. *Water*, 8(7):274, June 2016. doi:10.3390/w8070274. URL `http://www.mdpi.com/2073-4441/8/7/274`.

Matthew Gandy. Landscapes of disaster: water, modernity, and urban fragmentation in Mumbai. *Environment and Planning A*, 40(1):108–130, 2008. ISSN 0308-518X. doi:10.1068/a3994. URL `http://www.envplan.com/abstract.cgi?id=a3994`.

P H Gleick. Water and Energy. *Annual Review of Energy and the Environment*, 19(1):267–299, 1994. doi:10.1146/annurev.eg.19.110194.001411. URL `http://dx.doi.org/10.1146/annurev.eg.19.110194.001411`.

Government of India. INDC submission to UNFCCC, October 2015.

Government of India. Swachh Bharat Urban, 2020. URL `http://swachhbharaturban.gov.in/`.

Stephen Graham, Renu Desai, and Colin McFarlane. Water Wars in Mumbai. *Public Culture*, 25 (1 69):115–141, December 2013. ISSN 0899-2363, 1527-8018. doi:10.1215/08992363-1890486. URL `http://publicculture.dukejournals.org/content/25/1_69/115`.

P. Greve, T. Kahil, J. Mochizuki, T. Schinko, Y. Satoh, P. Burek, G. Fischer, S. Tramberend, R. Burtscher, S. Langan, and Y. Wada. Global assessment of water challenges under uncertainty in water scarcity projections. *Nat Sustain*, 1(9):486–494, September 2018. ISSN 2398-9629. doi:10.1038/s41893-018-0134-9. URL `https://www.nature.com/articles/s41893-018-0134-9/`.

Arnulf Grubler, Nebojsa Nakicenovic, Shonali Pachauri, Hans-Holger Rogner, and Kirk A. Smith. *Energy Primer*. International Institute for Applied Systems Analysis, Laxenburg, Austria, 2014. URL `http://www.energyprimer.org`.

Arnulf Grubler, Charlie Wilson, Nuno Bento, Benigna Boza-Kiss, Volker Krey, David L. McCollum, Narasimha D. Rao, Keywan Riahi, Joeri Rogelj, Simon De Stercke, Jonathan Cullen, Stefan Frank, Oliver Fricko, Fei Guo, Matt Gidden, Petr Havlík, Daniel Huppmann, Gregor Kiesewetter, Peter Rafaj, Wolfgang Schoepp, and Hugo Valin. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, 3(6):515–527, June 2018. ISSN 2058-7546. doi: 10.1038/s41560-018-0172-6.

Haripriya Gundimeda and Gunnar Köhlin. Fuel demand elasticities for energy and environmental policies: Indian sample survey evidence. *Energy Economics*, 30(2):517–546, March 2008. ISSN 0140-9883. doi:10.1016/j.eneco.2006.10.014. URL `http://www.sciencedirect.com/science/article/pii/S0140988306001290`.

James Houghton and Michael Siegel. Advanced Data Analytics for System Dynamics Models Using PySD. In *Proceedings of the 33rd International Conference of the System Dynamics Society*, 2015.

Wa'el A. Hussien, Fayyaz A. Memon, and Dragan A. Savic. An integrated model to evaluate water-energy-food nexus at a household scale. *Environmental Modelling & Software*, 93: 366–380, July 2017. ISSN 1364-8152. doi:10.1016/j.envsoft.2017.03.034. URL `http://www.sciencedirect.com/science/article/pii/S1364815216306594`.

International Energy Agency (IEA). IEA World Energy Statistics and Balances. Technical report, IEA/OECD, Paris, France, 2017.

International Energy Agency. *CO2 Emissions from Fuel Combustion 2013*. OECD, 2013. doi: 10.1787/co2_fuel-2013-en. URL `https://www.oecd-ilibrary.org/content/publication/co2_fuel-2013-en`.

International Energy Agency. *CO2 Emissions from Fuel Combustion 2018*. OECD, 2018. doi: 10.1787/co2_fuel-2018-en. URL `https://www.oecd-ilibrary.org/content/publication/co2_fuel-2018-en`.

Rebecca A. Kelly, Anthony J. Jakeman, Olivier Barreteau, Mark E. Borsuk, Sondoss ElSawah, Serena H. Hamilton, Hans Jørgen Henriksen, Sakari Kuikka, Holger R. Maier, Andrea Emilio Rizzoli, Hedwig van Delden, and Alexey A. Voinov. Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software*, 47:159–181, September 2013. ISSN 1364-8152. doi:10.1016/j.envsoft.2013.05.005. URL `http://www.sciencedirect.com/science/article/pii/S1364815213001151`.

Jacqueline M Klopp and Danielle L Petretta. The urban sustainable development goal: Indicators, complexity and the politics of measuring cities. *Cities*, 63:92–97, March 2017. ISSN 0264-2751. doi:10.1016/j.cities.2016.12.019. URL `http://www.sciencedirect.com/science/article/pii/S0264275116303122`.

Julius H. Kotir, Carl Smith, Greg Brown, Nadine Marshall, and Ron Johnstone. A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. *Science of The Total Environment*, 573:444–457, December 2016. ISSN 0048-9697. doi:10.1016/j.scitotenv.2016.08.081. URL `http://www.sciencedirect.com/science/article/pii/S0048969716317740`.

Krishna Kumar and Kailash Babar. Mumbai Development Plan 2034 puts focus on affordable homes and job creation. *The Economic Times*, April 2018. URL `https://economictimes.indiatimes.com/industry/services/property-/-cstruction/new-development-plan-for-mumbai-unveiled-city-to-get-more-land-for-housing/articleshow/63915163.cms`.

Paula Lucci and Alainna Lynch. The SDGs at city level: Mumbai's example. Technical report, Working Paper 432. London: ODI, 2016.

N. Mankiw. *Principles of Economics*. South-Western College Pub., Stamford, CT, 7 edition, January 2014. ISBN 978-1-285-16587-5.

Ignacio J. Martinez-Moyano. Documentation for model transparency. *Syst. Dyn. Rev.*, 28(2): 199–208, April 2012. ISSN 1099-1727. doi:10.1002/sdr.1471. URL `http://onlinelibrary.wiley.com/doi/10.1002/sdr.1471/abstract`.

MCGM Water Department. Love Grove Waste Water Treatment Facility handout booklet, 2016.

Fanxin Meng, Gengyuan Liu, Sai Liang, Meirong Su, and Zhifeng Yang. Critical review of the energy-water-carbon nexus in cities. *Energy*, 171:1017–1032, March 2019. ISSN 0360-5442. doi:10.1016/j.energy.2019.01.048. URL `http://www.sciencedirect.com/science/article/pii/S0360544219300519`.

Chandrarao More, Sarag J. Saikia, and Rangan Banerjee. An Analysis of Maharashtra's Power Situation. *Economic and Political Weekly*, 42(39):3943–3951, 2007. ISSN 0012-9976. URL `https://www.jstor.org/stable/40276471`.

National Sample Survey Organisation. Level and Pattern of Consumer Expenditure, 2011–2012 NSS 68th Round (July 2011–June 2012). Technical Report 555(68/1.0/1), Ministry of Statistics and Programme Implementation, Government of India, New Delhi, 2014.

Khoi Nguyen, Rodney A Stewart, Oz Sahin, Edoardo Bertone, Cara D. Beal, Andrea Cominola, Hong Zhang, and Abel Silva Vieira. Digital Multi-Utility Data for Contemporaneous Water-

Electricity-Gas End Use Categorization. In *2019 3rd International Conference on Smart Grid and Smart Cities (ICSGSC)*, pages 45–50, June 2019. doi:10.1109/ICSGSC.2019.00-20. ISSN: null.

Office of the Registrar General & Census Commissioner, India. Census 2001. Technical report, 2001.

Office of the Registrar General & Census Commissioner, India. Census 2011. Technical report, 2011.

Michael Pacione. Mumbai. *Cities*, 23(3):229–238, June 2006. ISSN 0264-2751. doi: 10.1016/j.cities.2005.11.003. URL `http://www.sciencedirect.com/science/article/pii/S0264275105001381`.

Shirish B. Patel. Slum Rehabilitation in Mumbai: Possible If Done Differently. *Economic and Political Weekly*, 31(18):1047–1050, 1996. ISSN 0012-9976. URL `https://www.jstor.org/stable/4404081`.

A. K. Plappally and J. H. Lienhard V. Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews*, 16(7):4818–4848, September 2012. ISSN 1364-0321. doi:10.1016/j.rser.2012.05.022. URL `http://www.sciencedirect.com/science/article/pii/S1364032112003541`.

R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2018. URL `https://www.R-project.org/`.

Anu Ramaswami, Dana Boyer, Ajay Singh Nagpure, Andrew Fang, Shelly Bogra, Bhavik Bakshi, Elliot Cohen, and Ashish Rao-Ghorpade. An urban systems framework to assess the trans-boundary food-energy-water nexus: implementation in Delhi, India. *Environ. Res. Lett.*, 12(2):025008, 2017. ISSN 1748-9326. doi:10.1088/1748-9326/aa5556. URL `http://stacks.iop.org/1748-9326/12/i=2/a=025008`.

B. Sudhakara Reddy. Metabolism of Mumbai - Expectation, Impasse and the Need for a New Beginning. *Mumbai: Indira Gandhi Institute of Development Research*, 2013. URL `http://www.igidr.ac.in/pdf/publication/WP-2013-002.pdf`.

B. Sudhakara Reddy and P. Balachandra. Urban mobility: A comparative analysis of megacities of India. *Transport Policy*, 21:152–164, May 2012. ISSN 0967-070X. doi:10.1016/j.tranpol.2012.02.002. URL `http://www.sciencedirect.com/science/article/pii/S0967070X12000261`.

Seyed Sadr, Fayyaz Memon, Arpit Jain, Shilpa Gulati, Andrew Duncan, Wael Hussein, Dragan Savić, and David Butler. An Analysis of Domestic Water Consumption in Jaipur, India. *British*

Journal of Environment and Climate Change, 6(2):97–115, January 2016. ISSN 22314784. doi:10.9734/BJECC/2016/23727. URL `http://www.sciencedomain.org/abstract/15375`.

O. Sahin, R. S. Siems, R. A. Stewart, and Michael G. Porter. Paradigm shift to enhanced water supply planning through augmented grids, scarcity pricing and adaptive factory water: A system dynamics approach. *Environmental Modelling & Software*, 75:348–361, January 2016. ISSN 1364-8152. doi:10.1016/j.envsoft.2014.05.018. URL `http://www.sciencedirect.com/science/article/pii/S1364815214001571`.

Abdul Shaban and R. N. Sharma. Water Consumption Patterns in Domestic Households in Major Cities. *Economic and Political Weekly*, June 2007.

E.S. Spang, W.R. Moomaw, K.S. Gallagher, P.H. Kirshen, and D.H. Marks. The water consumption of energy production: An international comparison. *Environmental Research Letters*, 9 (10), 2014. ISSN 1748-9318. doi:10.1088/1748-9326/9/10/105002.

Shweta Srinivasan, Nazar Kholod, Vaibhav Chaturvedi, Probal Pratap Ghosh, Ritu Mathur, Leon Clarke, Meredydd Evans, Mohamad Hejazi, Amit Kanudia, Poonam Nagar Koti, Bo Liu, Kirit S. Parikh, Mohammed Sahil Ali, and Kabir Sharma. Water for electricity in India: A multi-model study of future challenges and linkages to climate change mitigation. *Applied Energy*, 210:673–684, January 2018. ISSN 0306-2619. doi:10.1016/j.apenergy.2017.04.079. URL `http://www.sciencedirect.com/science/article/pii/S0306261917304725`.

Veena Srinivasan, Steven M. Gorelick, and Lawrence Goulder. A hydrologic-economic modeling approach for analysis of urban water supply dynamics in Chennai, India. *Water Resour. Res.*, 46(7):W07540, July 2010. ISSN 1944-7973. doi:10.1029/2009WR008693. URL `http://onlinelibrary.wiley.com/doi/10.1029/2009WR008693/abstract`.

Saurabh Srivastava. Analysing and Forecasting Energy Demand for A Sustainable Living: a Case Study of Mumbai, August 2012.

John Sterman. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill Higher Education, Boston, Mass.; London, December 2000. ISBN 978-0-07-117989-8.

Rodney A. Stewart, Khoi Nguyen, Cara Beal, Hong Zhang, Oz Sahin, Edoardo Bertone, Abel Silva Vieira, Andrea Castelletti, Andrea Cominola, Matteo Giuliani, Damien Giurco, Michael Blumenstein, Andrea Turner, Ariane Liu, Steven Kenway, Dragan A. Savić, Christos Makropoulos, and Panagiotis Kossieris. Integrated intelligent water-energy metering systems and informatics: Visioning a digital multi-utility service provider. *Environmental Mod-*

elling & Software, 105:94–117, July 2018. ISSN 1364-8152. doi:10.1016/j.envsoft.2018.03.006. URL `https://www.sciencedirect.com/science/article/pii/S1364815217311271`.

Surekha Sule. Understanding our Civic Issues: Mumbai's Water Supply. Technical report, The Bombay Community Public Trust, 2004. URL `http://www.bcpt.org.in/articles/watersupply.pdf`.

UN-Habitat. The Challenge of Slums: Global Report on Human Settlements 2003. *Management of Environmental Quality: An International Journal*, June 2004. ISSN 1477-7835. doi:10.1108/meq.2004.15.3.337.3. URL `https://www.emerald.com/insight/content/doi/10.1108/meq.2004.15.3.337.3/full/html`.

UNDESA. *The Sustainable Development Goals Report 2016*. United Nations Department of Economic and Social Affairs, 2016. URL `https://www.un-ilibrary.org/content/publication/3405d09f-en`. Type: doi:https://doi.org/10.18356/3405d09f-en.

