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EXECUTIVE SUMMARY OF THE THESIS

System Dynamics approach in Rural African context: Focus on Water-Energy-Food nexus

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AUTHOR: ANNA VINCIGUERRA

ADVISOR: RICCARDO MEREU

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1. Introduction

The United Nations created the Sustainable Development Goals (SDGs) in 2015 with the efforts to end poverty and promoting prosperity. The SDGs highlight the need for strategies to be put in place to enhance health, education, the disparity gap, and economic growth while taking the impact of humans on the environment into account. All nations are urged by these objectives to work together to address the world's difficulties.

The essential link between energy access and sustainable development is highlighted by Goal 7: "Ensure access to cheap, dependable, sustainable, and modern energy for everyone." Despite efforts being made globally, 1 billion people still do not have access to electricity, according to the present state of the globe. With 600 million people living in sub-Saharan Africa, 57 percent of the population lacks access to electricity, whereas South America and Asia have the largest populations [1]. The relationship between local rural development and the consumption of energy is not clearly understood or captured. The high degree of uncertainty in the dynamics, the nonlinear processes, and the availability of data must be taken into account for the characterization and formulation of the electricity-development nexus. It is obvious that a tool is needed that can handle not only the load's unpredictability but also conditions that are connected to socioeconomic factors as well as environmental factors. Energy modeling research in developing countries is focused on producing an integrated instrument that can deal with high levels of uncertainty, complicated diffusion mechanisms, and a full understanding of relevant causality. The multidimensional approach must consider complementary energy resources like water and food to have a holistic perspective on the issue of rural electrification. In areas affected by drought, the quantity of water increases rapidly, making it a major issue [2]. To ensure everyone's growth, it is crucial to have water available for the creation of food and energy. As the world's population grows, so will the demand for these resources; by 2030, energy consumption will have increased by around 50% [3]. The WEF Nexus FAO method focuses on the linkages between the systems of natural and human resources [4]. The nexus interaction concerns how we utilize and manage our resource systems considering their interdependence, limitations, and potential for mutually reinforcing or beneficial interactions.

To promote sustainability, interagency cooperation, and resource-use efficiency, the ideal nexus approach should include both short- and long-term analysis processes and policy-making that focuses on the connections between water, energy, food, and other related sectors [5]. The major goal of the strategy should be to enhance the sectoral methods and knowledge already in place, therefore minimizing trade-offs and promoting synergies.

1.1 Scope of the work

To get a clear image of the long-term sustainability and the beneficial impact on the rural communities in line with the 2030 Sustainable Development Goals, the work aims to develop a system dynamics model that can undertake ex-ante analysis in electrification projects. A simulation model based on system dynamics has been used to carry out the major objective of this research project. The model now includes a new component that describes the water supply system and how it affects the local environment. The chance provided by the university of Aachen has enabled the conclusion of this final section. The innovation resulted from the need to develop a more thorough planning process that also took the water, food, and energy nexus into account.

2. Literary review

The complex relationship between the variables that influence and decide rural energy planning has garnered a lot of attention in the literature. Hartvigsson notes the dearth of pertinent future development research in this area. In his opinion, the energy solution optimization method ignores driving dynamics feedback, which is crucial for long-term sustainability [6]. According to the strategy used to anticipate energy demand, Riva (2018) categorizes the strengths and weaknesses of several long-term rural energy planning strategies. Fixed demand, arbitrary trends, extrapolation, system dynamics, and input/output are the methods that have been identified [7]. He asserts that only system dynamics and agent-based models take the fluctuation in demand throughout the time horizon into account. The literature has acknowledged system dynamics as one of the best methods for capturing the effects of electricity on manner of life. In the beginning, it aids in developing a tool to map complex dynamics brought on by having access to energy. For instance, how the environment is affected, how much energy is used, how much money is made, and how the combined socio-economic factors affect how much power is needed. The ability to run long-term dynamics and return a reasonable future prediction is the second justification [8]. Other aspects emerged since the UN announced the SDGs in 2015, their integration has necessitated the use of a combinatorial model to perform simulations that can gauge sustainable advancement. Goals and the effectiveness of the activity taken to achieve them are related, according to Collste et al. (2017) [9].

The Integrated Sustainable Development Goals (iSDGs), a model to assist policy makers and key stakeholders in understanding the impact and response of policy measures to reach SGDs target, were created by The Millennium Institute in 2016 using system dynamics for the first time [10]. The theory that SD's characteristics operate smoothly while dealing with complicated linkages, delays between positive and negative feedbacks, and nonlinear connections is confirmed by the use of System Dynamic method in iSDGs national planning. It is evident that the multidisciplinary approach to achieving sustainable development requires a tool to identify the causal link between objectives and policies. According to the literature, the System Dynamics model is a reliable tool for locating these synergies. Surprisingly, the SD technique is most helpful in understanding policy impacts when a version of it introduces a series of modifications to the cause-and-effect loops, perturbing the model's structure and behavior [11].

2.1 Water-Energy-Food

Recent research has identified the connection between water, energy, and food as one of the main elements needed to achieve sustainable development [12], [13] .The World Economic Forum (2011) [14], which recognized the energy, food, and water management as a global concern brought on by the expanding world population and the complexity of contemporary civilization, was the first to recognize the nexus theoretical concept. While the real tendency is to combine environmental, economic, political, and social elements [15], much research first concentrated on defining the physical links between the three resources. The idea of the "water, energy, and food nexus" has grown more intricate, integrating several drivers and aspects. To handle WEF interaction, analytical instrument creation and utilization were necessary. Agent-based models, systems of systems models, and system dynamics models are the three primary types of approaches that have been utilized to represent the linkages of the integrated WEF system. System dynamics represent the idea based on flows and feedback loops, into a time evolution viewpoint, and reflect the actuality of the nexus [16]. The system dynamics is acknowledged for the design and process of WEF nexus even though all three of the tools proposed can model integrated systems across multiple dimensions [17]. This is because it can display long-term characteristics and has an elastic response to changes. Therefore, simulation models are the focus of this study's examination.

