Centre for Process Systems Engineering

Imperial College London

# Water and energy systems in sustainable city developments

*Resilience.io platform*

**Workshop on integrated energy system models incorporating spatial and temporal detail**

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# Outline

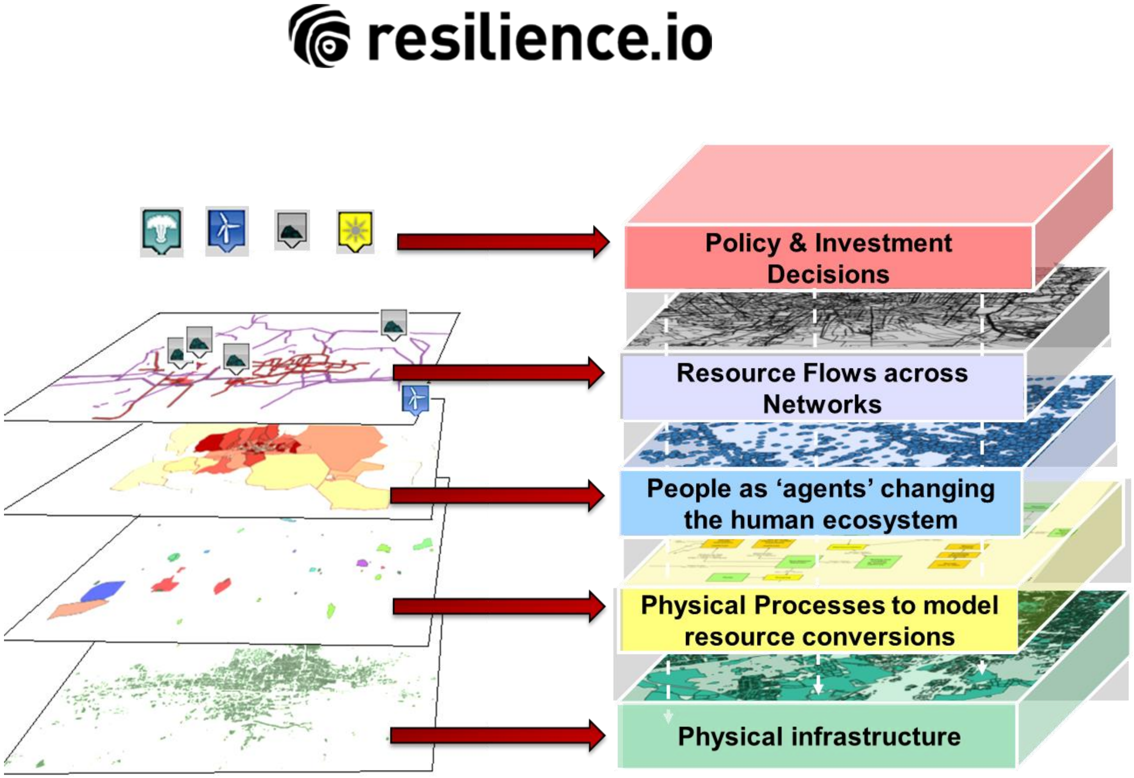
- Introduction and context
  - Sustainable development goals
  - Energy and water systems and their nexus

- Methodology
  - Workflow and data structure
  - Demand-side simulation: Agent-Based Modeling (ABM)
  - Supply-side optimization: Resource Technology Network (RTN)

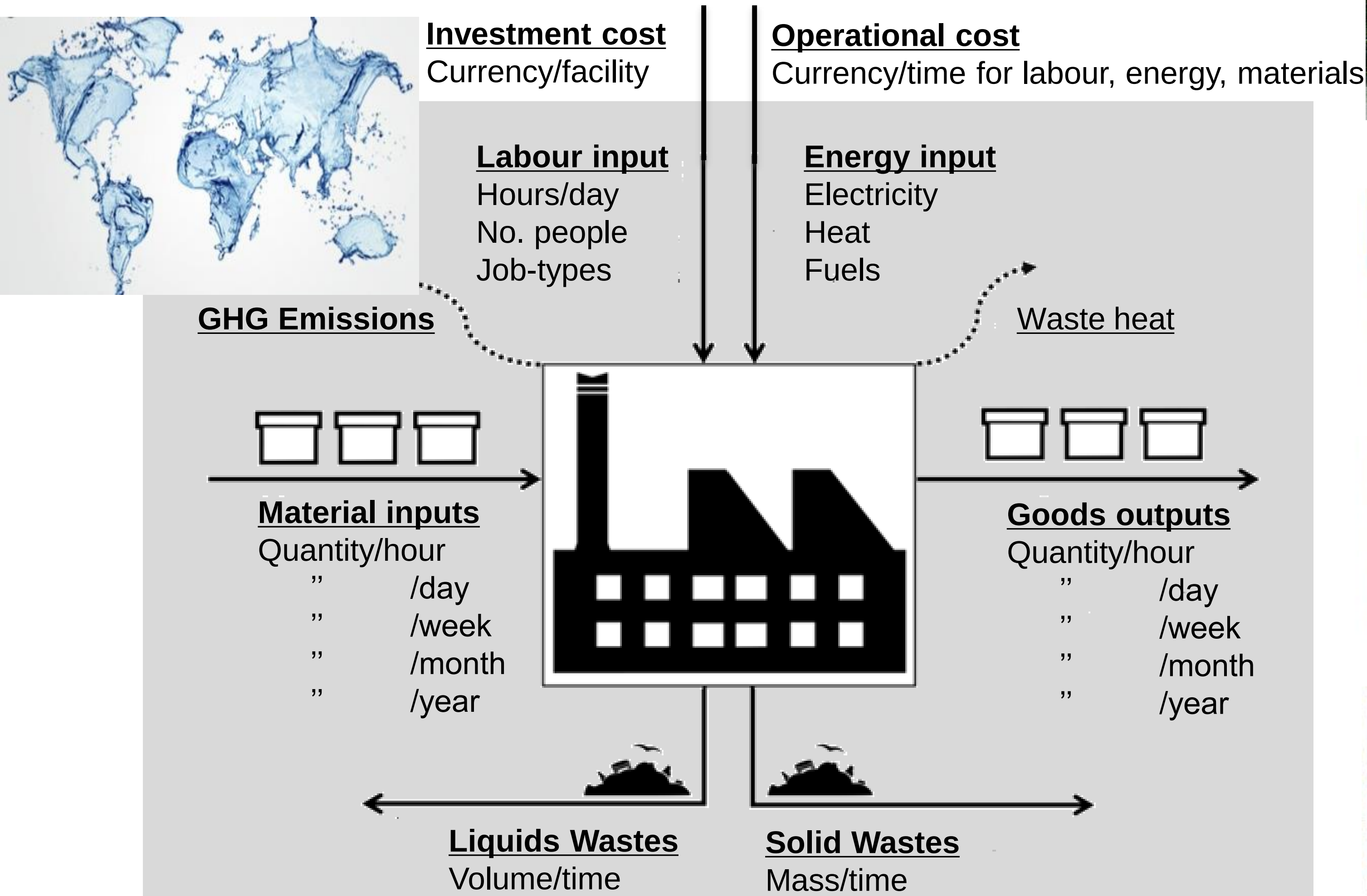
- Illustrative case and scenarios
  - Use cases in Ghana
  - Spatial and temporal scenarios