Chunyan Wang, Lu Lin, Gustaf Olsson, Yi Liu, and Ming Xu. The scope and understanding of the water–electricity nexus. *Resources, Conservation and Recycling*, 150:104453, November 2019. ISSN 0921-3449. doi:10.1016/j.resconrec.2019.104453. URL `http://www.sciencedirect.com/science/article/pii/S0921344919303593`.

Kai Wang and Evan G. R. Davies. Municipal water planning and management with an end-use based simulation model. *Environmental Modelling & Software*, 101:204–217, March 2018. ISSN 1364-8152. doi:10.1016/j.envsoft.2017.12.024. URL `http://www.sciencedirect.com/science/article/pii/S136481521730556X`.

Appendices

A. Data

Data for the model calibration in this study were collected from scientific literature, grey literature and personal communications. When we were unable to find data in those sources, we constructed estimates based on informed judgment and proxy variables. In this section, the reader will find justifications and sources for values used in the system dynamics model. It consists of the subsections demographics, water system, energy system, and economics.

A.1. Demographics

The decadal Census of India provides population data for Mumbai. The two censuses we consulted for this study are those from 2001 Office of the Registrar General & Census Commissioner, India (2001) and 2011 Office of the Registrar General & Census Commissioner, India (2011). Table A.3 lists all these values along with compound average growth rates. The immigration and emigration reference rates depend on the latter, specifically the difference between them; the emigration reference rate was arbitrarily chosen equal to the total population growth rate. The values for birth and death rates are both 3 per thousand per year but are irrelevant as they cancel each other out. In the model, the change in slum population is driven by a change in the slum share of the total population, and we calibrated this on the corresponding rate in table A.3.

Year	Total population	Slum population	Slum share (%)
2001	11.98m	6.48m	54
2011	12.44m	5.21m	42
cagr (%/yr)	0.4	-2.2	-2.5

Table A.3: Population numbers for the calibration of the model

A.2. Water system

We relied on various sources for the calibration of the representation of the water system in the model. The research visits to Mumbai yielded crucial data regarding water supply and wastewater services, both in terms of water flows as well as energy intensity, whereas literature provided estimates of water end use.

A.2.1. Water supply

The municipal water supply of Greater Mumbai is provided by the MCGM. It is predominantly surface water taken from two rivers in Maharashtra, the Bhatsa and the Vaitarna. Each have several dams. The sources for the numbers in this section are Bambale (2012) and Argade (2016).

The total water supply for Greater Mumbai at the time of data collection (2016) was about 3615 MLD. Two plants treat the water before distribution: Bhandup (2250 MLD) and Panjarapur (1365 MLD).

The total electricity consumption of the large upstream pumping stations including the water treatment plants equals 1.27 GWh per day[1]. This implies an energy intensity of the water supply of 0.35 kWh/m^3. We use the rounded value of 0.4 kWh/m^3 to take into account smaller pumping stations in the distribution network for which we have no data.

A.2.2. Water end use

Mumbai's population is highly heterogeneous in terms of water use. At the highest level of distinction, slum and non-slum dwellers have different water use patterns because of differences in access to water as well as differences in purchasing power. On a lower level there are also large differences among the non-slum population due to differences in available coping mechanisms with respect to the intermittent water supply. The water use of all these groups differs both in total quantity as well as in shares of the different uses. Shaban and Sharma (2007) performed a vast end-use survey which shows and quantifies this heterogeneity. Because of the large sample size for Mumbai, we use this study for the relative shares of water consumption. However, the study is at odds with the significantly larger per capita consumption values reported by Bambale (2012). In the model, we explain part of this difference by introducing a volume of water wastage.

Table A.4 shows the per capita consumption values used in the model for 2005. The shares are the average for Mumbai as reported by Shaban and Sharma (2007) and apply to slum as well as non-slum users. The totals are different: we assume that the average consumption in slums is 80 litres per capita per day, and 120 lpcd in other areas. These consumption values are net of the additional water wastage, which we assume in 2011 to be 80 lpcd and 20 lpcd for non-slum and slum users respectively, so that the total per capita consumption of non-slum citizens is in agreement with the 200 lpcd and 100 lpcd consumption values that Bambale (2012) asserts.

The parameters relating to future efficiency improvements are the same as in De Stercke et al.'s (2018) model for London.

A.2.3. Leakage

In the model, water distribution leakage and water end-use consumption determine the implied supply. In reality, the available supply limits water consumption which is smaller than

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[1] This is based on handwritten numbers and follows the omission of an ambiguous symbol which could be a leading 1 and in that case would bring the energy intensity of water supply to much higher than London's. The latter is unlikely because Mumbai's water sources are at elevations and therefore heads much greater with respect to the city than London's.

Service	Share (%)	Non-slum (lpcd)	Slum (lpcd)
Bathing	23.7	28.44	18.96
Washing clothes	24.3	29.16	19.44
Drinking	4.2	5.04	3.36
Cooking	1.7	2.04	1.36
Toilets	21.6	25.92	17.28
Cleaning house	6.6	7.92	5.28
Washing utensils	17.4	20.88	13.92
Others	0.5	0.6	0.4

Table A.4: Water consumption values for the average consumers in the model

actual water demand. We therefore implicitly take users' demands to have adjusted to the limited supply and take the system to be demand-driven, just like London's (De Stercke et al., 2018).

The equation determining leakage is the same as in the previous implementation of the model for the case of London (De Stercke et al., 2018). It corresponds to an economic level of leakage based on the lost revenue of water, and on the cost of reducing leakage by replacing pipes. In the model, leakage depends solely on the average age of the water system, in a sigmoid expression with two parameters: a scaling parameter for the age, and a midpoint age, for which the leakage rate equals 50%. We chose the value for both parameters such that the water price as well as the cost of water are consistent with published values. Holding all other model parameters constant, we found that values of 3 for the scaling parameter and 70 years for the midpoint age, yielding a water leakage rate in 2012 of 33%. This corresponds to that implied by the water department (Bambale, 2012) who report a supply of 3350 MLD and a total consumption of 2242 MLD. The latter is the combined billed estimate for the residential, commercial and industrial sectors.

A.2.4. Wastewater

Most of the wastewater that the water department collects, passes through primary treatment before outfalls transport it offshore into the ocean. Some undergoes secondary treatment in aerated lagoons, and a negligible fraction tertiary treatment. A part of the wastewater does however not pass through a sewage system. We assume that in the model base year, the sewage system captures all non-slum wastewater, and 20% of the slum wastewater. Table A.5 lists the wastewater treatment plants by degree of treatment, along with their capacities.

According to MCGM Water Department's (2016) numbers, there is ample capacity to treat all water consumed in Mumbai.

We use a primary treatment energy intensity of 0.04 kWh/m^3. We based this on the annual electricity use of the Love Grove WWTP plant (about 6 GWh) and its throughput (about 162 GL), which gives 0.0374 kWh/m^3. This value fits well with Plappally and Lienhard V's (2012)

Treatment level	Name	Capacity (MLD)
Primary	Bandra	796.8
	Colaba	41.1
	Malad	280.4
	Worli	756.9
	Total	1875.2
Secondary	Bhandup	230
	Ghatkopar	386.1
	Versova	180
	Total	796.1
Total		2671.3

Table A.5: Mumbai's main wastewater treatment plants in 2015, by treatment level and with capacities. Source: MCGM Water Department (2016).

values.

We assume an energy intensity of secondary treatment of 0.25 kWh/m^3. Plappally and Lienhard V (2012) found this value for aerated lagoons in China. For tertiary treatment we chose 0.45 kWh/m^3 from Plappally and Lienhard V's (2012) range.

A.3. Energy

A.3.1. End use

In the model, we focus on end use as what happens in the city does not influence the upstream dynamics much. Although we calculate the energy requirements of the urban water system, most important is the residential energy use.

We limit ourselves to two final energy carriers: gas in the form of LPG (Liquefied Petroleum Gases) and electricity. Reddy (2013) has shown, through their urban metabolism analysis of the Mumbai Metropolitan Region, that these energy carriers dominate residential final energy. Some consumers have a piped gas supply but this is still rare.

For Greater Mumbai, we might use the electricity consumption time series that Srivastava (2012) compiled for each of the three supplying companies but in doing so we encounter two problems: (1) at least one of the companies, Adani Electricity, formerly RInfra, also supplies customers outside of Greater Mumbai and these are included in the consumption totals; and (2) there is no differentiation between types of consumers, such as non-slum and slum. The second problem also arises when we infer LPG consumption from either Reddy (2013) or Srivastava (2012).

We solve these problems by estimating electricity and gas consumption bottom-up instead of top-down, and we do this by using the data from the 68th round of the National Sample Survey, collected from July 2011 through June 2012 (National Sample Survey Organisation, 2014). Scaling up residential electricity use to the national level yields 677 PJ for a year, while the International Energy Agency (, IEA) report 634 PJ for 2011 and 680 PJ for 2012. This strengthens our confidence in the bottom-up approach. With one assumption, this approach also allows for a slum/non-slum differentiation: assuming the slum consumers are the lowest 42 % (Table A.3) quantile by household income, we find the corresponding expenditure value (as a proxy for income) and thus obtain the electricity consumption of the groups on either side of it. We did the same for LPG consumption. LPG consumption is reported in grammes, and we used a heating value of 46.1 MJ/kg.

In this way, we obtain total per capita gas and electricity consumption values for the 2011 base year.

Water-related energy use follows from the water consumption, with additional assumptions:

- We only couple energy to water use for thermal purposes. Mechanical energy, apart from that for local pumping to tanks, is subsumed in other energy uses; e.g. the electricity to operate a household reverse-osmosis water filter.
- the ambient temperature of water is 20°C
- electrical water heating has an initial efficiency of 90%.
- gas heating has an initial efficiency of 50%, a low value because we assume a significant amount of open-flame heating.
- boilers (referred to as geysers) are electric. This also includes immersion heating rods.
- Of the services for which water is heated, the fraction of the water heated, the final temperature, and the final energy carrier are:
  - for *bathing*: non-slum 20% and 40°C (electricity), slum 10% and 30°C (gas). We based these numbers on the assumption that water is only heated in winter months, born from anecdotal evidence.
  - for *washing clothes*: non-slum 20% and 30°C (electricity). we chose these numbers from my experience and anecdotal indications that often consumers do not heat water for clothes washing.
  - for *cooking*: both slum and non-slum 50% and 100°C (gas). When setting the share we took into account latent heat which is not explicitly calculated.
  - for *house cleaning*: non-slum 10% and 40°C (electricity). The observation that not a lot of cleaning is done with hot water informs this assumption and choice.

  - for *utensils cleaning / dishwashing*: non-slum 25% and 25°C (electricity). We assume that on average only a quarter of dish washing is done with slightly heated water.

This puts the resulting water-related electricity for the non-slum population at about 7% of electricity use. This falls within the ranges that Chunekar et al. (2016) compiled, taking into account that some of the electricity use calculated here could be classified as other uses.

The parameters relating to future efficiency improvements are the same as in De Stercke et al.'s (2018) model for London. We note here that they are not relevant, because over the time period considered energy use increases monotonically, thus not requiring gains in efficiency in the model's formulation.

A.3.2. Greenhouse gas emissions

The model quantifies the residential carbon emissions from energy consumption, as an indicator of greenhouse gas emissions. We take a constant carbon intensity of 54 grammes per kWh for gas. For electricity, the equivalent carbon intensity changes over time. Assuming transmission and distribution losses of 20% and using the national average, the emissions intensity in 2011 is 292 grammes of carbon per kWh at the final energy level (International Energy Agency, 2013). The share of non-fossil fuel electricity generation fell from 20.2% in 2011 to 18.8% in 2016 (International Energy Agency, 2018). We therefore assume that the emissions intensity remains constant through the present year 2019. After that, it falls at a annual rate of 4.75% to 175 $\mathrm{g/kWh_{final}}$. This is the implied intensity with the Intended Nationally Determined Contribution goal of 40% generation from non-fossil fuel sources Government of India (2015), keeping the fossil-fuel generation mix identical. This trends persists beyond 2030, in the model.

A.3.3. Upstream water consumption

We estimate the water intensity of the upstream energy system with national level data. For electricity, we turn to Srinivasan et al.'s (2018) study, and use the implied water intensity of electricity generation from their LC scenario which represents a 50% emissions intensity reduction from Business-As-Usual. We use consumption values instead of withdrawal values. We find an average annual decrease of 1.34% between 2010 and 2050 and apply it. Assuming 20% T&D losses and departing from their 2010 intensity, we initialise the model with 4.5 $\mathrm{litre/kWh_{final}}$ in 2011.

In comparison, water use for gas production is very low: 0.0144 litre per kWh (thermal) as an average estimate (Spang et al., 2014) for conventional gas. We therefore neglect the upstream water use for the LPG consumption in our analysis of Greater Mumbai.

A.4. Economics

The mechanisms by which resource demands change in the model are economic, or rather microeconomic, in nature. The protagonist parameters in the model by De Stercke et al. (2018) are price changes and price elasticities. In this version of the model, made for Mumbai, we also require income trajectories and income elasticity.

A.4.1. Income

We use an annual growth rate of 11%. This is the compound average growth rate between the years 2000/2001 and 2010/2011, when according to Srivastava (2012, Table 22) the monthly average income per capita was ₹ 50,548 and ₹ 141,138 respectively.

A.4.2. Water

We calculated an average water price by volume of ₹ 7.06 per cubic metre, as a volume-weighted average of prices for different customer segments with data from Bambale (2012) (Table A.6).

Customer type	Average price (₹ /litre)	Volume (MLD)
slum	3	686
nonslum	4	1297
commercial	30	180
industry	40	80
All	**7.06**	

Table A.6: Water prices by customer segment and volumes, to calculate an average water price. Data from Bambale (2012).

We assume no income effect on per capita water demand, but we apply a price elasticity of -0.21 following Barah et al. (1998).