3. Materials and methods

3.1 System Dynamics approach

By simulating complex systems to the necessary degree of detail, system dynamics modeling is used to analyze complex systems. It may also be used as a tool to help policymakers and to comprehend the possible effects of policy implementation. SDMs are made up of convertors, flows, and stocks that store and transport material, respectively (which alter the flow rates). Connectors between these items communicate information inside the model, creating feedback loops and complexity [18]. Common model behavior types include exponential growth (positive feedback), goal-seeking (negative feedback), and oscillation (dynamic equilibrium). To ensure modeling tractability, the system boundary must be defined. The SDM was implemented using the SDM modeling program STELLA Professional.

3.2 Model adoption and replicability assessment

The main issue to be solved, beginning with the description of the problem, is the model's ability to be duplicated in many situations, making the application as general as possible. The original model developed by Politecnico di Milano, validated for the Ikondo village, in Njombe region of Tanzania, that served as the basis for this thesis is first examined to finish this phase [19]. The extreme condition and the boundary adequacy test led to the necessity to reinterpret some dynamics. New subsystems have been added to the description of the water-energy-food nexus to investigate the impact of the other two agents, food, and water, made available by the electrification effort. A new problem articulation that now focuses on the important feedback connections between the three dimensions of the nexus was developed because of the findings of this initial research. Every time a new factor must be considered, the iteration process continues and returns to the issue formulation. The testing step is continued throughout the iterative process. At each level of the procedure, numerous tests will really be run, and based on the results, it will either go on to the next phase or occur at a different stage.

3.2 Classification of the input parameter

As the part of the main purpose of replicability and creation of clear guideline for the model application in different context, different parameter classification of the input data is necessary to correctly define their value in application of diverse electrification project. To use the simplified model in other different context and countries some of the total input data need to be initiate. They have been classified in four different categories to know how to approach it:

I. Fixed parameters
II. Context dependent parameters
III. Free parameters
IV. Scenario settings parameters

The fixed parameters define which input data would be left fixed even if the context of application of the model is different while the context dependent parameters change every time the model is used in a different location. In case of free parameters, the choice is left to the modeler depending in the type of simulation that he wants to run. For the policy evaluation, new scenarios are generated by changing scenario setting parameters.

4. Case study

The village of Rutana serves as the thesis' intended backdrop. With the method employed in this study, the model can simulate the ex-ante dynamics related to the availability of water and energy in a rural community. To do this, the data categorization covered in chapter 4 describes the kinds of inputs that must be provided in order to represent a certain context.
The crucial endogenous dynamics must then be determined for the case study after the model's pertinent variables have been identified. In this way, actual findings about the influence of the policy's execution are tested, showing the positive effects on the village's socioeconomic dimension. Different sources provided the information that was needed to define the context. In Rutana, a field study has been set up to examine the model behavior through household interviews and additional data come from literature.

5. Results and simulations

The reshaping of the dynamics and sub-systems have been performed to allow the introduction of the water-food-energy nexus.

5.1 Formulation of the system dynamics model

Household's definition

However, it's crucial to introduce the model's primary actors first: the households. The distinction between High-Income Households, which run both productive and farming activity, and Low-Income Households, who rely solely on agricultural earnings, was used to describe the household in the first example of the model conceptualization (Riva, 2019). Even though this classification produces an accurate reflection of reality, the lack of data makes it challenging to diversify the input data required for the identification of the two income levels. The choice to represent each home as a single unit result in the loss of some interesting difference, but this simplification also makes it simpler to gather data and apply the model. By comparing the two models, the original one by Riva (2019) and the new one, using the Average Income as a control variable, both test's findings reveal a similar behavior. The Structure assessment test resulted on favorable feedback on the new household's definition.

Water supply and utilization sub-system

Water supply, water demand, and energy are the three basic subsystems that make up the model framework for the dynamic of water supply and demand. The three components of the water-energy-food (WEF) nexus should be simulated together since there is interest in the idea that these sectors are closely linked and function as a single complex system [20]. While energy is required to pump, purify, and distribute water as well as to treat wastewater, water is also required to irrigate crops. The population growth factor is what drives local water demand. The demand is determined by the amount of water consumed per person in each Dt of time. Literature has divided the demand into two categories: residential water use and agricultural water use. Because the model represents a small village in remote regions, the third sector—the industrial one—that is frequently cited in papers—won't be considered in this situation. The potential domestic demand is calculated in each time steps as follows:

$$Potential\ domestic\ demand(t) = Initial\ domestic\ demand \cdot Water\ availability\ effect(t) \cdot Income\ effect(t)$$

There are reasons to expect that economic growth will result in greater water use since richer people consume more products and services. The income influence on the water demand positively [21].

$$Income\ effect(t) = \left(\frac{Income(t)}{Initial\ income}\right)^{\varepsilon - income}$$

$$Water\ availability\ effect(t) = \left(\frac{Rel(t)}{Rel_0}\right)^{\gamma - rel}$$

The Income effect is a time-varying inputs where e-Income expresses the output proportionality in relation to a change in the input. Like the income effect, the reliability ones consider the g-rel elasticity which suggest the proportionality between the increase in the improving of the system and the water demand for domestic purpose. The time-varying variable Reliability(t) is computed as a delayed function which returns a delay for the output after a variation of the input. The water demand for agricultural use is strictly related to the food poverty definition. Although the fundamental reasons of poverty differ by farming system, water shortages and competitiveness in many countries represent a threat to future progress in poverty reduction. In fact, most places of prolonged poverty are characterized by a scarcity of water. However, in both absolute and relative terms, many irrigated