- Discussion and future work

# Sustainable Development Goals (SDG)

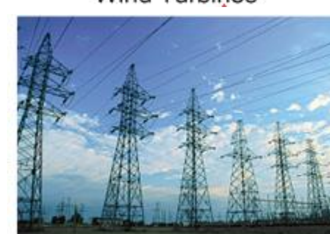
# Water and Energy Systems in Sustainable City Development




Hydro Plant

PV Panels

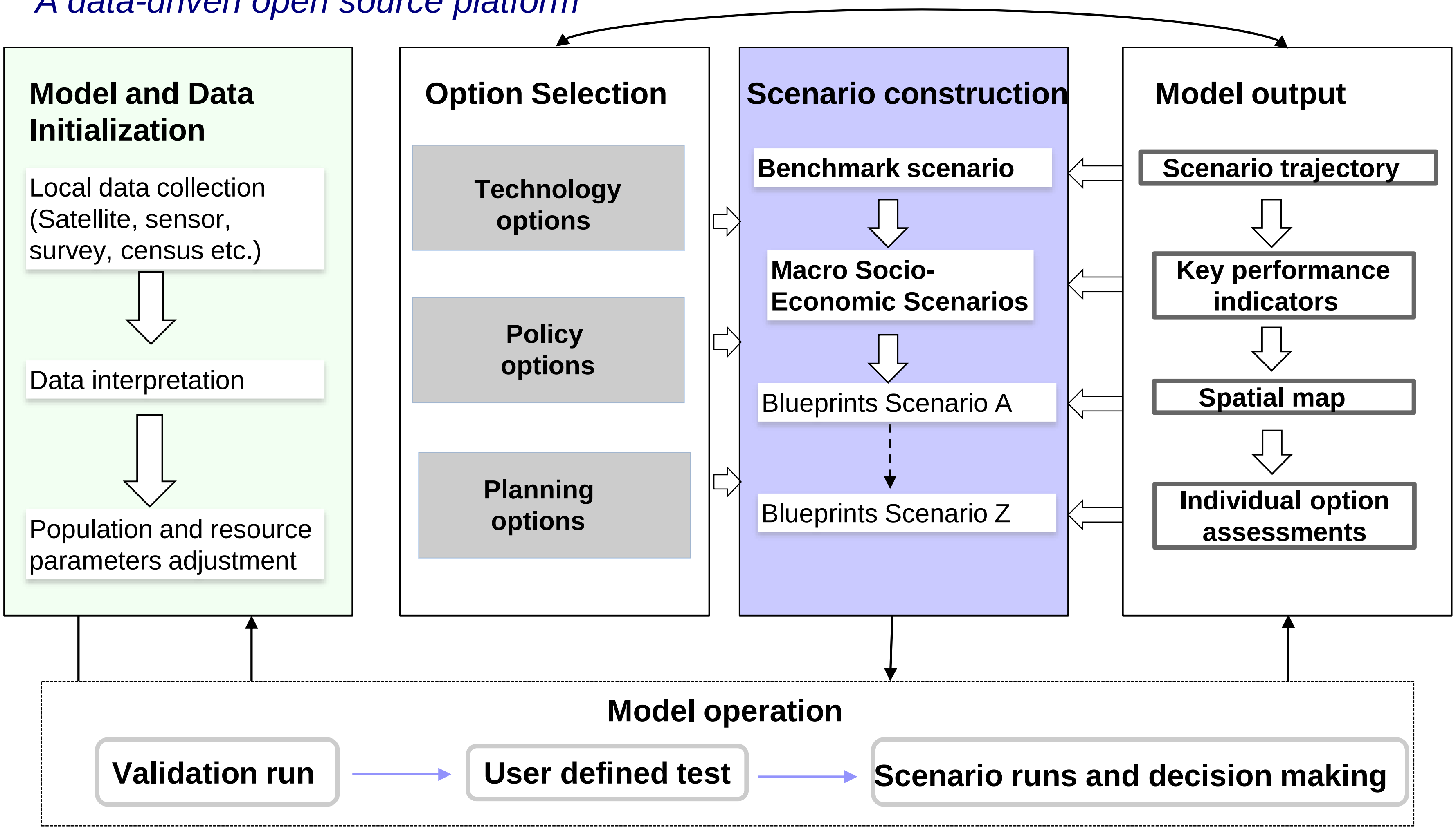
Wind Turbines



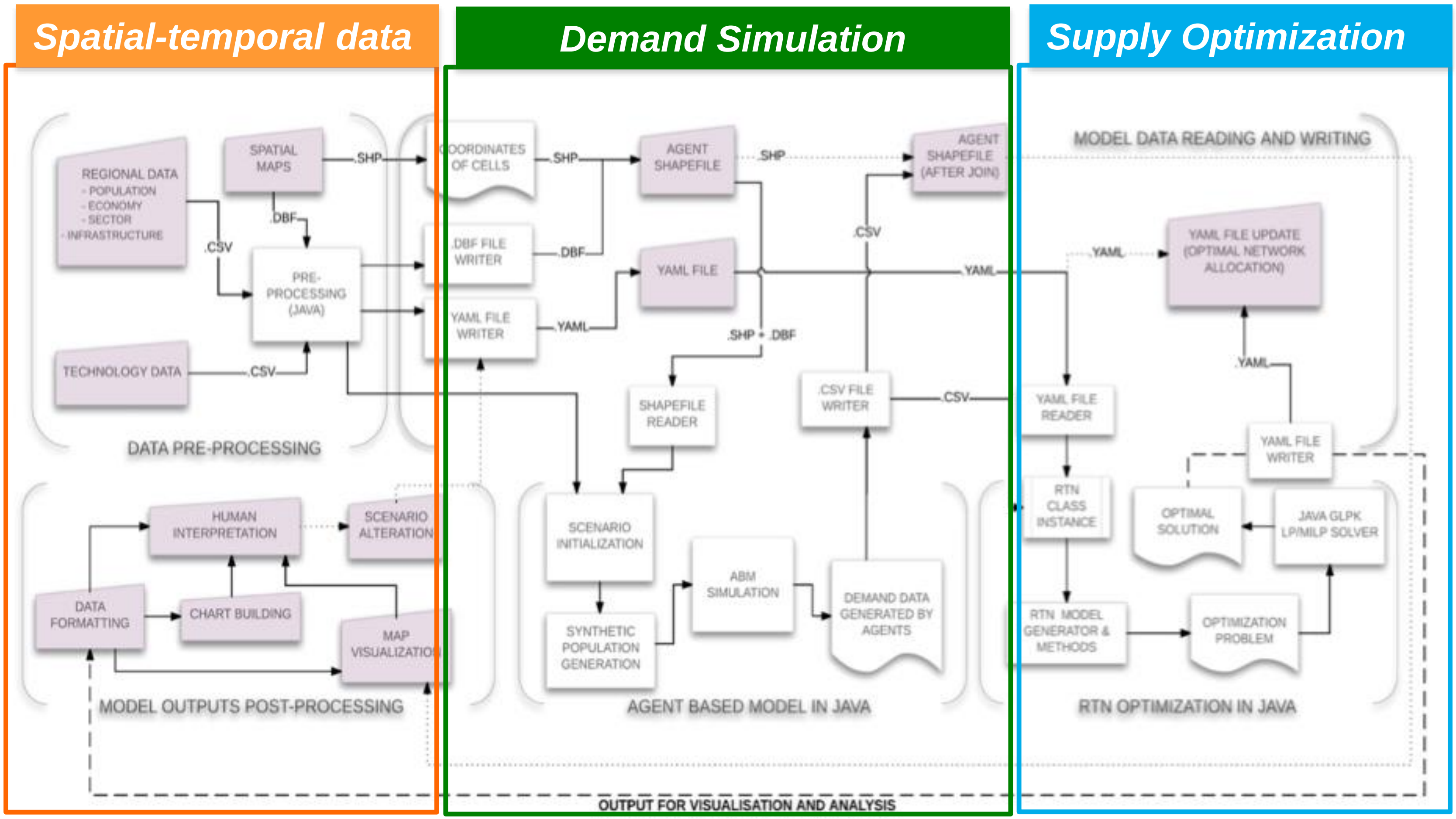
Grid