A.4.3. Electricity

Srivastava (2012) lists prices for BEST, the Brihanmumbai (formerly Bombay) Electricity Supply and Transport company, which supplies the district of Mumbai. For the tariff block for residential customers corresponding to the model's per capita electricity demand, the charges were ₹ 2.15 per kWh in 2006 and ₹ 3.81 per kWh in 2012. From this we derive an average annual growth rate of 10% and a price in 2011 of ₹ 3.46 per kWh that we use in the model.

We drew price and income elasticities from Gundimeda and Köhlin (2008) for the urban middle-income group and in so doing we assume that the income elasticity is equal to the expenditure elasticity. The values are -0.548 (Gundimeda and Köhlin, 2008, Table 10) and 0.526 (Gundimeda and Köhlin, 2008, Table 11), respectively.

A.4.4. Gas

Srivastava (2012) reports annual prices for 14.2kg LPG cylinders of ₹ 300 in 2006 and ₹ 350 in 2011. From this we derive an annual growth rate of 2.6% and, assuming a heating value of 46.1 MJ/kg, a price in 2011 of ₹ 1.92 per kWh.

We drew price and income elasticities from Gundimeda and Köhlin (2008) for the urban middle-income group and in so doing we assume that the income elasticity is equal to the expenditure elasticity. The values are -0.513 (Gundimeda and Köhlin, 2008, Table 10) and 0.658 (Gundimeda and Köhlin, 2008, Table 11), respectively.

B. Model Equations

The equations of which the model consists, including assignment of constants (with values corresponding to the standard model) are listed below in alphabetical order. In the pdf version of this manuscript, the variables are linked to their defining function or constant assignment. SDM-Doc (Martinez-Moyano, 2012) was used in the process of generating this documentation. Units are specified between parentheses and in boldface.

augmented water supply capacity (litre/day)
= $\int$water supply capacity expansion completion $dt + 1.0$
average age of water distribution capacity (year)
= water distribution capacity x age/water distribution capacity in operation
average extra water supply electricity intensity (kWh/litre)
= water supply capacity x electricity/augmented water supply capacity
average total water cost (INR/litre)
= water costs/(water total demand/(1-Water distribution leakage))
avoided leakage cost in dt (INR/year)
= marginal leakage rate*water average cost*water total demand/(1-Water distribution leakage)*TIME STEP*days in a years
birth rate (persons/persons/year)
= 0.003
carbon price (INR/kgC)
= $\int$carbon price net change $dt + 0.0$
carbon price change characteristic time (year)
= 5
carbon price net change (INR/kgC/year)
= 0 * max(carbon price*pressure to decrease GHG emissions/carbon price change characteristic time,-carbon price/TIME STEP)
days in a years (days/year)
= 365.25
death rate (persons/persons/year)
= 0.003
decent housing (persons)
= $\int$decent housing completed $dt + 0.0$
decent housing average construction time (years)
= 2
decent housing completed (persons/year)
= decent housing under construction/decent housing average construction time
decent housing construction begun (persons/year)
= max(STEP(decent housing needed/slum eradication time horizon,present),0) * decent housing construction urgency factor
decent housing construction urgency factor (Dmnl)
= 1.5
decent housing needed (persons)
= max(Slum population-decent housing under construction,0)
decent housing under construction (persons)
= $\int$decent housing construction begun-decent housing completed $dt + 0.0$
elecitricity hotwater efficiency slum net change (1/year)
= 0
Electricity appliance efficiency (kWh/kWh)
= $\int$Electricity appliance efficiency implementation $dt + 1.0$
Electricity appliance efficiency addition (kWh/kWh)
= $\int$Electricity appliance efficiency change-Electricity appliance efficiency implementation $dt + 0.0$
Electricity appliance efficiency change (kWh/kWh/year)
= max(min(Electricity appliance efficiency potential,Electricity appliance efficiency change desired),0) / TIME STEP
Electricity appliance efficiency change desired (kWh/kWh)
= Electricity demand appliance service per capita * (1 / (Electricity demand appliance consumption per capita nonslum+Electricity demand appliance per capita consumption change electricity * TIME STEP) - 1 / Electricity demand appliance consumption per capita nonslum)
Electricity appliance efficiency change time (year)
= 1
Electricity appliance efficiency implementation (kWh/kWh/year)
= Electricity appliance efficiency addition / Electricity appliance efficiency change time
Electricity appliance efficiency max (kWh/kWh)
= $\int$electricity appliance efficiency max net change dt + Electricity appliance efficiency max initial
electricity appliance efficiency max change characteristic time (years)
= 20
Electricity appliance efficiency max initial (kWh/kWh)
= 1.2
Electricity appliance efficiency max max (kWh/kWh)
= 1.6

electricity appliance efficiency max net change (kWh/kWh/year)

= (Electricity appliance efficiency max max-Electricity appliance efficiency max)/electricity appliance efficiency max change characteristic time

Electricity appliance efficiency potential (kWh/kWh)

= max(Electricity appliance efficiency max-Electricity appliance efficiency addition-Electricity appliance efficiency,0)

Electricity appliance efficiency slum (kWh/kWh)

= $\int$electricity appliance efficiency slum net change dt + 1.0

electricity appliance efficiency slum net change (1/year)

= 0

electricity appliance service benefit relative (Dmnl)

= max(xidz(Electricity demand appliance service per capita-electricity appliance service minimum per capita,electricity appliance service reference per capita-electricity appliance service minimum per capita,0),0)

electricity appliance service minimum per capita (kWh/person/day)

= $\int$electricity appliance service minimum per capita net change dt + 0.0

electricity appliance service minimum per capita net change (kWh/person/day/year)

= 0

electricity appliance service reference per capita (kWh/person/day)

= $\int$electricity appliance service reference per capita net change dt + electricity demand appliance consumption per capita initial

electricity appliance service reference per capita net change (kWh/person/day/year)

= 0

electricity carbon emissions (kgC/day)

= electricity carbon intensity*electricity total demand

electricity carbon intensity (kgC/kWh)

= $\int$electricity carbon intensity net change dt + 0.292

electricity carbon intensity net change (kgC/kWh/year)

= electricity carbon intensity*electricity carbon intensity rate of change

electricity carbon intensity rate of change (1/year)

= electricity carbon intensity rate of change historical + STEP(electricity carbon intensity rate of change future 2030-electricity carbon intensity rate of change historical,present)

electricity carbon intensity rate of change future 2030 (1/year)

= -0.0475

electricity carbon intensity rate of change historical (1/year)

= 0

electricity demand appliance consumption per capita (kWh/(person*day))

= Electricity demand appliance consumption per capita nonslum * (1-slum population share) + Electricity demand appliance consumption per capita slum*slum population share

electricity demand appliance consumption per capita initial (kWh/(person*day))

= 0.57

electricity demand appliance consumption per capita initial slum (kWh/(person*day))

= 0

Electricity demand appliance consumption per capita nonslum (kWh/person/day)

= $\int$Electricity demand appliance per capita consumption change electricity+Electricity demand appliance per capita consumption change water dt + electricity demand appliance consumption per capita initial

Electricity demand appliance consumption per capita slum (kWh/person/day)

= $\int$electricity demand appliance consumption per capita slum net change dt + electricity demand appliance consumption per capita initial slum

electricity demand appliance consumption per capita slum net change (kWh/(year*person*day))

= 0

Electricity demand appliance per capita consumption change electricity (kWh/person/day/year)

= Electricity demand per capita change * Electricity demand change appliance preference

Electricity demand appliance per capita consumption change water (kWh/person/day/year)

= Electricity demand appliance consumption per capita nonslum*Water demand appliance service per capita relative change water* toggle water electricity appliance

Electricity demand appliance per capita service change electricity (kWh/person/day/year)

= ((Electricity demand appliance service per capita / Electricity demand appliance consumption per capita nonslum+ Electricity appliance efficiency implementation* TIME STEP) * (Electricity demand appliance consumption per capita nonslum+Electricity demand appliance per capita consumption change electricity* TIME STEP) - Electricity demand appliance service per capita)/TIME STEP

Electricity demand appliance per capita service change water (kWh/person/day/year)

= Electricity demand appliance service per capita*Water demand appliance service per capita relative change water* toggle water electricity appliance

Electricity demand appliance service per capita (kWh/person/day)

= $\int$Electricity demand appliance per capita service change electricity+Electricity demand appliance per capita service change water dt + electricity demand appliance consumption per capita initial

Electricity demand appliance service per capita relative change electricity (kWh/kWh/year)

= Electricity demand appliance per capita service change electricity/Electricity demand appliance service per capita

Electricity demand appliance service per capita slum (kWh/person/day)

= $\int$electricity demand appliance service per capita slum net change dt + electricity demand appliance consumption per capita initial slum

electricity demand appliance service per capita slum net change (kWh/(year*person*day))

= 0

electricity demand benefit denominator (kWh/person/day)

= electricity appliance service benefit relativeˆ(-electricity demand per capita change sign)*Electricity demand appliance consumption per capita nonslum+ electricity only service benefit relativeˆ(-electricity demand per capita change sign)*Electricity demand only consumption per capita nonslum+ energy hotwater service benefit relativeˆ(-electricity demand per capita change sign)*Electricity demand hotwater consumption per capita nonslum+ energy heating service benefit relativeˆ(-electricity demand per capita change sign)*Electricity demand heating consumption per capita nonslum

Electricity demand change appliance preference (Dmnl)

= electricity appliance service benefit relativeˆ(-electricity demand per capita change sign)/electricity demand benefit denominator*Electricity demand appliance consumption per capita nonslum

electricity demand change from price (kWh/person/day/year)

= electricity demand per capita reference net change

electricity demand change from shortage (kWh/person/day/year)

= 100

Electricity demand change heating preference (Dmnl)

= energy heating service benefit relativeˆ(-electricity demand per capita change sign)*Electricity demand heating consumption per capita nonslum/electricity demand benefit denominator

Electricity demand change hotwater preference (Dmnl)

= energy hotwater service benefit relativeˆ(-electricity demand per capita change sign)*Electricity demand hotwater consumption per capita nonslum/electricity demand benefit denominator

Electricity demand change only preference (Dmnl)

= electricity only service benefit relativeˆ(-electricity demand per capita change sign)*Electricity demand only consumption per capita nonslum/electricity demand benefit denominator

electricity demand heating consumption per capita (kWh/(person*day))

= Electricity demand heating consumption per capita nonslum * (1-slum population share) + Electricity demand heating consumption per capita slum * slum population share

electricity demand heating consumption per capita initial (kWh/(person*day))

= 0.1

electricity demand heating consumption per capita initial slum (kWh/(person*day))

= 0

Electricity demand heating consumption per capita nonslum (kWh/person/day)

= $\int$electricity demand heating per capita consumption change electricity+electricity heating consumption substitution *dt* + electricity demand heating consumption per capita initial

Electricity demand heating consumption per capita slum (kWh/person/day)

= $\int$electricity demand heating consumption per capita slum net change *dt* + electricity demand heating consumption per capita initial slum

electricity demand heating consumption per capita slum net change (kWh/(year*person*day))

= 0

electricity demand heating per capita consumption change electricity (kWh/person/day/year)

= Electricity demand change heating preference * Electricity demand per capita change

electricity demand heating per capita service change electricity (kWh/person/day/year)

= ((Electricity demand heating service per capita / Electricity demand heating consumption per capita nonslum+ Electricity heating efficiency implementation* TIME STEP) * (Electricity demand heating consumption per capita nonslum+electricity demand heating per capita consumption change electricity* TIME STEP) - Electricity demand heating service per capita) / TIME STEP

Electricity demand heating service per capita (kWh/person/day)

= $\int$electricity demand heating per capita service change electricity+electricity heating service substitution *dt* + electricity demand heating consumption per capita initial

Electricity demand heating service per capita relative change electricity (kWh/kWh/year)

= electricity demand heating per capita service change electricity/Electricity demand heating service per capita

Electricity demand heating service per capita slum (kWh/(person*day))

= $\int$electricity demand heating service per capita slum net change *dt* + electricity demand heating consumption per capita initial slum

electricity demand heating service per capita slum net change (kWh/(year*person*day))

= 0

electricity demand hotwater consumption per capita (kWh/(person*day))

= Electricity demand hotwater consumption per capita nonslum * (1-slum population share) + Electricity demand hotwater consumption per capita slum*slum population share

electricity demand hotwater consumption per capita initial (kWh/(person*day))

= 0.22

electricity demand hotwater consumption per capita initial slum (kWh/(person*day))

= 0

Electricity demand hotwater consumption per capita nonslum (kWh/(person*day))

= $\int$(Electricity demand hotwater per capita consumption change Electricity+Electricity demand hotwater per capita consumption change water)+Electricity hotwater consumption substitution *dt* + electricity demand hotwater consumption per capita initial

Electricity demand hotwater consumption per capita slum (kWh/(person*day))

= $\int$electricity demand hotwater consumption per capita slum net change *dt* + electricity demand hotwater consumption per capita initial slum

electricity demand hotwater consumption per capita slum net change (kWh/(year*person*day))

= 0

Electricity demand hotwater per capita consumption change Electricity (kWh/(year*person*day))

= Electricity demand change hotwater preference * Electricity demand per capita change

Electricity demand hotwater per capita consumption change water (kWh/(year*person*day))

= Electricity demand hotwater consumption per capita nonslum*Water demand hotwater service per capita relative change water* toggle water electricity hotwater

Electricity demand hotwater per capita service change electricity (kWh/(year*person*day))

= ((Electricity demand hotwater service per capita / Electricity demand hotwater consumption per capita nonslum+ Electricity hotwater efficiency implementation* TIME STEP) * (Electricity demand hotwater consumption per capita nonslum+Electricity demand hotwater per capita consumption change Electricity* TIME STEP) - Electricity demand hotwater service per capita) / TIME STEP

Electricity demand hotwater per capita service change water (kWh/(year*person*day))

= Electricity demand hotwater service per capita*Water demand hotwater service per capita relative change water* toggle water electricity hotwater

