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Water and energy systems in sustainable city development: A case of Sub-Saharan Africa

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Abstract

Current urban water and energy systems are expanding while increasing attention is paid to their social, economic and environmental impacts. As a research contribution that can support real-world decision making and transitions to sustainable cities and communities, we have built a model-based and data-driven platform combining comprehensive database, agent-based simulation and resource technology network optimization for system level water and energy planning. Several use cases are demonstrated based on the Greater Accra Metropolitan Area (GAMA) city-region in Ghana, as part of the Future Cities Africa (FCA) project. The outputs depict an overall resource landscape of the studied urban area, but also provide the energy, water, and other resource balance of supply and demand from both macro and micro perspectives, which is used to propose environmental friendly and cost effective sustainable city development strategies. This work is to become a core component of the resilience.io platform as an open-source integrated systematic tool gathering social, environmental and economic data to inform urban planning, investment and policy-making for city-regions globally.

Keywords: Urban systems; Water; Energy; Sustainable development; Modeling

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1. Introduction

The grand challenges facing human societies are closely interconnected with the sustainable provisioning of energy, water and material resources, for growing and developing populations, and the subsequent processing and management of waste and pollution [1]. More than half of the population of the whole world is now urban, causing urbanization and its associated resource demand and supply affecting governmental decisions at all levels [2]. With global urbanization leading to brand new cities and a growing urban population in existing cities, there is an increasing challenge in managing city infrastructures such as electricity, gas, transport and water networks as well as waste handling including sewage and refuse. Many initiatives across the world have also been formed, and existing efforts are incrementally adjusted, to provide feasible solutions to energy and water scarcity and guide the sustainable development [3-7].

Sustainable city development is particularly important for developing countries where the pace of urbanization is highest, leading to huge challenges in handling this growth while providing improved quality of life without compromising the ability of future generations to meet their demands [8]. Sustainable development of these city-regions, which includes environmental, social and economic sustainability, is as such critical, particularly in tackling key challenges including sensitivity to the effects of climate change, suffering from poor sanitation and healthcare and significant social challenges such as economic inequality and migration [9]. It is especially formidable to achieve sustainable urban development in Africa considering the extensive amount of low-income populations who even live in slums [8].

Water and energy are vital to the delivery of urban services and they are also interlinked in intimate ways in the process of urban design and operation. Current urban water and energy systems are expanding, and increasing attention is paid to their social, economic and environmental impacts [10-12]. However, there lacks a sufficiently systematic approach to address these impacts and evaluate optimal strategies, either in the context of research or real-world decision making. Simulation and optimization models can help understand socio-technical systems by providing insights in current as well as future demands under different social, economic and environmental scenarios constrained by available technology. Therefore we have built the resilience.io platform as an open-source, data-driven, integrated systematic tool gathering social, environmental and economic data to inform evidence based infrastructure planning especially in water and energy sectors.

This paper presents how the platform is materialized by combining three components including a socio-demographic module for population and economic evolvement, an agent based modeling and simulation module for demand generation, and another resource technology network module for infrastructure planning and optimization. Section 2 will first describe the overall methodology, and the sub-sections 2.1 to 2.3 describes the three key components, i.e., demographics, demand, and supply respectively. Section 3 demonstrates how the whole methodology is applied to the Greater Accra Metropolitan Area (GAMA) city-region in Ghana. Conclusions and future work are discussed in Section 4.

2. Structure and Methodology

The urban simulation and optimization platform promotes systematic understanding of resource systems by incorporating three components connected with input and output data. The regional datasets are built with information of population, economy, infrastructure, and technologies. By pre-processing and validating the input data, several full master tables are built to describe the characteristics of residential, commercial, industrial, and institutional users. This laid the foundation for further analyses of the demand of water, energy, and other resources from a bottom-up approach, which is realized through the Agent-Based Modeling (ABM) by generating a synthetic population from the datasets, and simulating their activities [13,14]. The behavior of the agents, differentiated by individual characteristics, leads to real-time demands for water, energy and generation of wastes to be treated. The results from the ABM module can be used as input to further conduct the supply-side matching through Resource Technology Network (RTN) optimization models considering social, economic and environmental objectives [15]. To assist in international urban development, especially providing support to less developed countries, the whole package is built from scratch using Java programming. The structure overview for the whole platform is demonstrated in Fig. 1, and the following sub-sections briefly introduces the model components.