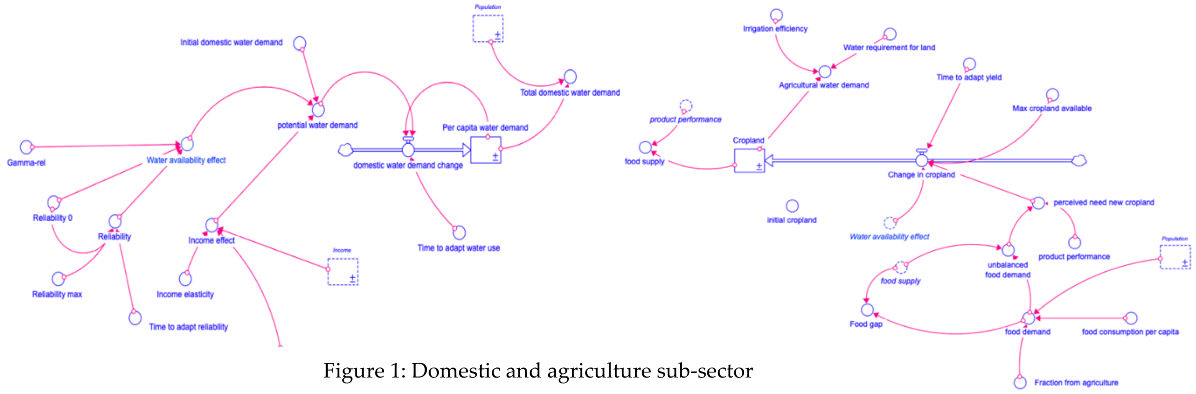

Figure 1: Domestic and agriculture sub-sector

areas with large-scale continue to be home to significant numbers of poor people. This is due to injustice in access to land and water resources, as well as low productivity as a result [22]. Starting with the notion of Unbalanced food demand, the entire demand for agricultural water is calculated. The water required arises from an unbalanced food demand, which is turned into a perceived requirement for more cropland because of fluctuating yield sizes to meet the food need. Water's importance in establishing food and nutrition security to promote human nutrition and health cannot be overstated. Water is critical to food and nutrition security because of its connections to all areas of economic food access.

$$Change\ in\ cropland(t) = \frac{Perceived\ new\ cropland(t)}{Time\ to\ adapt\ yield} \cdot Water\ availability\ effect(t)$$

$$Perceived\ new\ cropland(t) = Unbalanced\ food\ demand(t) \cdot Product\ performace$$

Finally, the overall agricultural water requirement is calculated as follows:

$$Agriculture\ water\ demand(t) = Water\ requirement\ fro\ land \cdot \frac{Cropland(t)}{Irrigation\ efficiency}$$

Where the weekly water requirement for a unit of land extension is represented by the water requirement for land. The component water supply are desalinated water, groundwater, and surface water. The systems dynamic model models current and future water supply by considering factors including population increase, agricultural and domestic water demand, and the portfolio mix of surface water-dependent dams, groundwater, and rain-independent desalinated water supply. Desalination plants are rain-independent supply sources that could help ease water scarcity and ensure a more stable supply. Starting with a small desalination capacity, the infrastructure will grow in size over time to meet the rising household demand for fresh water, assuming that the desalination water supply can meet the domestic demand. The amount of surface water accessible is computed taking into account the competition between surface water and hydropower generation. Understanding the value of water in its alternative uses is critical for fostering informed debate on water management and allocation, identifying the basis for making 'agreeable' trade-offs, identifying the potential for improvement, and establishing links with water allocation options, particularly in agricultural-based economies, where agriculture competes with other sectors and where water re-allocation decisions may involve large transfers of water from the sector generating the highest water demand such as hydropower generation [23]. Because groundwater requires higher energy input for extraction, the dynamics of groundwater have been modeled in a supplementary fashion to those of surface water.

Electricity sub-system

Hydropower, diesel generators, and solar power plants are all examined in terms of energy supply. The electrical consumption of irrigation networks drives the agriculture sector's electricity needs, the volume of residential water consumed is also taken into account when calculating electricity demand. Pumping for groundwater abstraction and the desalination process are two sources of electricity consumption on the supply side of the water infrastructure. The sum of the direct and indirect embodied energy necessary to generate a specific unit volume of water is stated as the energy consumed for water abstraction, treatment, and distribution in pressurized water distribution systems. The pipe features, the treatment technique, the quality of raw water, and the distance from the source are the key factors of direct energy in surface water delivery alternatives. Estimates of total direct and indirect energy consumption for various water treatment procedures are given in terms of the amount of energy required (kWh) to generate one unit volume (1 m3) [24]. The evaluation of the power required for each equipment is calculated as follows:

$$Electricity\ demand\left[\frac{kWh}{week}\right] = water\ pumping\ efficiency[-] \cdot Energy\ intensity\left[\frac{kWh}{m^3}\right] \cdot water\ flow\left[\frac{m^3}{week}\right]$$

Figure 3: energy demand

5.2 Model testing and validation

One of the most important steps of model development is to check its robustness. To do that, SD theory suggests twelve validation tests 18]. For this work were performed only the validation tests compatible with the peculiarities of the model that was developed. Some of the tests, such as the *Boundary adequacy test*, *Structure assessment test* and the *Parameter assessment*, were completed during the modelling phase to evaluate the appropriateness of model boundary, of physical laws and aggregation level, and to attribute to variables a real-life meaning. Additionally, the *Dimensional consistency test*, used to specify the unit of measure of each parameter, is proven through an automated dimensional analysis performed by Stella software. Two important checks that verify the stability of the model are the *Extreme condition test* and the *Behavior anomaly test*. The latter is done to assess the significance or strength of crucial formulation. For example, maximizing the initial population implies the increasing the village size, as shown in Figure 3 , it has the same effect on the trend in home connection thus confirming that the model is capable of simulating the behavior of different local context.