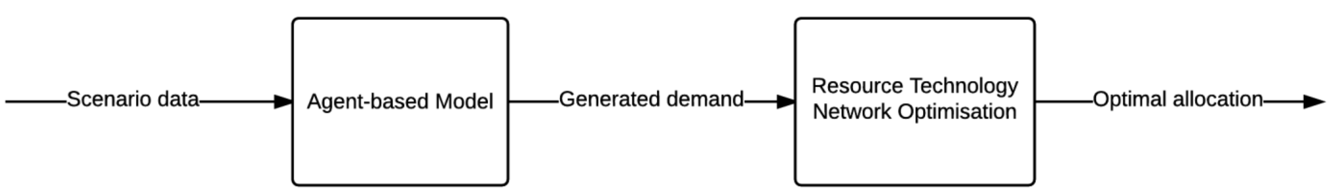
# Methodology of modeling and optimization

*A data-driven open source platform*



# Workflow and data structure

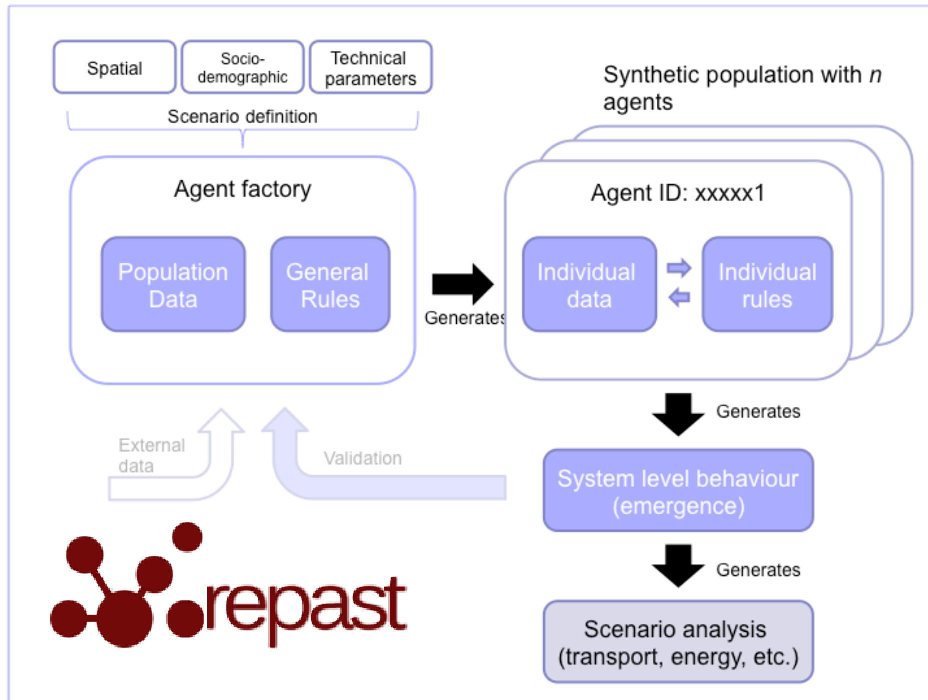


# Workflow and data structure

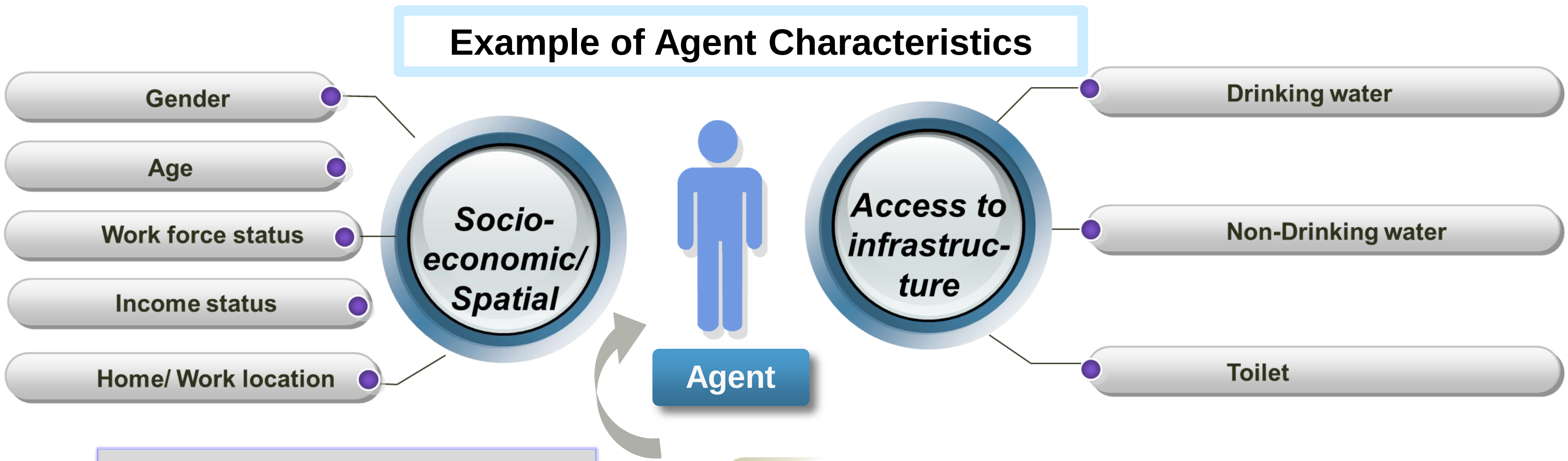
Spatial-temporal resource-socio-economic dynamics