Electricity demand hotwater service per capita (kWh/person/day)

= $\int$(Electricity demand hotwater per capita service change electricity+Electricity demand hotwater per capita service change water)+Electricity hotwater service substitution dt + electricity demand hotwater consumption per capita initial

Electricity demand hotwater service per capita relative change electricity (kWh/kWh/year)

= Electricity demand hotwater per capita service change electricity/Electricity demand hotwater service per capita

Electricity demand hotwater service per capita slum (kWh/person/day)

= $\int$electricity demand hotwater service per capita slum net change dt + electricity demand hotwater consumption per capita initial slum

electricity demand hotwater service per capita slum net change (kWh/(year*person*day))

= 0

electricity demand income elasticity (Dmnl)

= 0.526

electricity demand local pumping per capita (kWh/(person*day))

= electricity demand local pumping per capita nonslum * (1-slum population share)

electricity demand local pumping per capita change (kWh/(year*person*day))

= (water demand total consumption per capita nonslum*Local pumping energy intensity - electricity demand local pumping per capita nonslum)/TIME STEP

electricity demand local pumping per capita nonslum (kWh/(person*day))

= $\int$electricity demand local pumping per capita change dt + Local pumping energy intensity*water demand total consumption per capita nonslum

electricity demand only consumption per capita (kWh/(person*day))

= Electricity demand only consumption per capita nonslum * (1-slum population share) +Electricity demand only consumption per capita slum*slum population share

electricity demand only consumption per capita initial (kWh/(person*day))

= 0.77

electricity demand only consumption per capita initial slum (kWh/(person*day))

= 0.734

Electricity demand only consumption per capita nonslum (kWh/person/day)

= $\int$electricity demand only per capita consumption change electricity dt + electricity demand only consumption per capita initial

Electricity demand only consumption per capita slum (kWh/person/day)

= $\int$electricity demand only consumption per capita slum net change dt + electricity demand only consumption per capita initial slum

electricity demand only consumption per capita slum net change (kWh/(year*person*day))

= 0

electricity demand only per capita consumption change electricity (kWh/person/day/year)

= Electricity demand change only preference * Electricity demand per capita change

electricity demand only per capita service change electricity (kWh/person/day/year)

= ((Electricity demand only service per capita / Electricity demand only consumption per capita nonslum+ electricity only efficiency implementation*TIME STEP) * (Electricity demand only consumption per capita nonslum+electricity demand only per capita consumption change electricity*TIME STEP) -Electricity demand only service per capita)/TIME STEP

Electricity demand only service per capita (kWh/person/day)

= $\int$electricity demand only per capita service change electricity dt + electricity demand only consumption per capita initial

Electricity demand only service per capita relative change electricity (kWh/kWh/year)

= electricity demand only per capita service change electricity/Electricity demand only service per capita

Electricity demand only service per capita slum (kWh/person/day)

= $\int$electricity demand only service per capita slum net change dt + electricity demand only consumption per capita initial slum

electricity demand only service per capita slum net change (kWh/(year*person*day))

= 0

Electricity demand per capita change (kWh/person/day/year)

= electricity demand change from price + electricity demand per capita reference change from income effect

electricity demand per capita change sign (Dmnl)

= xidz(Electricity demand per capita change,abs(Electricity demand per capita change),1)

electricity demand per capita reference (kWh/person/day)

= $\int$(((electricity demand per capita reference change from cross effect+electricity demand per capita reference change from income effect)+electricity demand per capita reference change from local pumping change)+electricity demand per capita reference change from LT substitution)+electricity demand per capita reference net change dt + electricity demand total consumption per capita nonslum

electricity demand per capita reference change from cross effect (kWh/person/day/year)

= Electricity demand appliance per capita consumption change water+Electricity demand hotwater per capita consumption change water

electricity demand per capita reference change from income effect (kWh/(year*person*day))

= income growth rate*electricity demand income elasticity*electricity demand per capita reference

electricity demand per capita reference change from local pumping change (kWh/(year*person*day))

= electricity demand local pumping per capita change

electricity demand per capita reference change from LT substitution (kWh/person/day/year)

= electricity heating consumption substitution+Electricity hotwater consumption substitution

electricity demand per capita reference net change (kWh/person/day/year)

= electricity demand per capita reference*(electricity price reference net change/electricity price reference)*electricity demand price elasticity

electricity demand price elasticity (Dmnl)

= -0.548

electricity demand total consumption per capita (kWh/person/day)

= (electricity total demand nonslum + electricity total demand slum) / Population

electricity demand total consumption per capita nonslum (kWh/(person*day))

= Electricity demand appliance consumption per capita nonslum+ Electricity demand only consumption per capita nonslum+ Electricity demand heating consumption per capita nonslum+ Electricity demand hotwater consumption per capita nonslum+ electricity demand local pumping per capita nonslum

electricity demand total consumption per capita slum (kWh/(person*day))

= Electricity demand appliance consumption per capita slum +Electricity demand heating consumption per capita slum +Electricity demand hotwater consumption per capita slum +Electricity demand only consumption per capita slum

electricity heating consumption substitution (kWh/person/day/year)

= Electricity demand heating consumption per capita nonslum*electricity heating service substitution/Electricity demand heating service per capita

Electricity heating cost per unit service (INR/kWh)

= electricity price by unit/Electricity heating efficiency max

Electricity heating efficiency (kWh/kWh)

= $\int$Electricity heating efficiency implementation dt + 1.5

Electricity heating efficiency addition (kWh/kWh)

= $\int$Electricity heating efficiency change-Electricity heating efficiency implementation dt + 0.0

Electricity heating efficiency change (kWh/kWh/year)

= max(min(Electricity heating efficiency potential,electricity heating efficiency change desired),0) / TIME STEP

electricity heating efficiency change desired (kWh/kWh)

= Electricity demand heating service per capita * (1 / (Electricity demand heating consumption per capita nonslum+electricity demand heating per capita consumption change electricity * TIME STEP) - 1 / Electricity demand heating consumption per capita nonslum)

Electricity heating efficiency change time (year)

= 1

Electricity heating efficiency implementation (kWh/kWh/year)

= Electricity heating efficiency addition / Electricity heating efficiency change time

Electricity heating efficiency max (kWh/kWh)

= $\int$Electricity heating efficiency max change dt + electricity heating efficiency max initial

Electricity heating efficiency max change (kWh/kWh/year)

= (electricity heating efficiency max max-Electricity heating efficiency max)/electricity heating efficiency max change characteristic time

electricity heating efficiency max change characteristic time (years)

= 10

electricity heating efficiency max initial (kWh/kWh)

= 3

electricity heating efficiency max max (kWh/kWh)

= 8

Electricity heating efficiency potential (kWh/kWh)

= max(Electricity heating efficiency max-Electricity heating efficiency addition-Electricity heating efficiency,0)

Electricity heating efficiency slum (kWh/kWh)

= $\int$electricity heating efficiency slum net change dt + 1.5

electricity heating efficiency slum net change (1/year)

= 0

electricity heating service substitution (kWh/person/day/year)

= heating service demand per capita electricity for gas substitution

Electricity hotwater consumption substitution (kWh/(year*person*day))

= Electricity demand hotwater consumption per capita nonslum*Electricity hotwater service substitution/Electricity demand hotwater service per capita

Electricity hotwater cost per unit service (INR/kWh)

= electricity price by unit/Electricity hotwater efficiency max

Electricity hotwater efficiency (kWh/kWh)

= $\int$Electricity hotwater efficiency implementation dt + 1.5

Electricity hotwater efficiency addition (kWh/kWh)

= $\int$Electricity hotwater efficiency change-Electricity hotwater efficiency implementation dt + 0.0

Electricity hotwater efficiency change (kWh/kWh/year)

= max(min(Electricity hotwater efficiency potential,Electricity hotwater efficiency change desired),0)/ TIME STEP

Electricity hotwater efficiency change desired (kWh/kWh)

= Electricity demand hotwater service per capita * (1 / (Electricity demand hotwater consumption per capita nonslum+Electricity demand hotwater per capita consumption change Electricity * TIME STEP) - 1 / Electricity demand hotwater consumption per capita nonslum)

electricity hotwater efficiency change time (year)

= 1

Electricity hotwater efficiency implementation (kWh/kWh/year)

= Electricity hotwater efficiency addition / electricity hotwater efficiency change time

Electricity hotwater efficiency max (kWh/kWh)

= $\int$electricity hotwater efficiency max change dt + Electricity hotwater efficiency max initial

electricity hotwater efficiency max change (kWh/kWh/year)

= (Electricity hotwater efficiency max max-Electricity hotwater efficiency max)/electricity hotwater efficiency max change characteristic time

electricity hotwater efficiency max change characteristic time (years)

= 10

Electricity hotwater efficiency max initial (kWh/kWh)

= 1.5

Electricity hotwater efficiency max max (kWh/kWh)

= 5

Electricity hotwater efficiency potential (kWh/kWh)

= max(Electricity hotwater efficiency max-Electricity hotwater efficiency addition-Electricity hotwater efficiency,0)

Electricity hotwater efficiency slum (kWh/kWh)
= $\int$elecitricity hotwater efficiency slum net change dt + 1.5
Electricity hotwater service substitution (kWh/(year*person*day))
= hotwater service demand per capita electricity for gas substitution
electricity only efficiency (kWh/kWh)
= $\int$electricity only efficiency implementation dt + 1.0
electricity only efficiency addition (kWh/kWh)
= $\int$electricity only efficiency change-electricity only efficiency implementation dt + 0.0
electricity only efficiency change (kWh/kWh/year)
= max(min(electricity only efficiency potential,electricity only efficiency change desired),0) / TIME STEP
electricity only efficiency change desired (kWh/kWh)
= Electricity demand only service per capita * (1 / (Electricity demand only consumption per capita nonslum+electricity demand only per capita consumption change electricity*TIME STEP) - 1 / Electricity demand only consumption per capita nonslum)
electricity only efficiency change time (year)
= 1
electricity only efficiency implementation (kWh/kWh/year)
= electricity only efficiency addition/electricity only efficiency change time
electricity only efficiency max (kWh/kWh)
= $\int$electricity only efficiency max net change dt + electricity only efficiency max initial
electricity only efficiency max change characteristic time (years)
= 20
electricity only efficiency max initial (kWh/kWh)
= 1.6
electricity only efficiency max max (kWh/kWh)
= 1.6
electricity only efficiency max net change (kWh/kWh/year)
= (electricity only efficiency max max-electricity only efficiency max)/electricity only efficiency max change characteristic time
electricity only efficiency potential (kWh/kWh)
= max(electricity only efficiency max-electricity only efficiency+electricity only efficiency addition,0)
electricity only efficiency slum net change (1/year)
= 0
electricity only efficiencyslum (kWh/kWh)
= $\int$electricity only efficiency slum net change dt + 1.0
electricity only service benefit relative (Dmnl)
= max(xidz(Electricity demand only service per capita-electricity only service minimum per capita,electricity only service reference per capita-electricity only service minimum per capita,0),0)
electricity only service minimum per capita (kWh/person/day)
= $\int$electricity only service minimum per capita net change dt + 0.2
electricity only service minimum per capita net change (kWh/person/day/year)
= 0
electricity only service reference per capita (kWh/person/day)
= $\int$electricity only service reference per capita net change dt + 0.3
electricity only service reference per capita change rate (1/year)
= 0.1
electricity only service reference per capita net change (kWh/person/day/year)
= electricity only service reference per capita*electricity only service reference per capita change rate
electricity price by unit (INR/kWh)
= $\int$electricity price by unit change from carbon+electricity price by unit net change dt + 3.46
electricity price by unit change from carbon (INR/kWh/year)
= electricity price carbon contribution net change*STEP(1, present)
electricity price by unit change rate future (1/year)
= 0.025
electricity price by unit change rate historical (1/year)
= 0.025
electricity price by unit net change (INR/kWh/year)
= electricity price by unit*(electricity price by unit change rate historical+STEP(electricity price by unit change rate future-electricity price by unit change rate historical,present))
electricity price carbon contribution (INR/kWh)
= $\int$electricity price carbon contribution net change dt + electricity carbon intensity*carbon price
electricity price carbon contribution change time (year)
= 1
electricity price carbon contribution net change (INR/kWh/year)
= (carbon price*electricity carbon intensity - electricity price carbon contribution)/electricity price carbon contribution change time
electricity price reference (INR/kWh)
= $\int$electricity price reference net change dt + electricity price by unit
electricity price reference adjustment time (year)
= 1
electricity price reference net change (INR/kWh/year)
= (electricity price by unit-electricity price reference)/electricity price reference adjustment time
electricity system water per capita (litre/(person*day))
= electricity demand total consumption per capita*water intensity of electricity consumption from generation
electricity total demand (kWh/day)
= (electricity total demand nonslum+electricity total demand slum)*electricity total demand multiplier
electricity total demand multiplier (Dmnl)
= 1

electricity total demand nonslum (kWh/day)

= electricity demand total consumption per capita nonslum * (Population - Slum population)

electricity total demand slum (kWh/day)

= Slum population * electricity demand total consumption per capita slum * slum all uses consumption scaling factor

emigration rate (persons/person/year)

= (emigration rate reference/migration unity rate)ˆQuality of Life y * migration unity rate

emigration rate reference (persons/persons/year)

= 0.004

Energy demand hotwater service per capita relative change energy (1/year)

= (Gas demand hotwater per capita service change gas+Gas hotwater service substitution+Electricity hotwater service substitution+Electricity demand hotwater per capita service change electricity) /(Gas demand hotwater service per capita+Electricity demand hotwater service per capita)*toggle energy water hotwater

energy heating service benefit relative (Dmnl)

= max(xidz(Gas demand heating service per capita+Electricity demand heating service per capita-energy heating service minimum per capita,heating service reference per capita-energy heating service minimum per capita,0),0)

energy heating service minimum per capita (kWh/person/day)

= $\int$heating service minimum per capita net change $dt + 0.1$

energy hotwater service benefit relative (Dmnl)