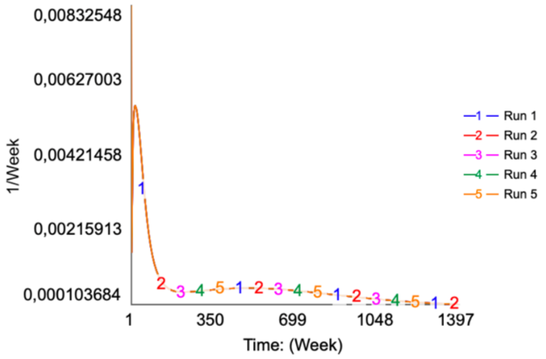

Figure 2: Trend in HHs connection for the different villages size

The *extreme condition test* is carried out to determine whether the behavior of the model is realistic even when excessive inputs are used. For example, The model was stressed to the lowest/highest achievable value of the *fraction of feasible HHs market supply.* The minimum shows extremely few IGAs are formed, only enough to meet the demand from

Figure 4:Extreme condition on fraction of feasible HHs market supply

outside sources and the supply chain of other IGAs. The response of the maximum simulation displays a higher number of IGAs formation, due to a higher market demand but also a higher market competition. These findings show that establishing access to electricity is particularly suited for a local context that has the resources to possibly meet all local market demand. Lastly, *integration error test* is performed to test the choice of the time step (DT) for model simulation: changing DT or the integration method should not influence in a significant way the behavior nor the results. The first tentative time step was chosen to be one-fourth (viz. 0.25), the size of the model's lowest time constant (viz. 1 week), in accordance with Starman's rule of thumb (Sterman 2000). The aim of the second part of this validation test is to determine whether the behavior persists even when the integration technique is changed. At the conclusion of the simulations, the values of the same four variables of the previous test were examined. Table 1 demonstrates that the model has acceptable error margins of approximately 5% and is not overly sensitive to changes in the integration approach.

Variable	ξ_Δt	ξ_RK4
Total connected HHs	0,03%	0,14%
Cumulated community electricity demand	2,33%	2,8%
Domestic Gap	0,33%	0,1%
Total water demand	0,53%	1,4%

Table 1: dt error term

5.3 Main results

Different policy scenarios were constructed and simulated over a 20-year period to assess the performance of an electricity project and its consequences for managing water supply for the household and agricultural sectors in the case study. Over the course of the simulation, the baseline run, or the *Energy scenario*, was first executed. Domestic water is a representation of what is accessible due to the electrical connection in Scenario 1: *Domestic Water*. Scenario 2, *Cropland expansion*, simulates the impact of farmland increase caused by an irrigation network powered by electricity within the settlements. This scenario also considers the requirement that a growth in acreage must be matched by an improvement in the efficacy of the water delivery network to solve the issue of water losses caused by inefficient infrastructure.

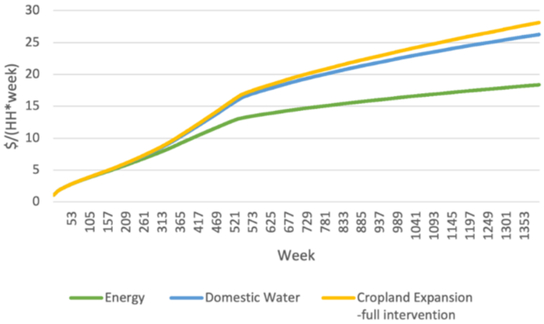

Figure 5:Policy testing on income

The Income variable clearly states how the project's electrification impacts the attainment of social and economic development as well as the availability of power in the region. These findings suggest that raising income may enhance human wellbeing, while increasing access to clean, potable water and installing irrigation systems may substantially boost already rising income. Health care expenditures will decrease as water availability rises, and agricultural productivity will increase farm income.

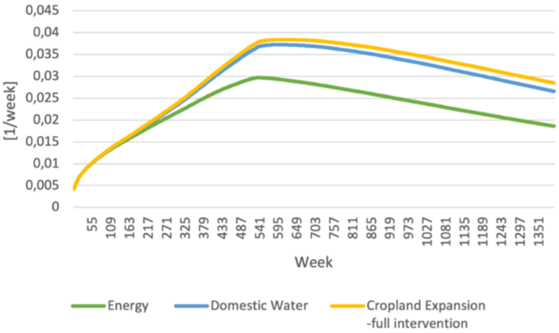

Figure 6: Policy testing on affordable connection

The affordable connection variable, which is a good indicator of the electrification project's performance, assesses the success of the electrification rate in the rural region. This study has considered the previous analysis' findings about the impact of policy implementation on income. The percentage of households that can pay the connection cost will increase as income does. The trend reversal, which roughly coincides with the middle of the time span, is brought on by the connection rate slowing down when innovation is introduced.

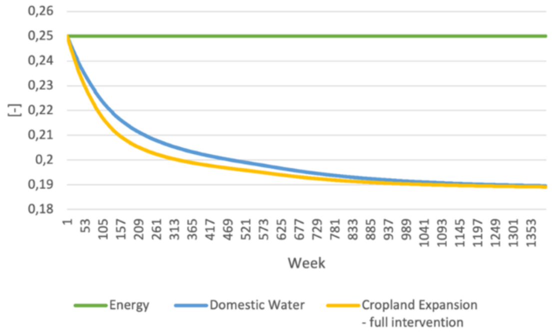

Figure 7:Policy testing on fractional income for medical expenditure

Improved health decreases the possibility of illness and lowers the expense of medical treatment, benefiting household finances. The development of better water infrastructure appears to be linked to a decline in illnesses in communities. In the Energy Scenario, it is expected that the portion of revenue designated for medical costs won't change during the course of the simulation. This is explained by the fact that no intervention for problems connected to health status is thought to exist in the base scenario. Both the domestic water scenario and the crop expansion scenario have the same long-term results, but the final one, after the transitory, reaches the regime value quicker.