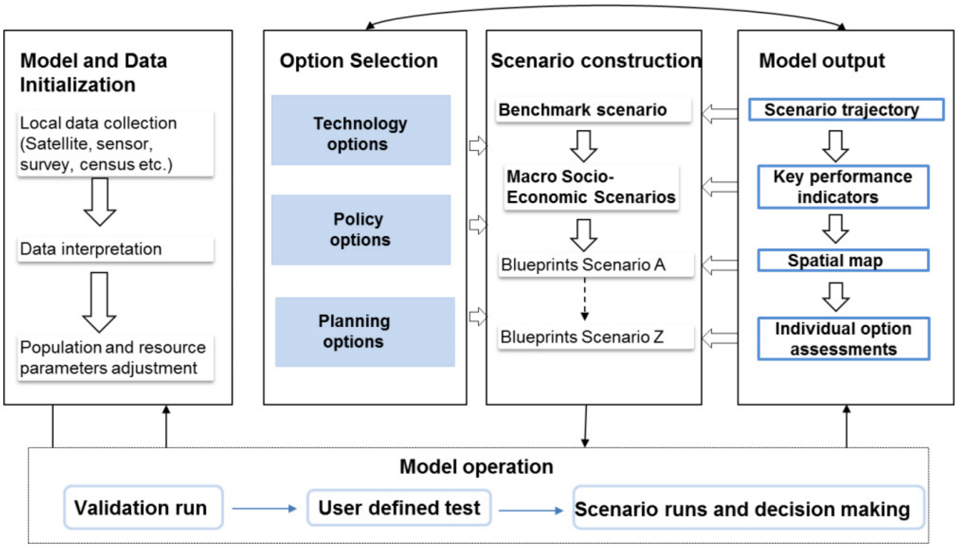

Fig. 1. Overview of the methodology to use the platform.

2.1. Demographics and socioeconomic workflow

This model component, as the first part of the whole package, can generate and update the socio-demographic and economic data in any future years selected by users. An agent master table is created following distributions of the various socio-demographic characteristics (e.g., gender, age, workforce status, and income levels) as well as locations and access to infrastructure (e.g., home and work location, water pipeline access, and electricity grid connection). The master table is thereby generated containing all possible combinations of characteristics as well as an indicator of how many population members have this set of values. All calculations are carried out for an individual year, and the next year takes into account the changes from the previous year, applied to each row, which represents each category of population, in the master table. The factors considered include population birth, death, and ageing, immigration and emigration changes, and employment growth. For each region studied, there first exists the relationship to update the population number by:

$$Population\ (t+1) = Population\ (t) + Births\ (t) - Deaths\ (t) + Immigration\ (t) - Emigration\ (t) \qquad (1)$$

After the new population numbers are estimated, a series of calculations are carried out to adjust the socio-economic status of the population, including the ratio of employed population, employment change within this population, and income level changes among three categories of low, medium, and high income family members. It is assumed that employment will grow from the current situation to a maximum level specified by user input according to the studied region. This parameter is used in a logistics S-curve type equation [16], which is implemented as:

$$EmploymentChangeRate\ (t+1) = 0.05 * employmentRatio\ (t)\ (1 - employmentRatio\ (t)\ /maxEmployment) \qquad (2)$$

Similarly, a set of company master tables are also generated and adjusted by time to denote non-residential information, especially with respect to water and energy consumption. The number of companies are also updated with the population and economic evolvement.

$$CompanyNo(t+1) = CompanyNo(t) * (1 + EmploymentChange) \quad (3)$$

It is noted that while the population data is cumulative, we implemented a limit of years to be simulated, as results would become less and less realistic.

2.2. Agent-based modeling for demand simulation

An agent-based simulation model for the region studied, with agents representing individual citizens based on demographics with socio-economic characteristics and access to infrastructure, is created as the second key component of the platform [17].

In the context of sustainable urban development, ABM can model energy and water consumption from the bottom-up approach related to human activities, considering demand sectors including residential, industrial, commercial, and transportation. An agent factory is first built to define the population data and behavior rules, and a synthetic population is selected as statistically representative sample based on certain distributions, along with individual data and rules, to represent the overall population. More specifically in this case, the agent factory is associated with the master table, either the base case, or a future scenario generated by the demographic module as described in Section 2.1, while the size of synthetic population can be manipulated by users. The behaviour of the agents, differentiated by individual characteristics, leads to demands for water, energy, and generation of wastes, which can be tracked every 5 minutes over any long-term period (e.g., 24-hour) per agent and per district in which the agents live and work.