= max(xidz(Gas demand hotwater service per capita+Electricity demand hotwater service per capita-energy hotwater service minimum per capita,energy hotwater service reference per capita-energy hotwater service minimum per capita,0),0)

energy hotwater service minimum per capita (kWh/person/day)

= $\int$energy hotwater service minimum per capita net change $dt + 0.0$

energy hotwater service minimum per capita net change (kWh/person/day/year)

= 0

energy hotwater service reference per capita (kWh/person/day)

= $\int$energy hotwater service reference per capita net change dt + energy hotwater service reference per capita initial

energy hotwater service reference per capita initial (kWh/(person*day))

= 0.5

energy hotwater service reference per capita net change (kWh/person/day/year)

= 0

environmental flow availability (litre/day)

= $\int$environmental flow availability net change dt + Water supply

environmental flow availability change in ppc (litre/day/year)

= (environmental flow availability-environmental flow availability ppc)/environmental flow availability tppc

environmental flow availability change in ptrend (1/year/year)

= (environmental flow availability itrend-environmental flow availability ptrend)/environmental flow availability tpt

environmental flow availability change in rc (litre/day/year)

= (environmental flow availability ppc-environmental flow availability rc)/environmental flow availability thrc

environmental flow availability change rate (1/year)

= 0

environmental flow availability itrend (1/year)

= (environmental flow availability ppc-environmental flow availability rc)/environmental flow availability rc/environmental flow availability thrc

environmental flow availability net change (litre/day/year)

= environmental flow availability*environmental flow availability change rate

environmental flow availability ppc (litre/day)

= $\int$environmental flow availability change in ppc dt + environmental flow availability

environmental flow availability ptrend (1/year)

= $\int$environmental flow availability change in ptrend dt + environmental flow availability change rate

environmental flow availability rc (litre/day)

= $\int$environmental flow availability change in rc dt + environmental flow availability

environmental flow availability thrc (year)

= 5.4

environmental flow availability tppc (year)

= 1.2

environmental flow availability tpt (year)

= 3.2

environmental flow forecast growth rate (1/year)

= environmental flow availability ptrend

extra water supply (litre/day)

= max(Water supply-local water supply,0)

extra water supply electricity consumption (kWh/day)

= average extra water supply electricity intensity*extra water supply

FINAL TIME (year)

= 2050.75

flow requirement (litre/day)

= 0

flow requirement forecast growth rate (1/year)

= 0

fractional replacement rate (1/year)

= $\int$fractional replacement rate net change dt + fractional replacement rate initial

fractional replacement rate change time (year)

= 1

fractional replacement rate initial (1/year)

= 0.02

fractional replacement rate net change (1/year/year)

= ((avoided leakage cost in dt)/water distribution capacity replacement cost per unit / water distribution capacity in operation- fractional replacement rate)/fractional replacement rate change time

Free area fraction (Dmnl)
= 0.5
FSI average (Dmnl)
= $\int$FSI average net change *dt* + FSI average initial
FSI average change rate (1/year)
= 0.02
FSI average initial (Dmnl)
= 2
FSI average net change (1/year)
= FSI average * FSI average change rate
gas carbon emissions (kgC/day)
= gas carbon intensity*gas total demand
gas carbon intensity (kgC/kWh)
= $\int$gas carbon intensity net change *dt* + 0.054
gas carbon intensity net change (kgC/kWh/year)
= 0
gas demand benefit denominator (kWh/person/day)
= energy hotwater service benefit relative^(-gas demand per capita change sign)*Gas demand hotwater consumption per capita nonslum+ (gas only service benefit relative*1)^(-gas demand per capita change sign)*Gas demand only consumption per capita nonslum+ energy heating service benefit relative^(-gas demand per capita change sign)*Gas demand heating consumption per capita nonslum
gas demand change from price (kWh/person/day/year)
= gas demand per capita reference net change
gas demand change from shortage (kWh/person/day/year)
= 100
Gas demand change heating preference (Dmnl)
= energy heating service benefit relative^(-gas demand per capita change sign)*Gas demand heating consumption per capita nonslum/gas demand benefit denominator
Gas demand change hotwater preference (Dmnl)
= energy hotwater service benefit relative^(-gas demand per capita change sign)*Gas demand hotwater consumption per capita nonslum/gas demand benefit denominator
Gas demand change only preference (Dmnl)
= (gas only service benefit relative*1)^(-gas demand per capita change sign)*Gas demand only consumption per capita nonslum/gas demand benefit denominator
gas demand heating consumption per capita (kWh/(person*day))
= Gas demand heating consumption per capita nonslum * (1-slum population share) + Gas demand heating consumption per capita slum*slum population share
gas demand heating consumption per capita initial (kWh/(person*day))
= 0.81
gas demand heating consumption per capita initial slum (kWh/(person*day))
= 0.587
Gas demand heating consumption per capita nonslum (kWh/person/day)
= $\int$gas demand heating per capita consumption change gas+gas heating consumption substitution *dt* + gas demand heating consumption per capita initial
Gas demand heating consumption per capita slum (kWh/person/day)
= $\int$gas demand heating consumption per capita slum net change *dt* + gas demand heating consumption per capita initial slum
gas demand heating consumption per capita slum net change (kWh/(year*person*day))
= 0
gas demand heating per capita consumption change gas (kWh/person/day/year)
= Gas demand change heating preference * Gas Demand per capita change
gas demand heating per capita service change gas (kWh/person/day/year)
= ((Gas demand heating service per capita / Gas demand heating consumption per capita nonslum+ Gas heating efficiency implementation * TIME STEP) * (Gas demand heating consumption per capita nonslum+gas demand heating per capita consumption change gas* TIME STEP) - Gas demand heating service per capita) / TIME STEP
Gas demand heating service per capita (kWh/person/day)
= $\int$gas demand heating per capita service change gas+gas heating service substitution *dt* + gas demand heating consumption per capita initial
Gas demand heating service per capita relative change gas (kWh/kWh/year)
= gas demand heating per capita service change gas/Gas demand heating service per capita
Gas demand heating service per capita slum (kWh/person/day)
= $\int$gas demand heating service per capita slum net change *dt* + gas demand heating consumption per capita initial slum
gas demand heating service per capita slum net change (kWh/(year*person*day))
= 0
gas demand hotwater consumption per capita (kWh/(person*day))
= Gas demand hotwater consumption per capita nonslum * (1-slum population share) + Gas demand hotwater consumption per capita slum* slum population share
gas demand hotwater consumption per capita initial (kWh/(person*day))
= 0.19
gas demand hotwater consumption per capita initial slum (kWh/(person*day))
= 0.18
Gas demand hotwater consumption per capita nonslum (kWh/person/day)
= $\int$(Gas demand hotwater per capita consumption change Gas+Gas demand hotwater per capita consumption change water)+Gas hotwater consumption substitution *dt* + gas demand hotwater consumption per capita initial
Gas demand hotwater consumption per capita slum (kWh/person/day)
= $\int$gas demand hotwater consumption per capita slum net change *dt* + gas demand hotwater consumption per capita initial slum
gas demand hotwater consumption per capita slum net change (kWh/(year*person*day))
= 0

Gas demand hotwater per capita consumption change Gas (kWh/person/day/year)

= Gas demand change hotwater preference * Gas Demand per capita change

Gas demand hotwater per capita consumption change water (kWh/person/day/year)

= Gas demand hotwater consumption per capita nonslum*Water demand hotwater service per capita relative change water*toggle water gas hotwater

Gas demand hotwater per capita service change gas (kWh/person/day/year)

= ((Gas demand hotwater service per capita / Gas demand hotwater consumption per capita nonslum+ gas hotwater efficiency implementation*TIME STEP) * (Gas demand hotwater consumption per capita nonslum+Gas demand hotwater per capita consumption change Gas*TIME STEP) - Gas demand hotwater service per capita)/TIME STEP

Gas demand hotwater per capita service change water (kWh/person/day/year)

= Gas demand hotwater service per capita*Water demand hotwater service per capita relative change water*toggle water gas hotwater

Gas demand hotwater service per capita (kWh/person/day)

= $\int$(Gas demand hotwater per capita service change gas+Gas demand hotwater per capita service change water)+Gas hotwater service substitution dt + gas demand hotwater consumption per capita initial

Gas demand hotwater service per capita relative change gas (kWh/kWh/year)

= Gas demand hotwater per capita service change gas/Gas demand hotwater service per capita

Gas demand hotwater service per capita slum (kWh/person/day)

= $\int$gas demand hotwater service per capita slum net change dt + gas demand hotwater consumption per capita initial slum

gas demand hotwater service per capita slum net change (kWh/(year*person*day))

= 0

gas demand income elasticity (Dmnl)

= 0.658

gas demand only consumption per capita (kWh/(person*day))

= Gas demand only consumption per capita nonslum * (1-slum population share) + Gas demand only consumption per capita slum*slum population share

gas demand only consumption per capita initial (kWh/(person*day))

= 0.01

gas demand only consumption per capita initial slum (kWh/(person*day))

= 0.01

Gas demand only consumption per capita nonslum (kWh/person/day)

= $\int$gas demand only per capita consumption change gas dt + gas demand only consumption per capita initial

Gas demand only consumption per capita slum (kWh/person/day)

= $\int$gas demand only consumption per capita slum net change dt + gas demand only consumption per capita initial slum

gas demand only consumption per capita slum net change (kWh/(year*person*day))

= 0

gas demand only per capita consumption change gas (kWh/person/day/year)

= Gas demand change only preference * Gas Demand per capita change

gas demand only per capita service change gas (kWh/person/day/year)

= ((Gas demand only service per capita / Gas demand only consumption per capita nonslum+ gas only efficiency implementation*TIME STEP) *(Gas demand only consumption per capita nonslum+gas demand only per capita consumption change gas*TIME STEP) - Gas demand only service per capita)/TIME STEP

Gas demand only service per capita (kWh/person/day)

= $\int$gas demand only per capita service change gas dt + gas demand only consumption per capita initial

Gas demand only service per capita relative change gas (kWh/kWh/year)

= gas demand only per capita service change gas/Gas demand only service per capita

Gas demand only service per capita slum (kWh/person/day)

= $\int$gas demand only service per capita slum net change dt + gas demand only consumption per capita initial slum

gas demand only service per capita slum net change (kWh/(year*person*day))

= 0

Gas Demand per capita change (kWh/person/day/year)

= gas demand change from price + gas demand per capita reference change from income

gas demand per capita change sign (Dmnl)

= xidz(Gas Demand per capita change,abs(Gas Demand per capita change),1)

gas demand per capita reference (kWh/person/day)

= $\int$((gas demand per capita reference change from cross effect+gas demand per capita reference change from income)+gas demand per capita reference change from LT substitution)+gas demand per capita reference net change dt + gas demand total consumption per capita nonslum

gas demand per capita reference change from cross effect (kWh/person/day/year)

= Gas demand hotwater per capita consumption change water

gas demand per capita reference change from income (kWh/(year*person*day))

= gas demand income elasticity * gas demand per capita reference * income growth rate

gas demand per capita reference change from LT substitution (kWh/person/day/year)

= gas heating consumption substitution+Gas hotwater consumption substitution

gas demand per capita reference net change (kWh/person/day/year)

= gas demand per capita reference*(gas price reference net change/gas price reference)*gas demand price elasticity

gas demand price elasticity (Dmnl)

= -0.513

gas demand total consumption per capita (kWh/person/day)

= (gas demand total nonslum + gas demand total slum) / Population

gas demand total consumption per capita nonslum (kWh/(person*day))

= Gas demand only consumption per capita nonslum+ Gas demand hotwater consumption per capita nonslum+ Gas demand heating consumption per capita nonslum

gas demand total consumption per capita slum (kWh/(person*day))

= Gas demand heating consumption per capita slum +Gas demand hotwater consumption per capita slum +Gas demand only consumption per capita slum

gas demand total nonslum (kWh/day)
= gas demand total consumption per capita nonslum * (Population - Slum population)

gas demand total slum (kWh/day)
= slum all uses consumption scaling factor * gas demand total consumption per capita slum* Slum population

gas heating consumption substitution (kWh/person/day/year)
= Gas demand heating consumption per capita nonslum*gas heating service substitution/Gas demand heating service per capita

Gas heating cost per unit service (INR/kWh)
= gas price by unit/Gas heating efficiency max

Gas heating efficiency (kWh/kWh)
= $\int$Gas heating efficiency implementation $dt + 1.0$

Gas heating efficiency addition (kWh/kWh)
= $\int$Gas heating efficiency change-Gas heating efficiency implementation $dt + 0.0$

Gas heating efficiency change (kWh/kWh/year)
= max(min(Gas heating efficiency potential,gas heating efficiency change desired),0) /TIME STEP

gas heating efficiency change desired (kWh/kWh)
= Gas demand heating service per capita * (1 / (Gas demand heating consumption per capita nonslum+gas demand heating per capita consumption change gas * TIME STEP) - 1 / Gas demand heating consumption per capita nonslum)

Gas heating efficiency change time (year)
= 1

Gas heating efficiency implementation (kWh/kWh/year)
= Gas heating efficiency addition / Gas heating efficiency change time

Gas heating efficiency max (kWh/kWh)
= $\int$gas heating efficiency max change $dt +$ gas heating efficiency max initial

gas heating efficiency max change (kWh/kWh/year)
= (gas heating efficiency max max-Gas heating efficiency max)/gas heating efficiency max change characteristic time

gas heating efficiency max change characteristic time (years)
= 20

gas heating efficiency max initial (kWh/kWh)
= 1.4

gas heating efficiency max max (kWh/kWh)
= 2.5

Gas heating efficiency potential (kWh/kWh)
= max(Gas heating efficiency max-Gas heating efficiency addition-Gas heating efficiency,0)