5.4 Sensitivity Analysis

Sensitivity analysis is an essential method for evaluating how well the model's outputs withstand changes in the input parameters within their permitted range of variation. The System Dynamic theory states that factors that are both highly unknown and likely to have an impact must undergo sensitivity analysis. Through scientific articles and online research, the probable variance ranges are identified. Table 2 lists the ranges of the values. The least and most favorable policy result, is then determined by doing sensitivity analysis on each parameter.Be aware that not all parameter range extremes correspond to the parameters' worst and optimal values. The results are the following.

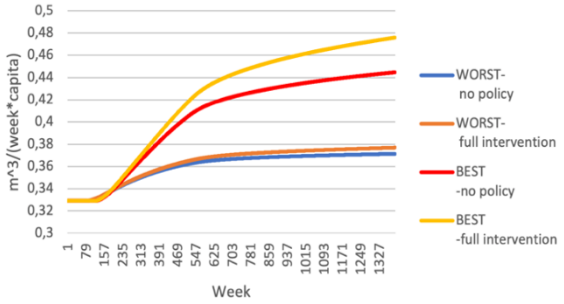

Figure 8:Per capita water demand

As seen in the figures, the home water consumption is much lower in the worst-case scenarios than in the best-case scenario. Poor service quality is to blame for this; in actuality, the worst-case scenario only results in a 1% increase in water demand over the case where no policy is implemented, while the best-case scenario sees a 7% rise in per capita water demand as a result of the policy's implementation. Additionally, the long-term trend is the same since the main variable affecting per capita water consumption is population growth, which is consistent across all scenarios.

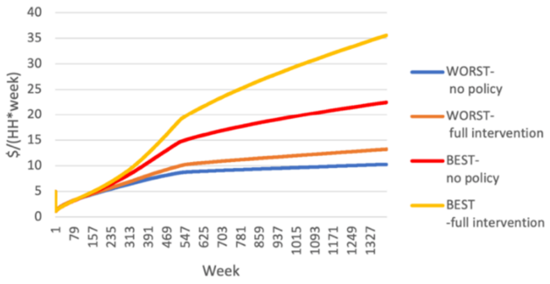

Figure 9:Fraction of connected HHs

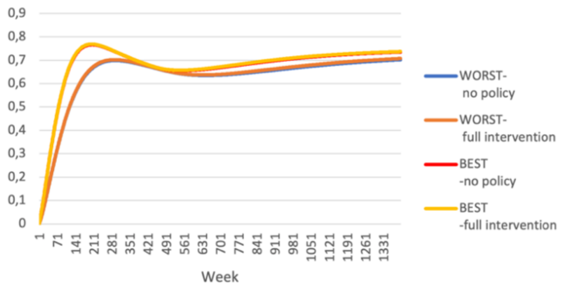

Figure 10:Income

Table 2

Variable	MIN	MAX	UDM	SOURCE
Irrigation efficiency	34%	42%	-	[25]
Income elasticity	0,06	0,15	-	[26]
Product performance	1,196	1,450	$^{kg}/_{m^2}$	[27]
Water requirement for land	0,0768	0,1152	$^{m^3}/_{(week \cdot m^2)}$	[27]
Efficiency of delivery networks	85%	65%	-	[28]
Willingness to pay	0,112	0,2	-	[29]
El Reliability	0,9583	0,9995	-	[19]
Fr change in external market demand	0,4484	0,4956	-	[19]
Reference Factor productivity	0,3534	0,3906	-	[19]
Fr of feasible HHs market supply	0,6	0,9	-	[19]

The fact that the difference in connections is only apparent between the two best and two worst scenarios informs us that the implications of water policy do not have an effect on the pace at which homes connect to the electrical grid.The disparities in income levels are most obvious under the worst conditions. This is so because having access to water increases agricultural productivity and decreases healthcare expenses, both of which lead to an increase in revenue.

6. Conclusions

The main objective of this research project was accomplished using a system dynamics-based simulation model developed for long-term electricity demand estimations in rural environments. The complexity of the case specific, significant, and parameterized model structure was particularly addressed via a simplification strategy in order to provide a simpler and more adaptable model for application in other cases. By comparing the reduced model to three distinct types of validation—direct structure tests, structure-oriented tests, and behavior pattern tests—the model's structure and behavior have been verified. It is now possible to employ a policy testing approach where many scenarios are considered to determine how the effect of complex electrification initiatives may increase their efficacy and success in rural situations. The model's usability and flexibility are improved by the removal of several dynamics and feedback loops from the model structure. The System-Dynamic model for long-term power demand forecasts and its effects on the water energy food nexus are also made possible by this. The validation enables for verifying the model structure's capacity to recreate the behavior in a different context and contributes to increasing confidence in the reduced model framework. The results of the policy testing show that promoting self-sustaining socioeconomic growth requires electrification and the development of a water supply distribution network tailored to local needs. Another important finding is that having access to clean water is important for both economic and social reasons because it raises income, which in turn speeds up electrification and its positive effects. Both the effect of model simulation on the goal of the SDGs and the quantitative data gleaned from the simulation have been established. The capacity to access energy is essential for attaining SDG 7. The project's ability to create jobs, which would boost the local economy, raises the possibility of links between poverty and economic objectives. In order to maximize the electrification project's beneficial effects on rural communities, policy testing allowed for the establishment of best practices, minimal requirements, and supporting activities. This suggests that in order to ensure the long- term viability of electricity access initiatives, future electrification programs might build on these results to determine the most important issues to address.

7. Bibliography

References

[1] IEA, "Energy Access Database," [Online]. Available: www.iea.org/energyaccess/database. [Accessed May 2022].