The procedures of demand-side simulation through ABM is described as:

- Synthetic population generated from a pre-processed master table that represents the actual population with socio-economic variants.
- Demand for water, electricity and other resources estimated based on agents activities.
- Output data visualized and connected to optimization model.

$$AP_i = \{(ACT_j, MT_j, SD_j, PS_j)\} \quad (4)$$

The behaviour rules are defined based on temporal and spatial activities. An example is listed in equation (4) where the agent conducts activity j (ACT_j) at mean starting time MT_j with standard time deviation of SD_j, and a probability of starting PS_j. These probability based models can fully describe agents' activities and denote their locations at each time step. On top of the activities, the time-varying usage of water, energy and other resources is analyzed and described by regression functions [18].

2.3. Resource-technology network modeling for optimal supply

Once the ABM component generates the corresponding demands of, for example, clean water to supply, waste-water to be treated, and electricity requirement, the RTN model is then initiated to calculate how these demands can be best met according to the current infrastructure and associated costs plus any investments required. The calculation is based on a large number of technology datasets, as some example set outlined in table 2 below, which describe for each type of generation and treatment plant/technology:

- The capital investment cost and operational costs.
- The electricity and fuel inputs necessary to operate the infrastructure, and outputs from the generation facilities.
- The material inputs and outputs, such as raw water input, chemicals for source water treatment, or pipes to establish a water distribution network.
- The wastes generated in operating the facility, including solid, liquid and gaseous wastes.
- Environmental impacts such as greenhouse gas emissions associated with construction and operation.

- The capacity range at which each technology is available, such as how much kWh a PV solar plant can generate per day, or m^3 of potable water a treatment plant can provided.
- The labour inputs required to operate the facility per hour and number of jobs.

The interrelationship between water and energy systems are addressed through material and energy balance. The optimization problem is formulated as a mixed-integer linear programming (MILP) with an objective function to minimize the multi-objectives of capital expenditures, operating expenditures and environmental impacts associated with *VIJ* for infrastructure construction, *VPJ* for production, *VQ* for flows, *VY* for building additional connections, and *VI* for imported resources.

$$\begin{aligned}
Z &= \sum WT(m,\ tm)\ VM(m,\ tm),\\
&\text{where } WT(m,tm) \text{ represents weighting factors for metrics,}\\
VM(m,\ tm) &= \sum VIJ\ (j,\ i,\ m)\ INV\ (j,\ i,\ tm) + \sum VPJ\ (j,\ i,\ m)\ P(j,\ i,\ tm)\\
&\quad + \sum VQ\ (r,\ m)\ dist\ (i,\ i')\ Q(r,\ i,\ i',\ tm)\\
&\quad + \sum VY\ (r,\ m)\ dist\ (i,\ i')\ Y(r,\ i,\ i'\ ,\ tm) + \sum VI\ (r,\ m)\ IM(r,\ i,\ t,\ tm)
\end{aligned} \tag{5}$$

Where *j* represents technologies of electricity generation plants, water treatment facilities and others such as the list in table 1. *i* and *i'* are the spatial districts within the study area. *m* are different terms in the objective metrics. *t* and *tm* are minor (peak, normal, off-peak hours during a day) and major (each year, or multiple years in a row) time periods respectively. Last, *r* are all resource involved in the model including raw water, waste-water, process chemicals, solid waste, electricity, labor and other related resources.

Table 1. - Outline of technology datasets for source water treatment, waste-water treatment, and electricity generation [18-21].