Gas heating efficiency slum (kWh/kWh)
= $\int$gas heating efficiency slum net change $dt + 1.0$

gas heating efficiency slum net change (1/year)
= 0

gas heating service substitution (kWh/person/day/year)
= -heating service demand per capita electricity for gas substitution

Gas hotwater consumption substitution (kWh/person/day/year)
= Gas demand hotwater consumption per capita nonslum*Gas hotwater service substitution/Gas demand hotwater service per capita

Gas hotwater cost per unit service (INR/kWh)
= gas price by unit/Gas hotwater efficiency max

gas hotwater efficiency (litre/litre)
= $\int$gas hotwater efficiency implementation $dt + 1.0$

Gas hotwater efficiency addition (litre/litre)
= $\int$Gas hotwater efficiency change-gas hotwater efficiency implementation $dt + 0.0$

Gas hotwater efficiency change (litre/litre/year)
= max(min(Gas hotwater efficiency potential,Gas hotwater efficiency change desired),0)/TIME STEP

Gas hotwater efficiency change desired (kWh/kWh)
= Gas demand hotwater service per capita * (1 / (Gas demand hotwater consumption per capita nonslum+Gas demand hotwater per capita consumption change Gas * TIME STEP) - 1 / Gas demand hotwater consumption per capita nonslum)

gas hotwater efficiency change time (year)
= 1

gas hotwater efficiency implementation (litre/litre/year)
= Gas hotwater efficiency addition/gas hotwater efficiency change time

Gas hotwater efficiency max (litre/litre)
= $\int$gas hotwater efficiency max net change $dt +$ Gas hotwater efficiency max initial

gas hotwater efficiency max change characteristic time (years)
= 20

Gas hotwater efficiency max initial (kWh/kWh)
= 1

Gas hotwater efficiency max max (kWh/kWh)
= 1.5

gas hotwater efficiency max net change (kWh/kWh/year)
= (Gas hotwater efficiency max max-Gas hotwater efficiency max)/gas hotwater efficiency max change characteristic time

Gas hotwater efficiency potential (litre/litre)
= max(Gas hotwater efficiency max-Gas hotwater efficiency addition-gas hotwater efficiency,0)

gas hotwater efficiency slum (litre/litre)
= $\int$gas hotwater efficiency slum net change $dt + 1.0$

gas hotwater efficiency slum net change (1/year)
= 0

Gas hotwater service substitution (kWh/person/day/year)
= -hotwater service demand per capita electricity for gas substitution

Gas only efficiency (kWh/kWh)
= $\int$gas only efficiency implementation $dt + 1.0$

Gas only efficiency addition (kWh/kWh)
= $\int$Gas only efficiency change-gas only efficiency implementation *dt* + 0.0
Gas only efficiency change (kWh/kWh/year)
= max(min(Gas only efficiency potential,gas only efficiency change desired),0)/TIME STEP
gas only efficiency change desired (kWh/kWh)
= Gas demand only service per capita * (1 / (Gas demand only consumption per capita nonslum+gas demand only per capita consumption change gas * TIME STEP) - 1 / Gas demand only consumption per capita nonslum)
gas only efficiency change time (year)
= 1
gas only efficiency implementation (kWh/kWh/year)
= Gas only efficiency addition/gas only efficiency change time
Gas only efficiency max (kWh/kWh)
= $\int$gas only efficiency max net change *dt* + gas only efficiency max initial
gas only efficiency max change characteristic time (years)
= 20
gas only efficiency max initial (kWh/kWh)
= 1.3
gas only efficiency max max (kWh/kWh)
= 2
gas only efficiency max net change (kWh/kWh/year)
= (gas only efficiency max max-Gas only efficiency max)/gas only efficiency max change characteristic time
Gas only efficiency potential (kWh/kWh)
= max(Gas only efficiency max-Gas only efficiency addition-Gas only efficiency,0)
Gas only efficiency slum (kWh/kWh)
= $\int$gas only efficiency slum net change *dt* + 1.0
gas only efficiency slum net change (1/year)
= 0
gas only service benefit relative (Dmnl)
= max(xidz(Gas demand only service per capita-gas only service minimum per capita,gas only service reference per capita-gas only service minimum per capita,1),0)
gas only service minimum per capita (kWh/person/day)
= $\int$gas only service minimum per capita net change *dt* + 0.0
gas only service minimum per capita net change (kWh/person/day/year)
= 0
gas only service reference per capita (kWh/person/day)
= $\int$gas only service reference per capita net change *dt* + 0.1
gas only service reference per capita net change (kWh/person/day/year)
= 0
gas price by unit (INR/kWh)
= $\int$gas price by unit change from carbon+gas price by unit net change *dt* + 1.92
gas price by unit change from carbon (INR/kWh/year)
= gas price carbon contribution net change*STEP(1 , present)
gas price by unit change rate future (1/year)
= 0.026
gas price by unit change rate historical (1/year)
= 0.026
gas price by unit net change (INR/kWh/year)
= gas price by unit*(gas price by unit change rate historical+STEP(gas price by unit change rate future-gas price by unit change rate historical,present))
gas price carbon contribution (INR/kWh)
= $\int$gas price carbon contribution net change *dt* + gas carbon intensity*carbon price
gas price carbon contribution change time (year)
= 1
gas price carbon contribution net change (INR/kWh/year)
= (carbon price*gas carbon intensity - gas price carbon contribution)/gas price carbon contribution change time
gas price reference (INR/kWh)
= $\int$gas price reference net change *dt* + gas price by unit
gas price reference adjustment time (year)
= 1
gas price reference net change (INR/kWh/year)
= (gas price by unit-gas price reference)/gas price reference adjustment time
gas total demand (kWh/day)
= gas total demand multiplier * (gas demand total slum + gas demand total nonslum)
gas total demand multiplier (Dmnl)
= 1
GHG emissions (kgC/day)
= electricity carbon emissions+gas carbon emissions
GHG emissions baseline value (kgC/day)
= 1.15e+007
GHG emissions change in ppc (kgC/day/year)
= (GHG emissions-GHG emissions ppc)/GHG emissions tppc
GHG emissions change in ptrend (1/(year*year))
= (GHG emissions itrend-GHG emissions ptrend)/GHG emissions tpt
GHG emissions change in rc (kgC/day/year)
= (GHG emissions ppc-GHG emissions rc)/GHG emissions thrc
GHG emissions excess in target year (Dmnl)
= GHG emissions * (1 + GHG emissions growth rate * TIME STEP) ˆ ((GHG emissions reduction target year- Time) / TIME STEP) / GHG emissions goal - 1

GHG emissions goal (kgC/day)
= (1-GHG emissions reduction goal) * GHG emissions baseline value

GHG emissions growth rate (1/year)
= GHG emissions ptrend

GHG emissions itrend (1/year)
= (GHG emissions ppc-GHG emissions rc)/GHG emissions rc/GHG emissions thrc

GHG emissions ppc (kgC/day)
= $\int$GHG emissions change in ppc dt + GHG emissions

GHG emissions ptrend (1/year)
= $\int$GHG emissions change in ptrend dt + -0.01

GHG emissions rc (kgC/day)
= $\int$GHG emissions change in rc dt + GHG emissions+1.0

GHG emissions reduction goal (Dmnl)
= GHG emissions reduction goal 1 + STEP(GHG emissions reduction goal 2-GHG emissions reduction goal 1,GHG emissions reduction target year 1)

GHG emissions reduction goal 1 (Dmnl)
= 0.6

GHG emissions reduction goal 2 (Dmnl)
= 0.8

GHG emissions reduction target year (year)
= GHG emissions reduction target year 1 + STEP(GHG emissions reduction target year 2-GHG emissions reduction target year 1,GHG emissions reduction target year 1)

GHG emissions reduction target year 1 (year)
= 2025

GHG emissions reduction target year 2 (year)
= 2050

GHG emissions thrc (year)
= 2

GHG emissions tppc (year)
= 1

GHG emissions tpt (year)
= 1

gravity constant (kWh/metre/litre)
= 9.81 / (3.6e+006)

heating electricitygas substitution (Dmnl)
= 2*(1/(1+exp(-(((Gas heating cost per unit service-Electricity heating cost per unit service)/min(Electricity heating cost per unit service,Gas heating cost per unit service))^2)/heating electricitygas substitution slope))-0.5)* ZIDZ(Gas heating cost per unit service-Electricity heating cost per unit service , abs(Gas heating cost per unit service-Electricity heating cost per unit service))

heating electricitygas substitution slope (Dmnl)
= 1

Heating electricitygas substitution time (year)
= 40

heating service demand per capita electricity for gas substitution (kWh/person/day/year)
= IF THEN ELSE(heating electricitygas substitution>0, Gas demand heating service per capita, Electricity demand heating service per capita)*heating electricitygas substitution/Heating electricitygas substitution time

heating service minimum per capita net change (kWh/person/day/year)
= 0

heating service reference per capita (kWh/person/day)
= $\int$heating service reference per capita net change dt + 0.3

heating service reference per capita net change (kWh/person/day/year)
= 0

hotwater electricitygas substitution (Dmnl)
= 2*(1/(1+exp(-(((Gas hotwater cost per unit service-Electricity hotwater cost per unit service)/min(Electricity hotwater cost per unit service,Gas hotwater cost per unit service))^2)/hotwater electricitygas substitution slope))-0.5)* ZIDZ(Gas hotwater cost per unit service-Electricity hotwater cost per unit service, abs(Gas hotwater cost per unit service-Electricity hotwater cost per unit service))

hotwater electricitygas substitution slope (Dmnl)
= 1

hotwater electricitygas substitution time (year)
= 40

hotwater service demand per capita electricity for gas substitution (kWh/person/day/year)
= IF THEN ELSE(hotwater electricitygas substitution>0, Gas demand hotwater service per capita, Electricity demand hotwater service per capita)*hotwater electricitygas substitution/hotwater electricitygas substitution time

immigration rate (persons/person/year)
= immigration rate reference*(Quality of Life y)^immigration rate exponent

immigration rate exponent (Dmnl)
= 2

immigration rate reference (persons/persons/year)
= 0.0078

income growth rate (1/year)
= 0.11

Initial population (persons)
= 1.24424e+007

INITIAL TIME (year)
= 2011

leakage midpoint age (year)
= 72.5

leakage scaling parameter (Dmnl)
= 4

Local pumping energy intensity (kWh/litre)
= gravity constant * Pumping head average / Pump efficiency average
local water supply (litre/day)
= min(environmental flow availability-flow requirement,Water supply)
local water supply electricity consumption (kWh/day)
= local water supply*local water supply electricity intensity
local water supply electricity intensity (kWh/litre)
= 0.00035
marginal leakage rate (1/year)
= Water distribution leakage*(1-Water distribution leakage)*leakage scaling parameter/leakage midpoint age
migration unity rate (persons/persons/year)
= 1
Population (persons)
= $\int$population increase-population decrease dt + Initial population
population change in ppc (persons/year)
= (Population-population ppc)/population tppc
population change in ptrend (1/(year*year))
= (population itrend-population ptrend)/population tpt
population change in rc (persons/year)
= (population ppc-population rc)/population thrc
population decrease (persons/year)
= (death rate+emigration rate)*Population
population forecast growth rate (1/year)
= population ptrend
population increase (persons/year)
= (birth rate+immigration rate)*Population
population itrend (1/year)
= (population ppc-population rc)/population rc/population thrc
population ppc (persons)
= $\int$population change in ppc dt + Initial population*(1.0+((immigration rate reference-emigration rate reference)*population thrc))
population ptrend (1/year)
= $\int$population change in ptrend dt + immigration rate reference-emigration rate reference
population rc (persons)
= $\int$population change in rc dt + Initial population
Population share sewered (Dmnl)
= (Population - Slum population * (1 - Slum sewered share)) / Population
population thrc (year)
= 5.4
population tppc (year)
= 1.2
population tpt (year)
= 10
present (years)
= 2019
pressure to decrease GHG emissions (Dmnl)
= max(2/(1+exp(-GHG emissions excess in target year)) - 1,0)
Pump efficiency average (Dmnl)
= 0.7
Pumping head average (metre)
= Free area fraction * FSI average * Storey height average
Quality of Life k (Dmnl)
= 0.025
Quality of Life x (Dmnl)
= electricity appliance service benefit relative*electricity only service benefit relative*gas only service benefit relative*energy hotwater service benefit relative*water appliance service benefit relative*water only service benefit relative*water hotwater service benefit relative*energy heating service benefit relative
Quality of Life y (Dmnl)
= Quality of Life x/(Quality of Life k+Quality of Life x)
replacement cost (INR)
= water distribution capacity in operation*water distribution capacity replacement cost per unit*fractional replacement rate * TIME STEP
SAVEPER (year)
= TIME STEP
SDG year (year)
= 2030
slum all uses consumption scaling factor (Dmnl)
= Slum relative consumption
slum eradication time horizon (years)
= max(SDG year-Time, 1)
Slum population (persons)
= Population*slum population share
slum population share (Dmnl)
= $\int$slum population share change from decent housing+slum population share historical net change dt + slum population share initial
slum population share change from decent housing (1/year)
= max(- decent housing completed/Population,-slum population share/TIME STEP)
slum population share change rate historical (1/year)
= -0.025

slum population share historical net change (1/year)

= slum population share * slum population share change rate historical

slum population share initial (Dmnl)

= 0.418447

Slum relative consumption (Dmnl)

= $\int$Slum relative consumption net change dt + 1.0

Slum relative consumption change rate (1/year)

= 0.01

Slum relative consumption net change (1/year)

= Slum relative consumption*Slum relative consumption change rate

Slum sewered share (Dmnl)

= slum sewered share reference

slum sewered share reference (Dmnl)

= $\int$slum sewered share reference net change dt + 0.2

slum sewered share reference future change rate (1/year)

= 0.05

slum sewered share reference net change (1/year)

= STEP((1-slum sewered share reference) * slum sewered share reference future change rate,present)

Storey height average (metre)

= 2.5

TIME STEP (year)

= 0.25

toggle electricity water appliance (Dmnl)