[2] M. C. R. P. G. G. Heather Cooley, "Water risk hotspots for agriculture," OECD.

[3] IEA, "World energy outlook," IEA, 2010.

[4] FAO, "The future of food and agriculture Trends and challenges," FAO, Rome, 2014.

[5] M. G. J. K. M. P. M. R.∵∵ T. a. V. O. Keskinen, "The water-energy-food nexus and the trans-boundary context: insights from large asian rivers," 2016.

[6] S. M. a. C. G. Hartvigsson Elias, "Rural electrification and capacity expansion with an integrated modeling approach," 2018.

[7] A. T. G. C. Fabio Riva, "Long-term energy planning and demand forecast in remote areas of developing countries: Classification of case studies and insights from a modelling perspective," 2018.

[8] E. C. Fabio Riva, "System-dynamics modelling of the electricity-development nexus in rural electrification based on a Tanzanian case study," 2020.

[9] D. P. M. &. C. S. Collste, "Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies," 2017.

[10] M. Institute, "iSDG integrated simulation," [Online]. Available: https://www.millennium-institute.org/isdg.

[11] N. O. L. Pretorius, "Analysis of policy options for projects in the electricity sector in sub-Saharan Africa : a system dynamics approach," 2017.

[12] J. W. L. P. Alex Smajgla, "The water–food–energy Nexus – Realising a new paradigm," 2016.

[13] E. B. B. H. ,. P. M. A. N. V. O. C. H. D. I. Eloise M.Biggs, "Sustainable development and the water–energy–food nexus: A perspective on livelihoods," 2015.

[14] D. Waughray, " Water security : the water-food-energy-climate nexus; the world economic forum water initiative," 2011.

[15] S. K. d. V. Maryam Ghodsvali, "Review of transdisciplinary approaches to food-water-energy nexus: A guide towards sustainable development," 2019.

[16] P. L. L. Z. L. X. Maoyuan Feng, "Modeling the nexus across water supply, power generation and environment systems using the system dynamics approach: Hehuang Region, China," 2016.

[17] C. Robinson, Dynamical System. Stability, Symbolic Dynamics, and Chaos, CRC Press, 1999.

[18] J. D. Sterman, Business dynamics : systems thinking and modeling for a complex world, 2000.

[19] F. Riva, "MODELLING ENDOGENOUS COMPLEXITIES IN RURAL ELECTRIFICATION: ON THE LOCAL DYNAMICS OF GROWTH AND THE PLANNING OF OFF-GRID SYSTEMS," Politecnico di Milano, 2019.

[20] T. R. A. o. Engineering, Global Water Security – an engineering perspective, London: The Royal Academy of Engineering, 2010.

[21] T. Kurz, The Psychology of Enviromentally Sustainable Behavior: Fitting together pieces of the puzzle.

[22] R. E. &. H. M. A. &. C. G. E. &. R. H. M. &. S. L. &. V. K. B. Namara, Agricultural water management and poverty linkages, 2010.

[23] S. Morardet, "Water for irrigation or hydropower generation?—Complex questions regarding water allocation in Tanzania," Agricultural Water Management,, 2008.

[24] N. K. a. N. K. Pauline Macharia, "Applying the Water-Energy Nexus for WaterSupply—A Diagnostic Review on Energy Use forWater Provision in Africa," 2020.

[25] S. E. ,. A. M. ,. J. A.-K. ,. A. M. B. ,. K. M. Alireza Gohari, "Water transfer as a solution to water shortage: A fix that can Backfire," 2013.

[26] W. Bank, "The demand for water in rural areas: determinants and policy implications," World Bank. Water Demand Research Team, 1993.

[27] S. H. M. J. ⇑. ,. H. E. Mohammad Javad Keyhanpour, "System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach," 2020.

[28] H. I. Mohamed, "EGYPT'S WATER RESOURCES MANAGEMENT UNDER PRESSURE OF DEVELOPMENT," 2000.

[29] van Gevelt, T.; Canales Holzeis, C.; Jones, B.; Safdar, M.T, " Journal Article Insights from an energy poor Rwandan village," 2016.

[30] "https://support.microsoft.com/en-us/word," [Online].

[31] D. Alighieri, Comedia, Firenze: Goose Feather Press, 1321.

[32] J. Watson, F. Cric, "Molecular structure of nucleic acids: a structure for deoxyrobose nucleic acid," *Nature,* vol. 171, p. 737–738, 1953.

[33] Prometeus, "Fire". Olympus Patent 1, 300.000 BC.

[34] S. H. M. J. ,. H. E. Mohammad Javad Keyhanpour, " System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach," *Ain Shams Engineering Journal,* 2020.

[35] S. H. M. J. ⇑. H. H. D. Mehdi Rahmani, "SD-DSS model of sustainable groundwater resources management using the water-food-energy security Nexus in Alborz Province," *Ain Shams Engineering Journal,* 2022.

[36] H. I. Mohamed, "EGYPT'S WATER RESOURCES MANAGEMENT UNDER PRESSURE OF DEVELOPMENT".

[37] T. van Gevelt, C. Canales Holzeis, B. Jones and M. Safdar, " Journal Article Insights from an energy poor Rwandan village," 2016.

[38] S. E. ,. A. M. ,. J. A.-K. ,. A. M. B. ,. K. M. Alireza Gohari, "Water transfer as a solution to water shortage: A fix that can Backfire," 2013.

[39] W. D. R. Team, "The demand for water in rural areas: determinants and policy implications," World Bank, 1993.