Process Block	**Description**	**Outputs**
Central source water treatment plant	Regular surface water treatment through addition of chemicals and sand filtration	Potable water
Borehole pumping systems	Direct borehole abstraction and additional residual disinfection	Potable water
Bottled water packaging	The production of water into bottled containers	Bottled water
Sachet water packaging	The production of water into sachets	Sachet water
Desalination treatment plant	Pressurized systems of membrane filtration and reverse osmosis to remove salt and other impurities	Potable water
Central waste-water treatment plant	Conventional waste-water treatment with filtration, settlement activated sludge microbial systems, sludge treatment, and the UASB variants thereof	Treated waste water
Decentralized activated sludge treatment (small scale)	Industrial facility based systems for the neutralization of sludge based on aerobic oxidation by pumping air within an aeration tank or system, and subsequent clarification and settlement	Treated waste water
Waste stabilization ponds	Passive treatment of waste water in open pond systems based on sedimentation, facultative treatment, and aerobic maturation stages	Treated waste water
Anaerobic digestion/biogas	The anaerobic digestion of human excrete connected to toilet systems for production of biogas and effluents	Biogas and effluents
Fossil-fuel power station	Coal, natural gas or petroleum based power plants to produce electricity	Electric power
Hydroelectricity station	Using of the gravitational force of falling or flowing water to produce renewable energy	Renewable electric power
Photovoltaic solar power stations	Converting sunlight directly into electric power using solar panels	Renewable electric power

3. Case study

In this application, we demonstrate how to use the platform to enhance understanding of the urban environment and guide decision making by analyzing two essential sectors to guarantee human living, which are the provision of clean potable water, and electric power. The use cases are associated with the Greater Accra Metropolitan Area (GAMA) in Sub-Saharan African country Ghana. By functional definition of regions, 15 distinct districts are studied with respect to their population, resource demand, and development plans. A sample of the master data table is shown in table 2 indicating some of the characteristics included in the model, such as gender, age categories (0-14 years and 15+), workforce status (employed, not_active_or_unemployed), and income levels (low, medium, high) [20].

Table 2. Sample of population-household master table.

DISTRICT	GENDER	AGE GROUP	WORKFORCE	INCOME	NONDRINK SOURCE	DRINK SOURCE	TOILETS	POPULATION	HOUSEHOLD
ACCRA_METROPOLITAN	Female	15+	Employed	Medium income family	private_pipe_access	private_pipe_access	Public Toilet	95691	26958
ACCRA_METROPOLITAN	Male	15+	Employed	Medium income family	private_pipe_access	private_pipe_access	Public Toilet	86225	24291
GA_WEST	Female	15+	Not_active_or_unemployed	Medium income family	Protected decentralised source	Sachet water	Kumasi VIP	2954	768
ADENTAN	Female	0-14	Not_active_or_unemployed	Medium income family	Tanker supply/Vendor provided	Tanker supply/Vendor provided	Kumasi VIP	156	42
ASHAIMAN	Female	0-14	Employed	Low income family	Protected decentralised source	Sachet water	No facilities	111	53

The results first return the population change of the studied urban area from base year 2010 with full datasets for an accurate representation of the current state of the city-region, to 2030 with projected demographic development. Each year's overall situation is stored in a spreadsheet called master table, as the basis for demand simulation. The ABM module can then generate the synthetic population of thousands of agents for example, define their activity rules, and calculate the time and location dependent demand. The total population of GAMA is estimated to increase from 4.39 million in 2015 to 6.49 million in 2030 from the demographic calculation, which is a 47.8% increase due to the emerging urbanization trend. The electricity profiles every 5 minutes over a day of all residential users in the studied regions are demonstrated in Fig. 2.

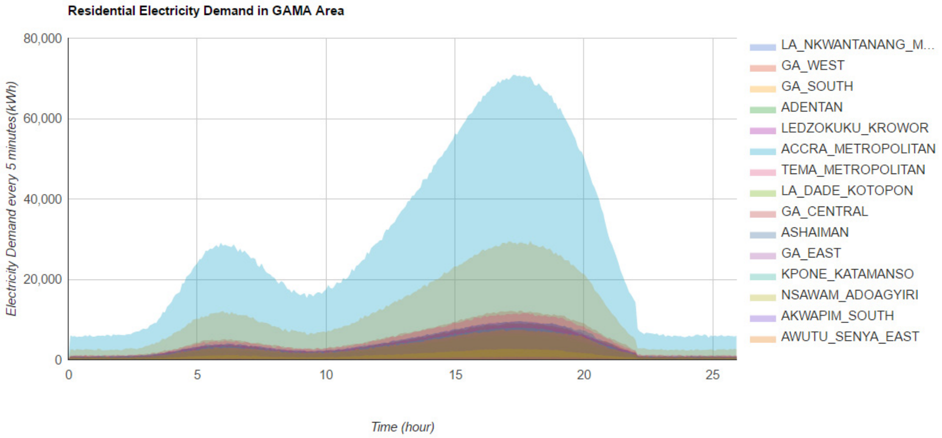

Fig. 2. Residential electricity demand profile per district over 24 hour period in year 2030.