= 1

toggle energy water hotwater (Dmnl)

= 1

toggle water electricity appliance (Dmnl)

= 1

toggle water electricity hotwater (Dmnl)

= 1

toggle water gas hotwater (Dmnl)

= 1

wastewater capacity margin (Dmnl)

= 0.05

Wastewater electricity consumption (kWh/day)

= Wastewater treatment energy intensity*Water supply * Water share sewered

Wastewater primary treatment capacity construction completion (litres/(day*year))

= Wastewater primary treatment capacity under construction/Wastewater primary treatment capacity construction time

Wastewater primary treatment capacity construction time (year)

= 1

Wastewater primary treatment capacity decommission (litres/(day*year))

= 0

Wastewater primary treatment capacity in operation (litres/day)

= $\int$(Wastewater primary treatment capacity construction completion-Wastewater primary treatment capacity decommission)-wastewater treatment capacity primary to secondary upgrade dt + 1875.2*(10.0ˆ6.0)

Wastewater primary treatment capacity planned (litres/(day*year))

= 0

Wastewater primary treatment capacity under construction (litres/day)

= $\int$Wastewater primary treatment capacity planned-Wastewater primary treatment capacity construction completion dt + 0.0

Wastewater primary treatment energy intensity (kWh/litre)

= 4e-005

Wastewater secondary treatment capacity construction completion (litres/(day*year))

= Wastewater secondary treatment capacity under construction/Wastewater secondary treatment capacity construction time

Wastewater secondary treatment capacity construction time (year)

= 1

Wastewater secondary treatment capacity decommission (litres/(day*year))

= 0

Wastewater secondary treatment capacity in operation (litres/day)

= $\int$((Wastewater secondary treatment capacity construction completion+wastewater treatment capacity primary to secondary upgrade)-Wastewater secondary treatment capacity decommission)-wastewater treatment capacity secondary to tertiary upgrade dt + 796.1*(10.0ˆ6.0)

Wastewater secondary treatment capacity planned (litres/(day*year))

= max(0,wastewater treatment capacity addition needed/TIME STEP)

Wastewater secondary treatment capacity under construction (litres/day)

= $\int$Wastewater secondary treatment capacity planned-Wastewater secondary treatment capacity construction completion dt + 0.0

Wastewater secondary treatment energy intensity (kWh/litre)

= 0.00025

Wastewater tertiary treatment capacity construction completion (litres/(day*year))

= Wastewater tertiary treatment capacity under construction/Wastewater tertiary treatment capacity construction time

Wastewater tertiary treatment capacity construction time (year)

= 1

Wastewater tertiary treatment capacity decommission (litres/(day*year))

= 0

Wastewater tertiary treatment capacity in operation (litres/day)

= $\int$(Wastewater tertiary treatment capacity construction completion+wastewater treatment capacity secondary to tertiary upgrade)-Wastewater tertiary treatment capacity decommission dt + 0.0

Wastewater tertiary treatment capacity planned (litres/(day*year))

= 0

Wastewater tertiary treatment capacity under construction (litres/day)
= $\int$Wastewater tertiary treatment capacity planned-Wastewater tertiary treatment capacity construction completion $dt + 0.0$
Wastewater tertiary treatment energy intensity (kWh/litre)
= 0.00045
wastewater treatment capacity addition needed (litre/day)
= water total demand * (1+wastewater capacity margin) - (Wastewater treatment capacity under construction+ Wastewater treatment capacity in operation)
wastewater treatment capacity construction completion (litre/(day*year))
= Wastewater primary treatment capacity construction completion +Wastewater secondary treatment capacity construction completion +Wastewater tertiary treatment capacity construction completion
Wastewater treatment capacity in operation (litres/day)
= Wastewater primary treatment capacity in operation +Wastewater secondary treatment capacity in operation +Wastewater tertiary treatment capacity in operation
wastewater treatment capacity primary to secondary upgrade (litres/(year*day))
= Wastewater primary treatment capacity in operation * wastewater treatment capacity primary to secondary upgrade rate annual
wastewater treatment capacity primary to secondary upgrade rate annual (1/year)
= 0.1
wastewater treatment capacity secondary to tertiary upgrade (litres/(day*year))
= Wastewater secondary treatment capacity in operation * wastewater treatment capacity secondary to tertiary upgrade rate annual
wastewater treatment capacity secondary to tertiary upgrade rate annual (1/year)
= 0.01
Wastewater treatment capacity under construction (litre/day)
= Wastewater primary treatment capacity under construction +Wastewater secondary treatment capacity under construction +Wastewater tertiary treatment capacity under construction
wastewater treatment capacity upgrade (litre/(day*year))
= wastewater treatment capacity primary to secondary upgrade +wastewater treatment capacity secondary to tertiary upgrade
Wastewater treatment energy intensity (kWh/litre)
= (Wastewater primary treatment energy intensity * Wastewater primary treatment capacity in operation+Wastewater secondary treatment energy intensity * Wastewater secondary treatment capacity in operation+Wastewater tertiary treatment energy intensity * Wastewater tertiary treatment capacity in operation) /Wastewater treatment capacity in operation
water appliance efficiency (litre/litre)
= $\int$water appliance efficiency implementation $dt + 1.0$
water appliance efficiency addition (litre/litre)
= $\int$water appliance efficiency change-water appliance efficiency implementation $dt + 0.0$
water appliance efficiency change (litre/litre/year)
= max(min(water appliance efficiency potential,water appliance efficiency change desired),0) / TIME STEP
water appliance efficiency change desired (litre/litre)
= Water demand appliance service per capita * (1 / (Water demand appliance consumption per capita nonslum+water demand appliance per capita consumption change water *TIME STEP) - 1 / Water demand appliance consumption per capita nonslum)
water appliance efficiency change time (year)
= 1
water appliance efficiency implementation (litre/litre/year)
= water appliance efficiency addition/water appliance efficiency change time
water appliance efficiency max (litre/litre)
= $\int$water appliance efficiency max net change $dt +$ water appliance efficiency max initial
water appliance efficiency max change characteristic time (years)
= 20
water appliance efficiency max initial (litre/litre)
= 1.2
water appliance efficiency max max (litre/litre)
= 2
water appliance efficiency max net change (litre/litre/year)
= (water appliance efficiency max max-water appliance efficiency max)/water appliance efficiency max change characteristic time
water appliance efficiency potential (litre/litre)
= max(water appliance efficiency max-water appliance efficiency addition-water appliance efficiency,0)
water appliance efficiency slum (litre/litre)
= $\int$water appliance efficiency slum net change $dt + 1.0$
water appliance efficiency slum net change (1/year)
= 0
water appliance service benefit relative (Dmnl)
= max(xidz(Water demand appliance service per capita-water appliance service minimum per capita,water appliance service reference per capita-water appliance service minimum per capita,0),0)
water appliance service minimum per capita (litre/person/day)
= $\int$water appliance service minumum per capita net change $dt + 0.0$
water appliance service minumum per capita net change (litre/person/day/year)
= 0
water appliance service reference per capita (litre/person/day)
= $\int$water appliance service reference per capita net change $dt + 10.0$
water appliance service reference per capita net change (litre/person/day/year)
= 0
water average cost (INR/litre)
= water supply electricity expenditure/water total demand*water average cost multiplier*(1-Water distribution leakage)

water average cost multiplier (Dmnl)

= 3.6

Water cost recovery ratio (Dmnl)

= water revenues/water costs

water costs (INR/day)

= water distribution capacity replacement cost+water supply electricity expenditure*water average cost multiplier

water demand appliance consumption per capita (litre/(person*day))

= Water demand appliance consumption per capita nonslum*(1-slum population share) + Water demand appliance consumption per capita slum*slum population share

water demand appliance consumption per capita initial (litre/(person*day))

= 22.93

water demand appliance consumption per capita initial slum (litre/(person*day))

= 0

Water demand appliance consumption per capita nonslum (litre/person/day)

= $\int$water demand appliance per capita consumption change electricity+water demand appliance per capita consumption change water *dt* + water demand appliance consumption per capita initial

Water demand appliance consumption per capita slum (litre/person/day)

= $\int$water demand appliance consumption per capita slum net change *dt* + water demand appliance consumption per capita initial slum

water demand appliance consumption per capita slum net change (litre/(year*person*day))

= 0

water demand appliance per capita consumption change electricity (litre/person/day/year)

= Electricity demand appliance service per capita relative change electricity*Water demand appliance consumption per capita nonslum* toggle electricity water appliance

water demand appliance per capita consumption change water (litre/person/day/year)

= Water demand change appliance preference * Water Demand per capita change

water demand appliance per capita service change electricity (litre/person/day/year)

= Electricity demand appliance service per capita relative change electricity*Water demand appliance service per capita* toggle electricity water appliance

water demand appliance per capita service change water (litre/person/day/year)

= ((Water demand appliance service per capita / Water demand appliance consumption per capita nonslum+ water appliance efficiency implementation* TIME STEP) * (Water demand appliance consumption per capita nonslum+water demand appliance per capita consumption change water*TIME STEP) - Water demand appliance service per capita)/TIME STEP

Water demand appliance service per capita (litre/person/day)

= $\int$water demand appliance per capita service change electricity+water demand appliance per capita service change water *dt* + water demand appliance consumption per capita initial

Water demand appliance service per capita relative change water (litre/litre/year)

= water demand appliance per capita service change water/Water demand appliance service per capita

Water demand appliance service per capita slum (litre/person/day)

= $\int$water demand appliance service per capita slum net change *dt* + water demand appliance consumption per capita initial slum

water demand appliance service per capita slum net change (litre/(year*person*day))

= 0

water demand benefit denominator (litre/person/day)

= (water appliance service benefit relativeˆ(-water demand per capita change sign)*Water demand appliance consumption per capita nonslum+ water hotwater service benefit relativeˆ(-water demand per capita change sign)*Water demand hotwater consumption per capita nonslum+ water only service benefit relativeˆ(-water demand per capita change sign)*Water demand only consumption per capita nonslum)

Water demand change appliance preference (Dmnl)

= water appliance service benefit relativeˆ(-water demand per capita change sign)/water demand benefit denominator*Water demand appliance consumption per capita nonslum

water demand change from price (litre/person/day/year)

= water demand per capita reference net change

water demand change from shortage (litre/person/day/year)

= 300

Water demand change hotwater preference (Dmnl)

= water hotwater service benefit relativeˆ(-water demand per capita change sign)/water demand benefit denominator*Water demand hotwater consumption per capita nonslum

Water demand change only preference (Dmnl)

= water only service benefit relativeˆ(-water demand per capita change sign)/water demand benefit denominator*Water demand only consumption per capita nonslum

water demand forecast (litre/day)

= (water total demand/(1-Water distribution leakage))*(1+water total consumption forecast growth rate*TIME STEP)ˆ(water supply margin forecast time horizon/TIME STEP)

water demand hotwater consumption per capita (litre/(person*day))

= Water demand hotwater consumption per capita nonslum*(1-slum population share) + Water demand hotwater consumption per capita slum*slum population share

water demand hotwater consumption per capita initial (litre/(person*day))

= 10.34

water demand hotwater consumption per capita initial slum (litre/(person*day))

= 4.47

Water demand hotwater consumption per capita nonslum (litre/person/day)

= $\int$water demand hotwater per capita consumption change energy+water demand hotwater per capita consumption change water *dt* + water demand hotwater consumption per capita initial

Water demand hotwater consumption per capita slum (litre/person/day)

= $\int$water demand hotwater consumption per capita slum net change *dt* + water demand hotwater consumption per capita initial slum

water demand hotwater consumption per capita slum net change (litre/(year*person*day))
= 0
water demand hotwater per capita consumption change energy (litre/person/day/year)
= Energy demand hotwater service per capita relative change energy*Water demand hotwater consumption per capita nonslum
water demand hotwater per capita consumption change water (litre/person/day/year)
= Water demand change hotwater preference * Water Demand per capita change
water demand hotwater per capita service change energy (litre/person/day/year)
= Energy demand hotwater service per capita relative change energy*Water demand hotwater service per capita
water demand hotwater per capita service change water (litre/person/day/year)
= ((Water demand hotwater service per capita / Water demand hotwater consumption per capita nonslum+ water hotwater efficiency implementation*TIME STEP)* (Water demand hotwater consumption per capita nonslum+water demand hotwater per capita consumption change water*TIME STEP) - Water demand hotwater service per capita)/TIME STEP
Water demand hotwater service per capita (litre/person/day)
= $\int$water demand hotwater per capita service change energy+water demand hotwater per capita service change water dt + water demand hotwater consumption per capita initial
Water demand hotwater service per capita relative change water (litre/litre/year)
= water demand hotwater per capita service change water/Water demand hotwater service per capita
Water demand hotwater service per capita slum (litre/person/day)
= $\int$water demand hotwater service per capita slum net change dt + water demand hotwater consumption per capita initial slum
water demand hotwater service per capita slum net change (litre/(year*person*day))
= 0
water demand only consumption per capita (litre/(person*day))
= Water demand only consumption per capita nonslum *(1-slum population share)+ Water demand only consumption per capita slum*slum population share
water demand only consumption per capita initial (litre/(person*day))
= 86.72
water demand only consumption per capita initial slum (litre/(person*day))
= 75.53
Water demand only consumption per capita nonslum (litre/person/day)
= $\int$water demand only per capita consumption change water dt + water demand only consumption per capita initial
Water demand only consumption per capita slum (litre/person/day)
= $\int$water demand only consumption per capita slum net change dt + water demand only consumption per capita initial slum
water demand only consumption per capita slum net change (litre/(year*person*day))
= 0
water demand only per capita consumption change water (litre/person/day/year)
= Water demand change only preference * Water Demand per capita change
water demand only per capita service change water (litre/person/day/year)
= ((Water demand only service per capita / Water demand only consumption per capita nonslum+ water only efficiency implementation*TIME STEP) * (Water demand only consumption per capita nonslum+water demand only per capita consumption change water*TIME STEP) - Water demand only service per capita)/TIME STEP
Water demand only service per capita (litre/person/day)
= $\int$water demand only per capita service change water dt + water demand only consumption per capita initial
Water demand only service per capita relative change water (litre/litre/year)
= water demand only per capita service change water/Water demand only service per capita
Water demand only service per capita slum (litre/person/day)
= $\int$water demand only service per capita slum net change dt + water demand only consumption per capita initial slum
water demand only service per capita slum net change (litre/(year*person*day))
= 0
Water Demand per capita change (litre/person/day/year)
= min(water demand change from price,water demand change from shortage)
water demand per capita change sign (Dmnl)
= xidz(Water Demand per capita change,abs(Water Demand per capita change),1)
water demand per capita reference (litre/person/day)
= $\int$(water demand per capita reference change from cross effect+water demand per capita reference change from wastage change)+water demand per capita reference net change dt + water demand total consumption per capita nonslum
water demand per capita reference change from cross effect (litre/person/day/year)
= water demand appliance per capita consumption change electricity+water demand hotwater per capita consumption change energy
water demand per capita reference change from wastage change (litre/(year*person*day))
= Water wastage net change
water demand per capita reference net change (litre/person/day/year)
= water demand per capita reference * water demand price elasticity * water price reference net change/ water price reference
water demand price elasticity (Dmnl)
= -0.21
water demand total consumption per capita (litre/(person*day))
= (water total demand nonslum + water total demand slum)/ Population
water demand total consumption per capita nonslum (litre/(person*day))
= Water demand appliance consumption per capita nonslum +Water demand only consumption per capita nonslum +Water demand hotwater consumption per capita nonslum +Water wastage nonslum
water demand total consumption per capita slum (litre/(person*day))
= Water demand appliance consumption per capita slum +Water demand hotwater consumption per capita slum +Water demand only consumption per capita slum +Water wastage slum
water demand total pcc change in ppc (litre/person/day/year)
= (water demand total consumption per capita-water demand total pcc ppc)/water demand total pcc tppc

water demand total pcc change in ptrend (1/(year*year))