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E DELL'INFORMAZIONE

System Dynamics approach in Rural African context: Focus on Water-Energy-Food nexus

TESI DI LAUREA MAGISTRALE IN
ENERGY ENGINEERING
INGEGNERIA ENERGETICA

Author: **Anna Vinciguerra**

Student ID: 953565
Advisor: Riccardo Mereu
Co-advisor: Francesco Tonini
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Abstract

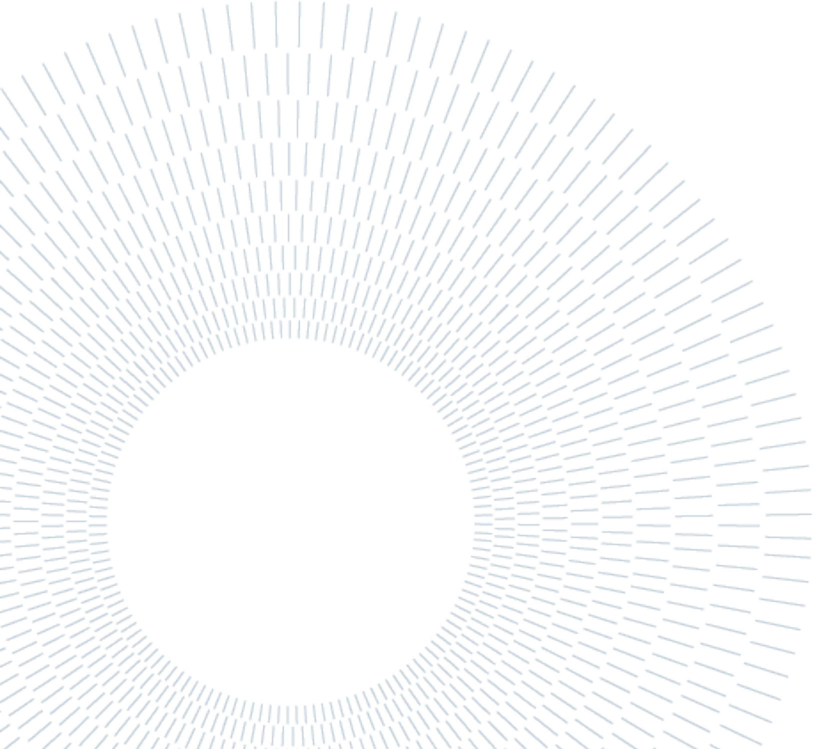
According to the United Nations' Agenda 2030, which was unveiled in 2015, ensuring that everyone has access to affordable, dependable, sustainable, and contemporary energy is now acknowledged as a crucial objective to achieve by 2030. Focusing on electrification, it is projected that 2.6 billion people would need to be electrified by 2030 to provide universal access to power, underscoring the necessity and urgency of developing adequate and sustainable methods to electricity planning. As a result, the methodologies, approaches, and models discussed in this thesis are intended to suggest a universal, flexible, and adaptable energy demand model for usage at the community level, such as in villages and rural regions. System Dynamics has been chosen as a particularly suitable approach for reproducing the endogenous dynamics concerning the Water-Energy-Food nexus, well represented in an existing model. But due to its intrinsic complexity, this model must be simplified in order to be more user-friendly for those involved in energy projects and more adaptable for usage in a variety of situations. As a result, after being simplified, it was able to validate tests to see if they could be repeated. In order to ensure that rural electrification projects offer both access to energy and sustainable development, the impacts of policy will be evaluated in the final stage. Therefore, once the simplification and the adaptation of model structure, another section has been added. The model now includes a new component that describes the water supply system and how it affects the local environment. The innovation resulted from the need to develop a more thorough planning process that also took the water, food, and energy nexus into account.

Key-words: sustainability, access to electricity, System Dynamics, water-energy-food nexus, validation, policy testing

Abstract in italiano

Secondo l'Agenda 2030 delle Nazioni Unite, presentata nel 2015, garantire che tutti abbiano accesso a un'energia economica, affidabile, sostenibile e moderna è ora riconosciuto come un obiettivo cruciale da raggiungere entro il 2030. Concentrandosi sull'elettrificazione, si prevede che 2,6 miliardi di persone dovrebbero essere elettrificate entro il 2030 per fornire un accesso universale all'energia, sottolineando la necessità e l'urgenza di sviluppare metodi adeguati e sostenibili per la pianificazione dell'elettricità. Di conseguenza, le metodologie, gli approcci e i modelli discussi in questa tesi intendono suggerire un modello di domanda di energia universale, flessibile e adattabile per l'utilizzo a livello di comunità, come nei villaggi e nelle regioni rurali. System Dynamics è stato scelto come approccio particolarmente adatto per riprodurre la dinamica endogena relativa al nesso Acqua-Energia-Cibo, ben rappresentata in un modello esistente. Ma a causa della sua complessità intrinseca, questo modello deve essere semplificato per essere utilizzato più facilmente per coloro che sono coinvolti in progetti energetici e più adattabile per l'uso in una varietà di contesti. Di conseguenza, dopo essere stato semplificato, sono stati condotti dei test di validazione per provarne la replicabilità. Per garantire che i progetti di elettrificazione rurale offrano sia l'accesso all'energia che lo sviluppo sostenibile, gli impatti delle politiche saranno valutati nella fase finale. Pertanto, una volta effettuata la semplificazione e l'adeguamento della struttura del modello, è stata aggiunta un'altra sezione. Il modello include ora un nuovo componente che descrive il sistema di approvvigionamento idrico e come influisce sull'ambiente locale. L'innovazione è nata dalla necessità di sviluppare un processo di pianificazione più approfondito e integrato che tenesse conto anche del nesso tra acqua, cibo ed energia.

Parole chiave: sostenibilità, accesso all’elettricità, System Dynamics, water-energy-food nexus, validazione, policy testing



Contents

1 Introduction and Motivation

1.1. Universal Energy Access

In 2015 The U.N. designed SDGs to end poverty, promote prosperity, highlighting the needs to set up strategies to improve health, education, disparity gap, economic growth, all in consideration of human footprint on planet. These goals are a call for all countries, stated to face global challenges through cooperation acts.