As the population and social-economic conditions develop with time, the aggregated yearly demand can also be obtained for future planning. As shown in Fig. 3, the projected water demand increased from 124.84 million m^3 per year for the whole region in 2010, to 281.50 m^3 in 20 years. Similarly, the other metrics such as the waste-water to be treated or electricity demand for each year are also returned in results sheets as basis for RTN optimization.

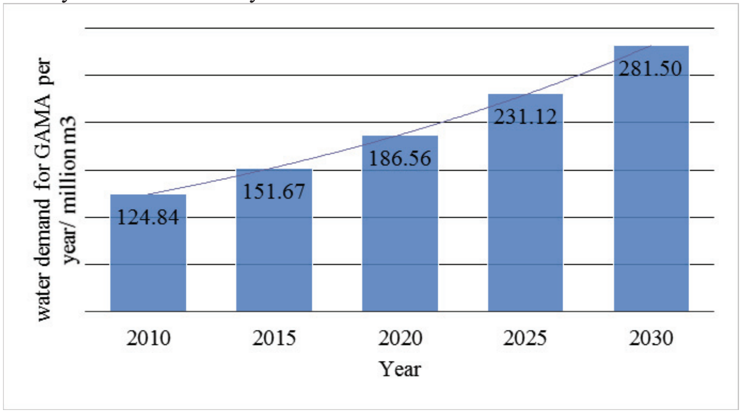

Fig. 3. Projection of water demands (m3) for 2010-2030 socio-demographic scenario.

In the next module run, the model selects cost optimal strategies to invest and operate among water treatment and electricity generation facilities to meet the increasing demand in year 2030 through the optimization program with user defined objective functions. As returned by the optimization, Ga South Metropolitan Area (GSMA), associated with the green bar, is selected by the model solver as an optimal investment location for building additional source water treatment plants by its geographical and economic advantage. Simultaneously, the power sector is influenced so that an increased capacity of PV solar generation is suggested, with details shown in Fig. 4, not only to provide electricity to residential users, but also to satisfy the water sector's extensive power requirement, considering the associated region has large-scale source water treatment plants to be built. The balance between using imported electricity from outside of GAMA through the transmission line, and consuming decentralized generation within the region, is also reflected in the results (see Fig. 5 for the amount of imported electricity of each districts), which will be impacted by the real-time price to purchase electricity from the grid as a user defined parameter.

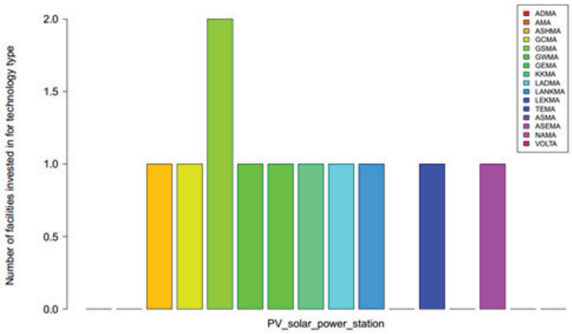

Fig. 4. Number of additional PV solar power stations suggested to be built for electricity supply by year 2030.

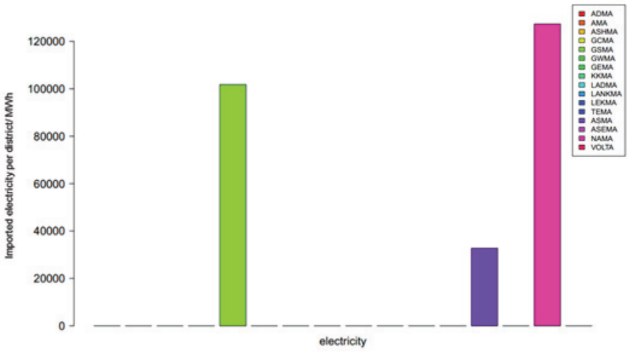

Fig. 5. Imported electricity from outside of the region to cover demands per district per year.