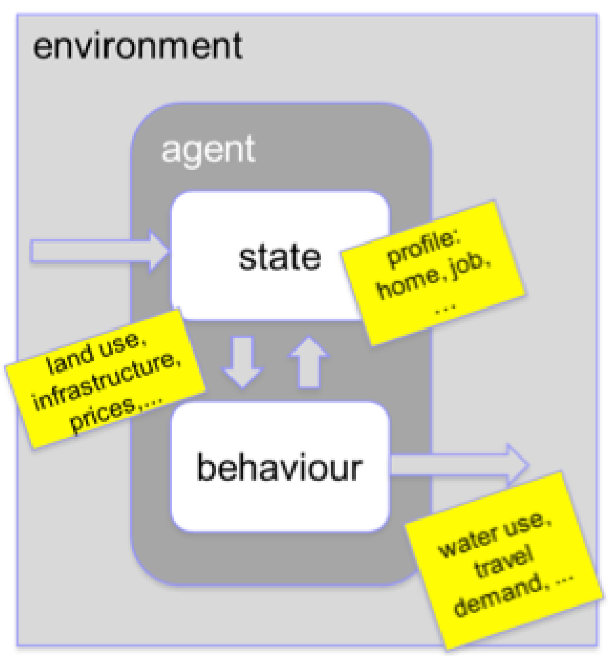
- resilience.io.agent
  - DefaultAgent.java
  - IAgent.java
- resilience.io.environment
  - Node11KV.java
  - Route.java
  - Zone.java
- resilience.io.environment.contexts
  - Grid11KVContext.java
  - ZoneContext.java
- > resilience.io.main
  - AgentFactory.java
  - ContextManager.java
  - > GlobalVars.java
- resilience.io.socioeconomic.matching
  - AgentMasterTableChange.java
  - Aggregation.java
  - CSV.java
  - MANIPULATEMethods.java
  - Matching.java




GAMS (prototyping the model)
YAML (data side)
JAVA (model construction)
GLPK (optimizer)
R (visualizations)

# Demand-side: Agent-Based Modeling (ABM)




# Demand-side: Agent-Based Modeling (ABM)

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

*Master Table* (part)

| DISTRICT | GENDER | AGEGROUP | WORKFORCE | INCOME | NONDRINKA | DRINKACCES | RATIONING | TOILETS | POPULATION | HOUSEHOLD |
|---|---|---|---|---|---|---|---|---|---|---|
| ACCRA_MET | Female | 15+ | Employed | Medium inco | private_pipe | private_pipe | NO | Public Toilet | 70811 | 19949 |
| ACCRA_MET | Male | 15+ | Employed | Medium inco | private_pipe | private_pipe | NO | Public Toilet | 63807 | 17975 |
| ACCRA_MET | Female | 15+ | Employed | Medium inco | private_pipe | private_pipe | NO | W.C. | 61738 | 17393 |
| ACCRA_MET | Male | 15+ | Employed | Medium inco | private_pipe | private_pipe | NO | W.C. | 55631 | 15672 |
| ACCRA_MET | Female | 15+ | Not_active_ | Medium inco | private_pipe | private_pipe | NO | Public Toilet | 39566 | 11147 |
| ACCRA_MET | Female | 15+ | Not_active_ | Medium inco | private_pipe | private_pipe | NO | W.C. | 34497 | 9718 |
| ACCRA_MET | Male | 15+ | Not_active_ | Medium inco | private_pipe | private_pipe | NO | Public Toilet | 32653 | 9199 |
| ACCRA_MET | Female | 0-14 | Not_active_ | Medium inco | private_pipe | private_pipe | NO | Public Toilet | 30086 | 8476 |
| ACCRA_MET | Male | 0-14 | Not_active_ | Medium inco | private_pipe | private_pipe | NO | Public Toilet | 29140 | 8210 |
| ACCRA_MET | Female | 15+ | Employed | Medium inco | private_pipe | Sachet water | NO | Public Toilet | 28875 | 8135 |
| ACCRA_MET | Male | 15+ | Not_active_ | Medium inco | private_pipe | private_pipe | NO | W.C. | 28469 | 8020 |
| ACCRA_MET | Female | 15+ | Employed | Medium inco | private_pipe | private_pipe | NO | Kumasi VIP | 26641 | 7505 |
| ACCRA_MET | Female | 0-14 | Not_active_ | Medium inco | private_pipe | private_pipe | NO | W.C. | 26231 | 7390 |

Time-variant simulation:
*electricity/ water demand every 5 minutes*
Aggregated per region

*Agent Activities*

$$AP_i = \{(ACT_j, MDT_j, SD_j, PD_j)\}$$

***$ACT_j$*** : **Activity j**
***$MDT_j$*** : **Mean departure time**
***$SD_j$*** : **Standard deviation**
***$PD_j$*** : **Probability of departure**

Time dependent regressive functions adopted to estimate each agent's water, electricity and facilities use based on their characteristics and activities throughout the day

# Supply-side: Resource Technology Network (RTN)

**Data-driven optimization model using mixed-integer linear programming (MILP)**

Objective function: min *L* (Demand, Supply, Scenarios)
= $\Sigma\alpha_1$(Capital Expenditure) + $\Sigma\alpha_2$(Operating and Maintenance Cost)
+ $\Sigma\beta$ (Environmental Cost) − $\Sigma\lambda$(Economic Benefits)

Summation over minor time periods *t* (e.g., peak, normal, off-peak hours) to guarantee supply-demand matching over all major time periods *tm* (e.g., whole year, multi-year period)

Constraints:

Technology and Investment balance/ limits, $N(j, i, tm) = N(j, i, tm\text{-}1) + INV(j, i, tm)$.

Resource balance and capacity limits- mass and energy balance.

Production limits based on capacities, $P(j, i, t, tm) \leq N(j, i, tm)\ CF(j)\ CAP(j)$.

Flow limits based on pipe and grid connections and capacities- geometric distance related.

Other realistic factors, e.g.,
-pipe leakage/transmission loss: treated as pseudo-demand;
-existing infrastructure: set as pre-allocation matrix.