= (water demand total pcc itrend-water demand total pcc ptrend)/water demand total pcc tpt

water demand total pcc change in rc (litre/person/day/year)

= (water demand total pcc ppc-water demand total pcc rc)/water demand total pcc thrc

water demand total pcc itrend (1/year)

= (water demand total pcc ppc-water demand total pcc rc)/water demand total pcc rc/water demand total pcc thrc

water demand total pcc ppc (litre/person/day)

= $\int$water demand total pcc change in ppc dt + water demand total consumption per capita+1.0

water demand total pcc ptrend (1/year)

= $\int$water demand total pcc change in ptrend dt + 0.0

water demand total pcc rc (litre/person/day)

= $\int$water demand total pcc change in rc dt + water demand total consumption per capita

water demand total pcc thrc (year)

= 5.4

water demand total pcc tppc (year)

= 1.2

water demand total pcc tpt (year)

= 3.2

water distribution capacity construction time (year)

= 2

water distribution capacity in operation (litre/day)

= $\int$water distribution capacity operation addition dt + water total demand

water distribution capacity initial average age (year)

= 60

water distribution capacity operation addition (litre/day/year)

= water distribution capacity under construction / water distribution capacity construction time

water distribution capacity planned (litre/day/year)

= max(water total demand*(1+water total consumption forecast growth rate*TIME STEP)^(water distribution capacity construction time/TIME STEP)-water distribution capacity in operation-water distribution capacity under construction,0)/ TIME STEP

water distribution capacity replacement cost (INR/day)

= fractional replacement rate*water distribution capacity in operation*water distribution capacity replacement cost per unit/days in a years

water distribution capacity replacement cost per unit (INR/(litre/day))

= 1

water distribution capacity under construction (litre/day)

= $\int$water distribution capacity planned-water distribution capacity operation addition dt + 0.0

water distribution capacity x age (litre/day*year)

= $\int$water distribution capacity x age increase-water distribution capacity x age decrease dt + water distribution capacity initial average age*water total demand

water distribution capacity x age decrease (litre/day*year/year)

= fractional replacement rate*water distribution capacity x age

water distribution capacity x age increase (litre/day*year/year)

= water distribution capacity in operation

Water distribution leakage (Dmnl)

= 1/(1+exp(-leakage scaling parameter*(average age of water distribution capacity-leakage midpoint age)/(leakage midpoint age)))

water hotwater efficiency (litre/litre)

= $\int$water hotwater efficiency implementation dt + 1.0

water hotwater efficiency addition (litre/litre)

= $\int$water hotwater efficiency change-water hotwater efficiency implementation dt + 0.0

water hotwater efficiency change (litre/litre/year)

= max(min(water hotwater efficiency potential,water hotwater efficiency change desired),0)/TIME STEP

water hotwater efficiency change desired (litre/litre)

= Water demand hotwater service per capita * (1 / (Water demand hotwater consumption per capita nonslum+water demand hotwater per capita consumption change water * TIME STEP) - 1 / Water demand hotwater consumption per capita nonslum)

water hotwater efficiency change time (year)

= 1

water hotwater efficiency implementation (litre/litre/year)

= water hotwater efficiency addition/water hotwater efficiency change time

water hotwater efficiency max (litre/litre)

= $\int$water hotwater efficiency max net change dt + water hotwater efficiency max initial

water hotwater efficiency max change characteristic time (years)

= 20

water hotwater efficiency max initial (litre/litre)

= 1.5

water hotwater efficiency max max (litre/litre)

= 3

water hotwater efficiency max net change (litre/litre/year)

= (water hotwater efficiency max max-water hotwater efficiency max)/water hotwater efficiency max change characteristic time

water hotwater efficiency potential (litre/litre)

= max(water hotwater efficiency max-water hotwater efficiency addition-water hotwater efficiency,0)

water hotwater efficiency slum (litre/litre)

= $\int$water hotwater efficiency slum net change dt + 1.0

water hotwater efficiency slum net change (1/year)

= 0

water hotwater service benefit relative (Dmnl)
= max(xidz(Water demand hotwater service per capita-water hotwater service minimum per capita,water hotwater service reference per capita-water hotwater service minimum per capita,0),0)
water hotwater service minimum per capita (litre/person/day)
= $\int$water hotwater service minimum per capita net change dt + 0.0
water hotwater service minimum per capita net change (litre/person/day/year)
= 0
water hotwater service reference per capita (litre/person/day)
= $\int$water hotwater service reference per capita net change dt + 15.0
water hotwater service reference per capita net change (litre/person/day/year)
= 0
water intensity of electricity consumption from generation (litre/kWh)
= $\int$water intensity of electricity consumption from generation net change dt + 4.5
water intensity of electricity consumption from generation net change (litre/kWh/year)
= water intensity of electricity consumption from generation*water intensity of electricity consumption from generation rate of change
water intensity of electricity consumption from generation rate of change (1/year)
= -0.0134
water only efficiency (litre/litre)
= $\int$water only efficiency implementation dt + 1.0
water only efficiency addition (litre/litre)
= $\int$water only efficiency change-water only efficiency implementation dt + 0.0
water only efficiency change (litre/litre/year)
= max(min(water only efficiency potential,water only efficiency change desired),0)/TIME STEP
water only efficiency change desired (litre/litre)
= Water demand only service per capita * (1 / (Water demand only consumption per capita nonslum+water demand only per capita consumption change water * TIME STEP) - 1 / Water demand only consumption per capita nonslum)
water only efficiency change time (year)
= 1
water only efficiency implementation (litre/litre/year)
= water only efficiency addition/water only efficiency change time
water only efficiency max (litre/litre)
= $\int$water only efficiency max net change dt + water only efficiency max initial
water only efficiency max change characteristic time (years)
= 20
water only efficiency max initial (litre/litre)
= 1.4
water only efficiency max max (litre/litre)
= 3
water only efficiency max net change (litre/litre/year)
= (water only efficiency max max-water only efficiency max)/water only efficiency max change characteristic time
water only efficiency potential (litre/litre)
= max(water only efficiency max-water only efficiency addition - water only efficiency,0)
water only efficiency slum (litre/litre)
= $\int$water only efficiency slum net change dt + 1.0
water only efficiency slum net change (1/year)
= 0
water only service benefit relative (Dmnl)
= max(xidz(Water demand only service per capita-water only service minimum per capita,water only service reference per capita-water only service minimum per capita,0),0)
water only service minimum per capita (litre/person/day)
= $\int$water only service minimum per capita net change dt + 30.0
water only service minimum per capita net change (litre/person/day/year)
= 0
water only service reference per capita (litre/person/day)
= $\int$water only service reference per capita net change dt + 80.0
water only service reference per capita net change (litre/person/day/year)
= 0
water price adjustment time (year)
= 3
Water price by volume (INR/litre)
= $\int$water price by volume net change dt + water price by volume initial
water price by volume initial (INR/litre)
= 0.00706
water price by volume net change (INR/litre/year)
= (water price to break even-Water price by volume)/water price adjustment time * water price increase pressure
water price increase pressure (Dmnl)
= water revenue increase pressureˆ2
water price reference (INR/litre)
= $\int$water price reference net change dt + Water price by volume
water price reference adjustment time (year)
= 1
water price reference net change (INR/litre/year)
= (Water price by volume-water price reference)/water price reference adjustment time
water price to break even (INR/litre)
= Water price by volume/Water cost recovery ratio
water revenue increase pressure (Dmnl)
= max(1,1/Water cost recovery ratio)

water revenues (INR/day)
= Water price by volume*water total demand
Water share sewered (Dmnl)
= (Slum sewered share * water total demand slum + water total demand nonslum) / water total demand
Water supply (litre/day)
= water total demand/(1-Water distribution leakage)
water supply availability (litre/day)
= environmental flow availability+augmented water supply capacity-flow requirement
water supply availability forecast (litre/day)
= environmental flow availability*(1 + environmental flow forecast growth rate*TIME STEP)^(water supply margin forecast time horizon/TIME STEP)- flow requirement*(1+flow requirement forecast growth rate*TIME STEP)^(water supply margin forecast time horizon/TIME STEP) + augmented water supply capacity+water supply capacity augmentation under construction
water supply capacity augmentation under construction (litre/day)
= $\int$water supply capacity expansion-water supply capacity expansion completion dt + 455.0*(10.0^6.0)
water supply capacity expansion (litre/day/year)
= max(0,(water supply margin minimum-water supply margin forecast)*(water total demand)/(1-Water distribution leakage)*(1+water total consumption forecast growth rate* TIME STEP)^(water supply margin forecast time horizon/TIME STEP))/water supply capacity expansion planning time
water supply capacity expansion completion (litre/day/year)
= water supply capacity augmentation under construction/water supply capacity expansion completion time
water supply capacity expansion completion time (year)
= 2
water supply capacity expansion marginal electricity intensity (kWh/litre)
= $\int$water supply marginal electricity intensity increase dt + local water supply electricity intensity
water supply capacity expansion planning time (year)
= 1
water supply capacity x electricity (kWh/litre*(litre/day))
= $\int$water supply capacity x electricity increase dt + local water supply electricity intensity*augmented water supply capacity
water supply capacity x electricity increase ((kWh/litre)*(litre/day)/year)
= water supply capacity expansion completion*water supply capacity expansion marginal electricity intensity
Water supply electricity consumption (kWh/day)
= local water supply electricity consumption+extra water supply electricity consumption
water supply electricity expenditure (INR/day)
= electricity price by unit*Water system electricity consumption
water supply electricity intensity marginal slope ((kWh/litre)/(litre/day))
= 1.5e-012
water supply margin (Dmnl)
= (water supply availability-water total demand/(1-Water distribution leakage))/(water total demand/(1-Water distribution leakage))
water supply margin forecast (Dmnl)
= (water supply availability forecast-(water total demand/(1-Water distribution leakage))*(1+water total consumption forecast growth rate*TIME STEP)^(water supply margin forecast time horizon/TIME STEP))/(water total demand/(1-Water distribution leakage))*(1+water total consumption forecast growth rate*TIME STEP)^(water supply margin forecast time horizon/TIME STEP)
water supply margin forecast time horizon (year)
= water supply capacity expansion completion time
water supply margin minimum (Dmnl)
= 0
water supply marginal electricity intensity increase (kWh/litre/year)
= water supply capacity expansion*water supply electricity intensity marginal slope
Water system electricity consumption (kWh/day)
= Wastewater electricity consumption + Water supply electricity consumption
water system electricity per capita (kWh/(person*day))
= water demand total consumption per capita*water system electricity per litre consumption
water system electricity per litre consumption (kWh/litre)
= Water system electricity consumption/water total demand
water total consumption forecast growth rate (1/year)
= population forecast growth rate+water total consumption pc forecast growth rate
water total consumption pc forecast growth rate (1/year)
= water demand total pcc ptrend
water total demand (litre/day)
= water total demand multiplier * (water total demand nonslum + water total demand slum)
water total demand multiplier (Dmnl)
= 1.13
water total demand nonslum (litres/day)
= (Population-Slum population) * water demand total consumption per capita nonslum
water total demand slum (litres/day)
= Slum population * water demand total consumption per capita slum * slum all uses consumption scaling factor
water total supply (litre/day)
= water total demand / (1 - Water distribution leakage)
Water wastage net change (litre/(year*person*day))
= Water wastage nonslum*(water waste rate of change historical + STEP(water waste rate of change future-water waste rate of change historical,present))
Water wastage nonslum (litre/(day*person))
= $\int$Water wastage net change dt + 80.0

water wastage per capita (litre/(person*day))
= Water wastage nonslum*(1-slum population share)+Water wastage slum*slum population share
Water wastage slum (litre/(day*person))
= $\int$water wastage slum net change dt + 20.0
water wastage slum net change (litre/(day*year*person))
= 0
water waste rate of change future (1/year)
= -0.02
water waste rate of change historical (1/year)
= -0.02