Also, the flow resources and suggested extension of connections (e.g., pipelines and transmission grids) are part of the optimal results demonstrated in Fig. 6 and Fig. 7 for flows of potable water and electrical power grid extensions respectively.

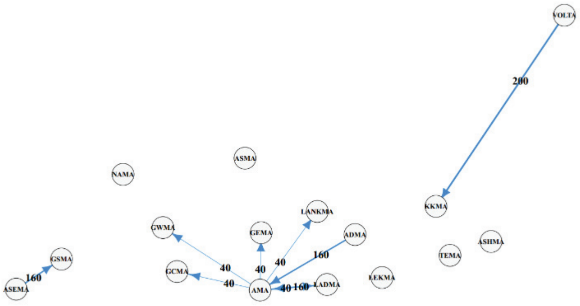

Fig. 6. Flows of potable water (1000 m3 per day) among districts (excluding leaks).

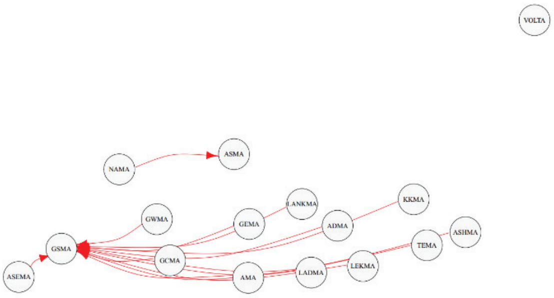

Fig. 7. Electrical power grid extension suggested for the electricity network (CAPEX of around 70.42 million USD).

Most importantly, the economic and environmental costs including capital expenditures (CAPEX), operational expenditures (OPEX), and revenues collected from operating these systems, as well as environmental impacts such as greenhouse gas (GHG) emissions are obtained directly from the optimal results for development strategies. Fig. 8 illustrated the results for the sustainable development scenario with respect to the cost terms in water sector. These results have also been refined and presented along with live model runs in workshops to local stakeholders in Ghana including national government, local governments, and researchers, with dataset and scenarios developed collaboratively with local experts and problem owners. As a scenario-based test bed, a variety of use cases and scenarios to describe the future situation can be designed and simulated in this platform, and the results indicators and visualization are automatically returned as reference for decision-making.

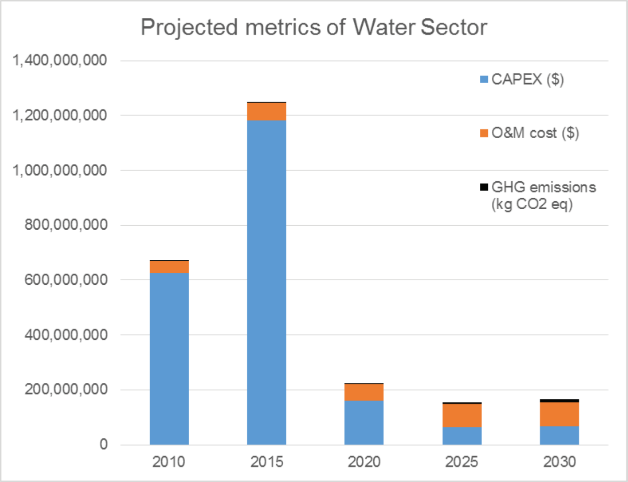

Fig. 8. Projected costs in water sector for every 5-year period.

4. Conclusions

This paper has introduced the methodology and software platform developed to plan resilient and sustainable development and transitions of urban systems, especially in water and energy sectors. The current regional demographics, infrastructure and economic information is used as input for the initial state of the focused urban system incorporating energy, water and other related resources. Detailed spatial-temporal resource demand data, obtained by simulating a synthetic population, is further used to plan capacity utilization and expansion by supply-side matching on a cost optimal basis, eventually aiming to explore the optimal design and operational strategies for residential, commercial, industrial, and other sectors with respect to water, energy and resource consumption. Moreover, long-term socio-economic scenarios are addressed in the process of urban systems development. The bottom-up approach allows the user to make changes to the scenarios together with local stakeholders and re-run the model to produce updated outputs easily, giving full flexibility to explore a range of socio-demographic, behavioral and technology scenarios. The case study of Sub-Saharan African city regions demonstrates the applicability of the tool to support evidence based planning for sustainable development and urban transitions.

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