# Supply-side: Resource Technology Network (RTN)

**Data-driven optimization model using mixed-integer linear programming (MILP)**

Objective function: $Z = \Sigma WT(m, tm)\, VM(m, tm)$, where

$WT(m, tm)$: weighting factors for metrics including CAPEX, OPEX, GHG

$VM(m, tm) = \sum VIJ(j, i, m)\, INV(j, i, tm) + \sum VPJ(j, i, m)\, P(j, i, tm) + \sum VQ(r, m)\, dist(i, i')\, Q(r, i, i', tm)$
$+ \sum VY(r, m)\, dist(i, i')\, Y(r, i, i', tm) + \sum VI(r, m)\, IM(r, i, t, tm)$

*j* – Technologies: electricity generation plants, water treatment facilities …
*i* – Districts: spatial zones/ cells
*r* – Resource: raw water, wastewater, process chemicals, solid waste, electricity, labor…

Decision variables:

$INV_{j, i, t}$ (investment of technology *j* in district *i* during time period *t*)

$P_{j, i, t}$ (production rate of technology *j* in district *i* during time period *t*)

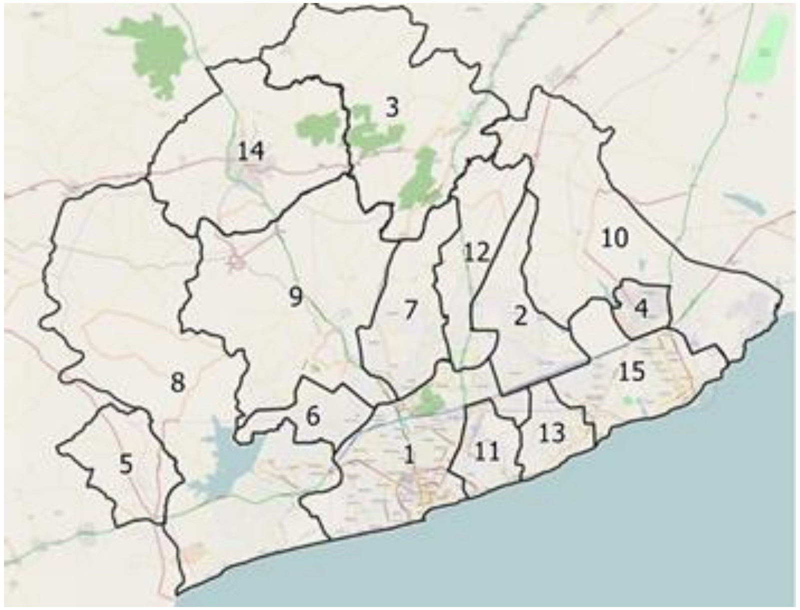
$Q_{r, i, i', t}$ (flow of resource *r* from district *i* to *i'* during time period *t*)

$IM_{r, i, t}$ (import of resource *r* to district *i* during time period *t*)

$Y_{r, i, t}$ (distance based connection expansion (binary),
e.g., water pipeline, electrical grid, for resource *r* in district *i* during time period *t*)

# **Case Study** (WASH and electricity sectors in GAMA)

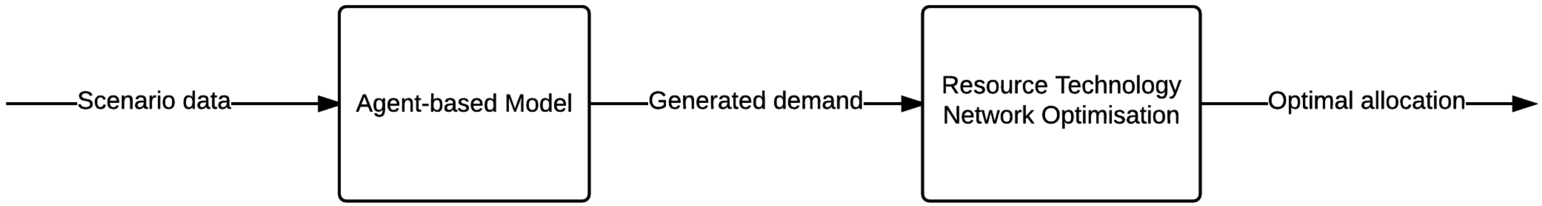
Central source watertreatment plant
Borehole with pipes
Protected wells and spring
Sachet drinking water plant
Bottled water plant
Unimproved tanked vendor water
Central waste water treatment plant
Waste stabilization pond
Aerated lagoon
Decentralized activated sludge system
Decentralized anaerobic bio-gas treatment plant
Decentralized aerobic treatment plant
Desalination plant
Chlor-alkali plant (example industrial plant)
Fossil fuel electricity station
Hydro electricity station
PV solar electricity station

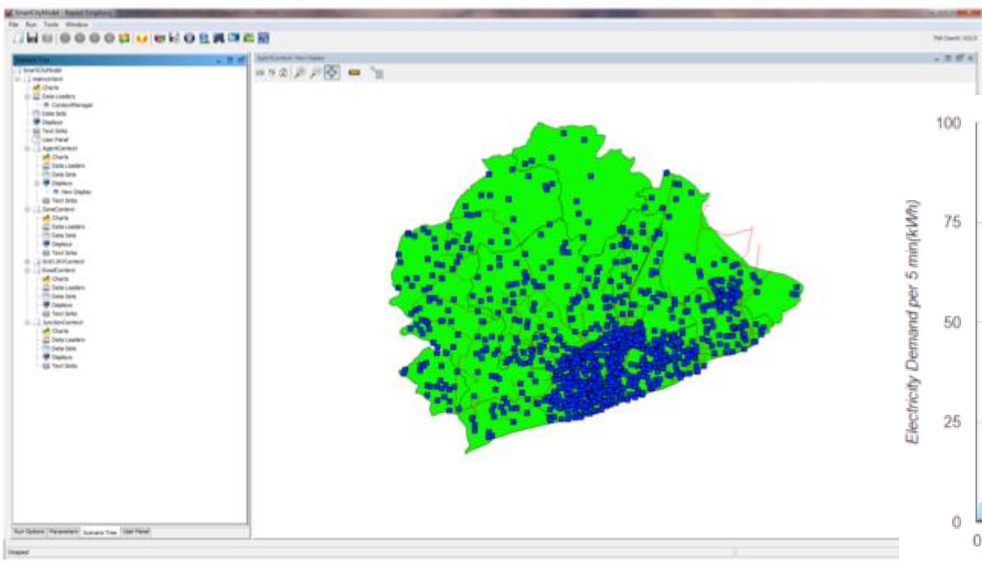


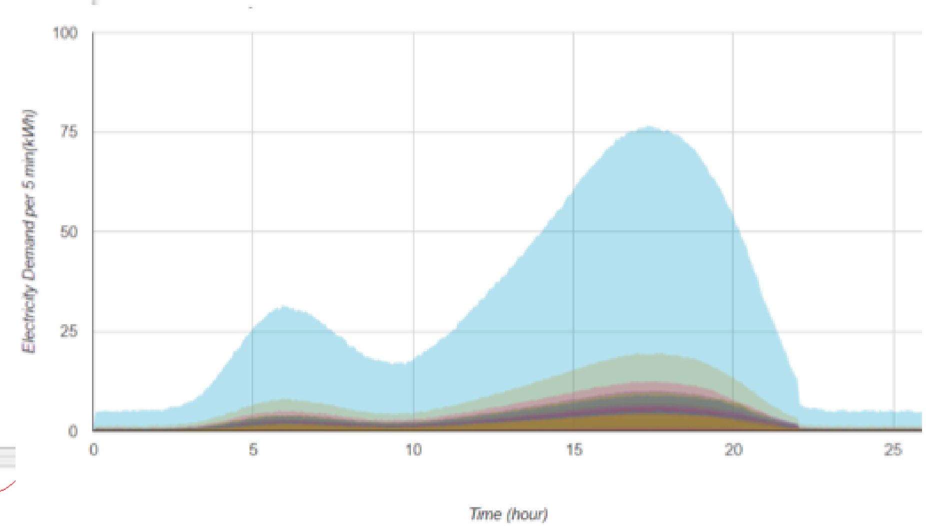

Example optimization model output:

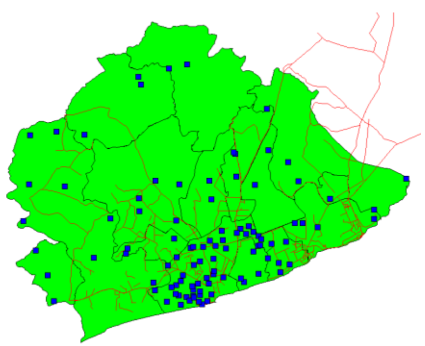
- Resource supply & demand matching
- Investment suggestions in energy and water sectors (i.e., infrastructure expansion, operational strategies).

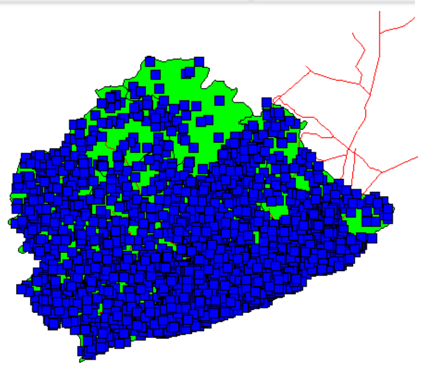
# **Case Study** (demand simulation)





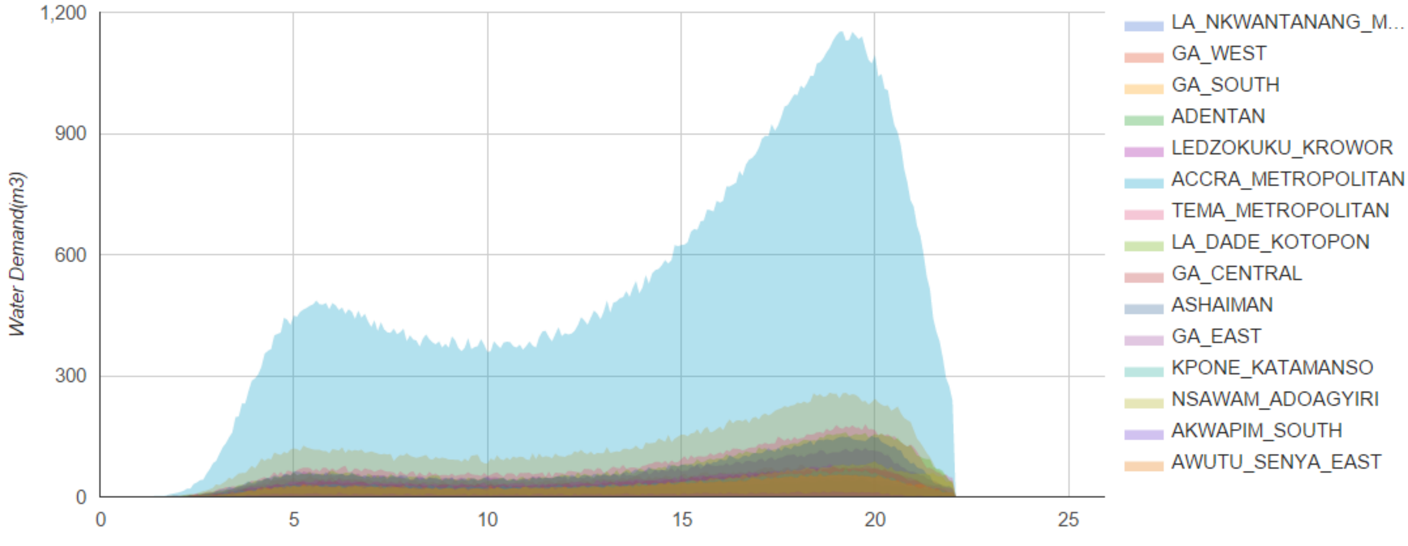





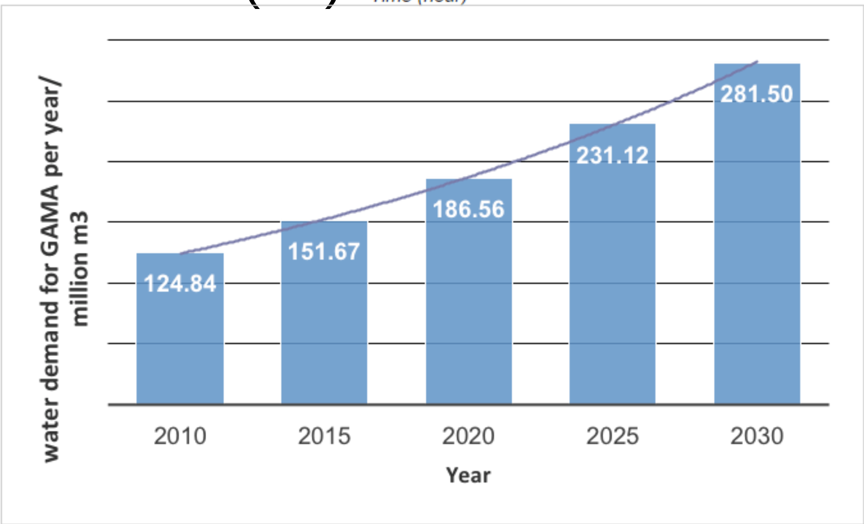
Residential electricity demand profile per district over 24 hour period

# Sub-results for residential water use

- Total residential demand profile per MMDA over 24 hour period

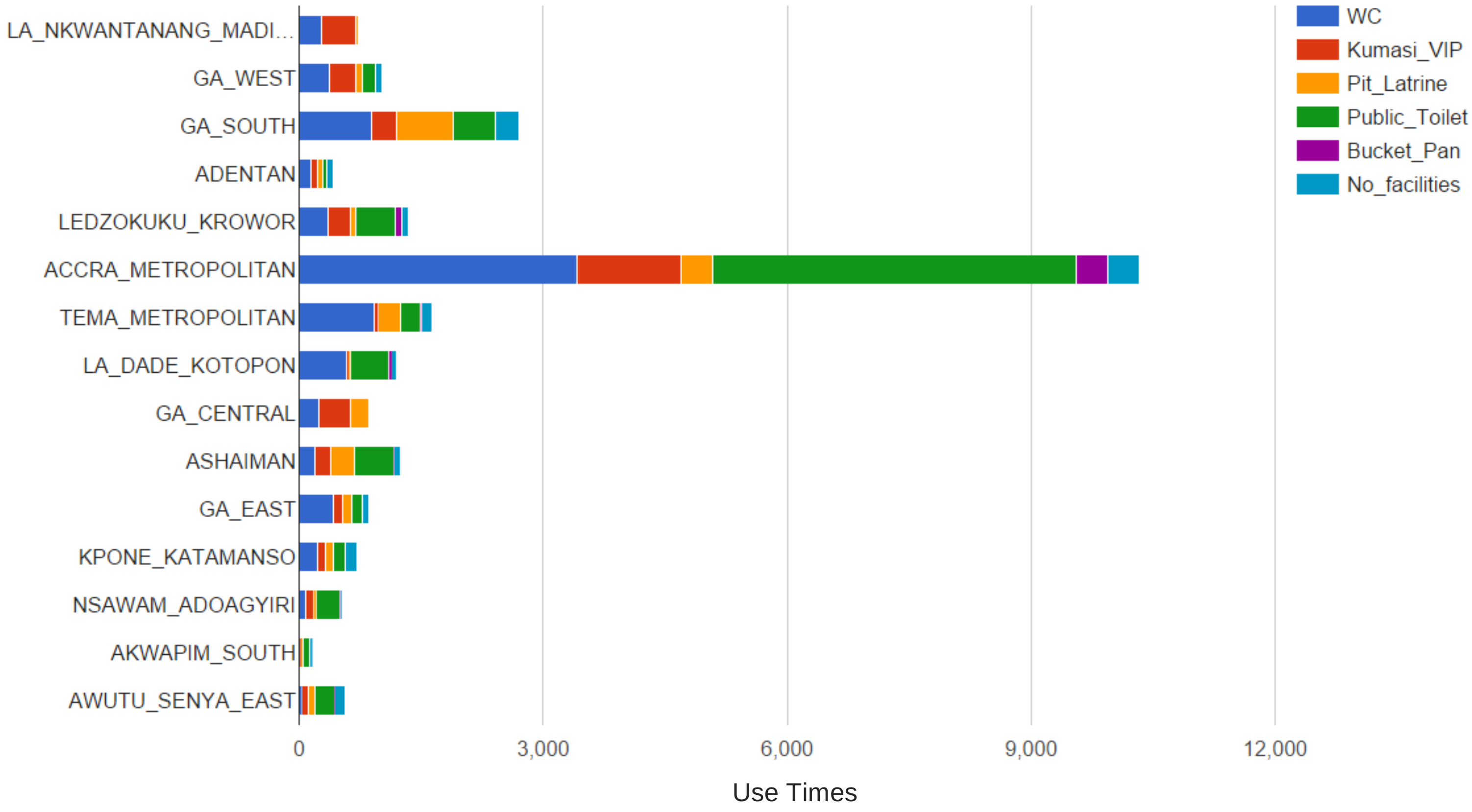



- Projection of demands ($m^3$) for 2010-2030 socio-demographic scenario

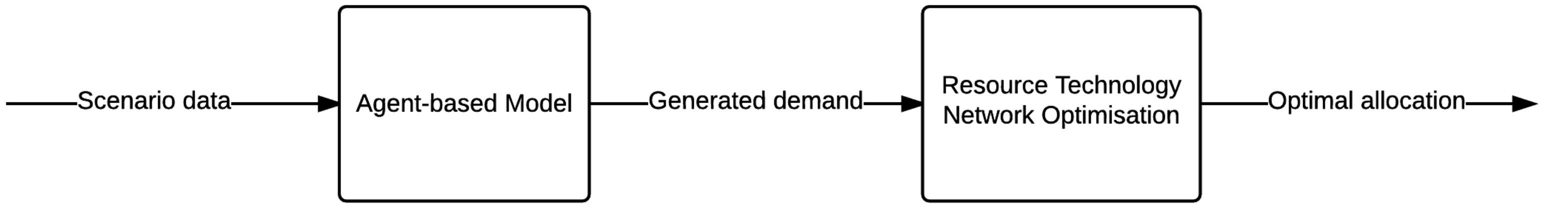


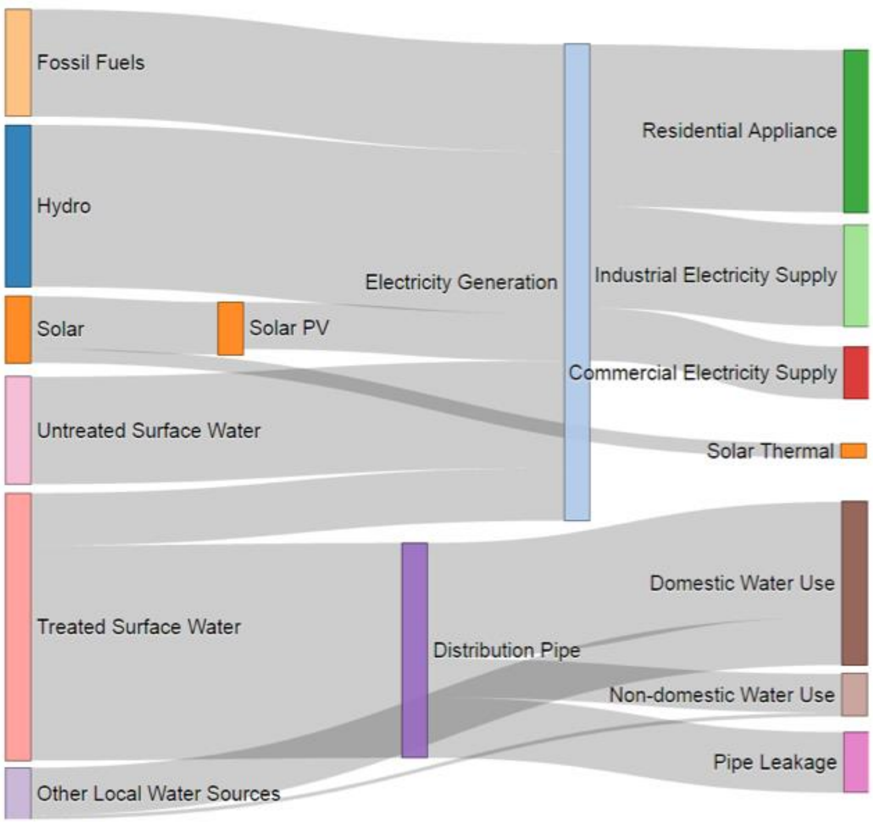
# Sub-results for Sanitation

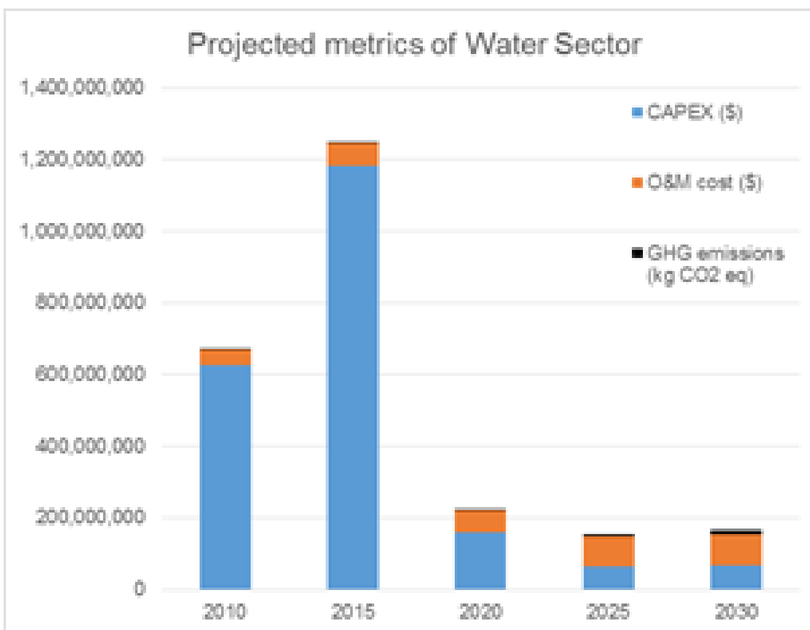
- Total toilet use profile per MMDA per MMDA over 24 hour period



# **Case Study** (supply optimization)



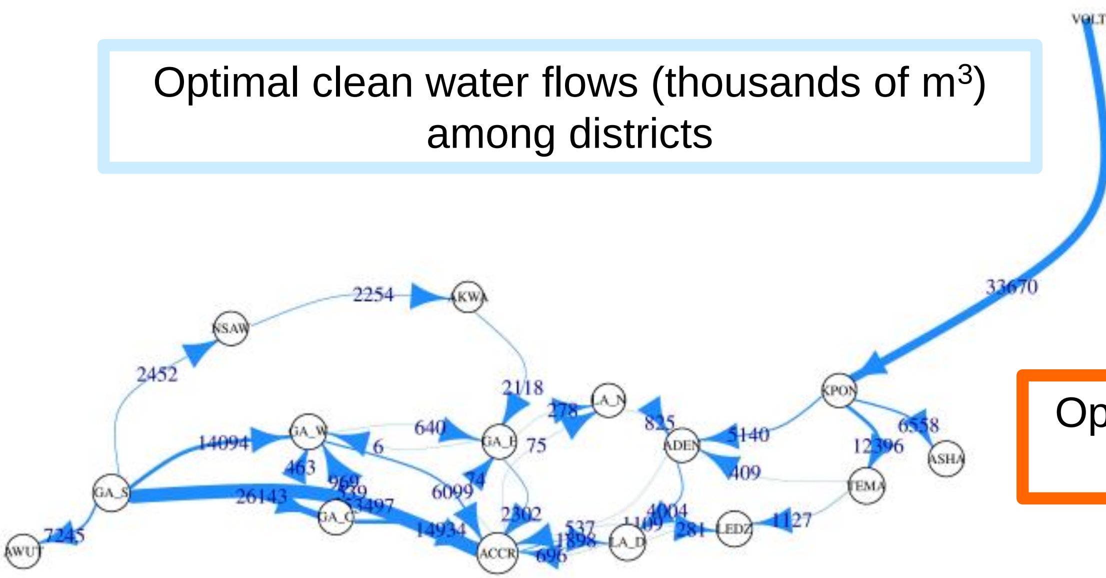



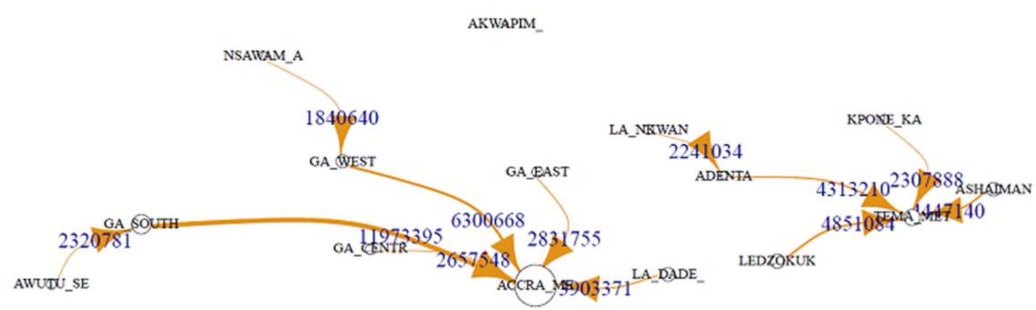
# **Case Study** (investment strategies)

*GAMA WASH SDG* - 100% water supply and wastewater treatment by 2030

Optimal clean water flows (thousands of m$^3$) among districts




Optimal un-treated waste water flows (m$^3$) among districts



# Summary and Discussions

- Agent-based modeling generates water and energy demand profiles from micro-level simulation and updates according to demographics and infrastructure evolution.
- Resource technology network adopts demand data to plan capacity utilization and expansion by supply-side matching on a cost optimal basis.
- Several representative use cases are developed based on Greater Accra Metropolitan Area in Ghana to propose environmental friendly and cost effective sustainable urban development strategies for local stakeholders.

# Next steps and future work

- Multi-sector model
  - water-energy-food nexus integrated modelling
  - entire urban economy
  - climate change scenarios analyses

- Resilience.IO

  Data-driven platform is to be fully built to form a comprehensive ‘system of systems’ approach studying human society inclusive of environmental, social and economic impacts.

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# Thank you! Any questions?

**agent-based modelling and resource network optimisation**

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*Resilience.io platform*

**Workshop on integrated energy system models incorporating spatial and temporal detail**

# Application: WASH in GAMA

Explore per district water and wastewater related outcomes for the Greater Accra Metropolitan Area:

- Socio-economic scenarios
- Electric energy generation
- Electricity transmission and distribution
- Source water treatment
- Potable water distribution
- Water demands and usage
- Toilet use
- Waste water collection
- Waste water treatment