With the Goal 7 – ensure access to affordable, reliable, sustainable, and modern energy for all- the world's government recognize the pivotal role of energy for the key challenges that our society is dealing with. Within the targets defined, it come out the strong connection between energy access and sustainable development. By 2030, U.N. have set the goal to ensure universal access to clean fuels and modern energy services. Looking at global current situation, despite the efforts being made worldwide, 1 billion people still live without access to electricity. In sub-Saharan Africa 57% of population lack access to electricity, which accounts for 600 million people, meanwhile the remining part is in Asia and South America. [1]

Lack of energy, and particularly of electricity most affects rural areas of developing countries. In this region the electrification challenge is attributable to several barriers as for example: weak institutions, donor dependency, lack of private sector involvement, low household affordability, absence of local engagement, scarcity of skilled personnel, cultural mindset, limited rural infrastructure, long-distance transmission etc. [2]

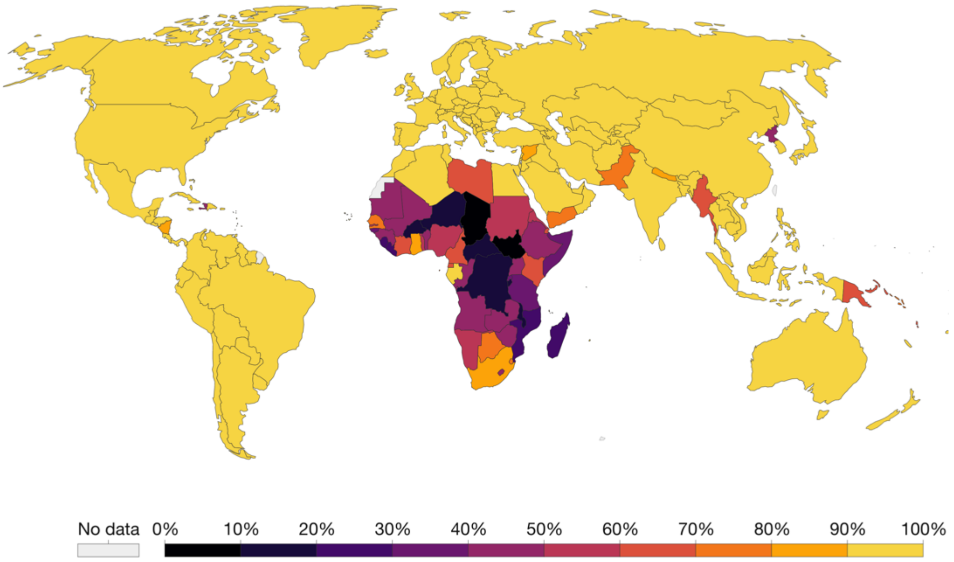


Figure 1: Electricity access, 2019, World Bank

1.2. Socio-economic complexities

The relation between electricity uses and development in local rural context are not fully captured and defined. In fact, the complexity of the problem came from the issue that in electrification project simple and deterministic relation between energy and social development can't describe the reality.

The critical part of the energy planning is the right assessment of long-term energy demand and its dependence with local socio-economic dynamics. Inappropriate long-term prediction impacts negatively on household's life causing an insufficient or over-sized energy infrastructure which in most of the case leads to the failure in objective achievement. This is due to the lack of considering complexity among endogenous and exogenous dynamics and how they affect each other, causing ineffective policies and wrong prediction.

For the characterization and the formulation of the electricity-development nexus it must be considered the high uncertain of the dynamics, the nonlinear phenomena, and the availability of data.

It's clear that there is the necessity of an instrument capable to manage not only the uncertainty of the load which depend also on condition not only related to the environment, but also on socio economic determinants such as social networks, willingness, and technology perception. Being able to design an appropriate modeling framework for catch the dynamics behind this complex nexus can result in reliable energy forecast and appropriate planning strategies.In the field of energy modelling in developing countries the efforts are research-oriented to a comprehensive and integrated tool able to handle with high uncertainty, complex diffusion mechanism and a holistic understanding relevant causality.

The synergies should be searched among fundamental drivers, such as, market and prices, industrial leapfrog, agricultural and urbanization innovation, demographic change ,diversification of diet, and more context depended ones like cultural beliefs and behaviors.

1.3. WFE Nexus

With the aim of having an holist compression of the issue of rural electrification the multidimensional approach must also take account of complementary resources for energy such as water and food. The three resources are closely related to each other, and they are fundamental for the sustainable development, because they are the basic requirements for individual survival. The agricultural sector , through which food is produced, is the largest using sector and the major polluter of water, in fact farming account for around 70% of water consumption in the world and a quarter of the global energy. Differently from energy, water is a finite resource on the planet and only the 1% of all available water is secure water. The water security is crucial question and the water supply becomes exponentially in drought-stricken regions [3].Therefore it is vital to make water accessible for the production of food and energy to ensure everyone's development. The demand of such resources will increase with the rise in population, by 2030, global energy consumption will rise by around 50% . With rising agricultural input , both energy and water will grow , increasing energy and water competition within users [4].Everything must be done considering the problem of climate change and environmental protection.

The water food nexus means that there are three sectors – water, energy, and food security- are indissolubly linked and the action on one sector have impact in one or both other [5]. FAO defines food security as the state at which "all people at all times have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active, healthy life' (FAO 1996). The developed concept used to describe and address the complex relation between our natural resources, on which we relay to better understand the interaction between human activities and the natural environment is show in the figure.

The FAO approach is a holistic vision of sustainable development and tries to find the equilibrium between different objective, environment and need of people.

The synergies among endogenous and exogenous factors take place through fundamental drivers , such as, market and prices, industrial leapfrog , agricultural and urbanization innovation, demographic change ,diversification of diet, and more context depended ones like cultural beliefs and behaviors.

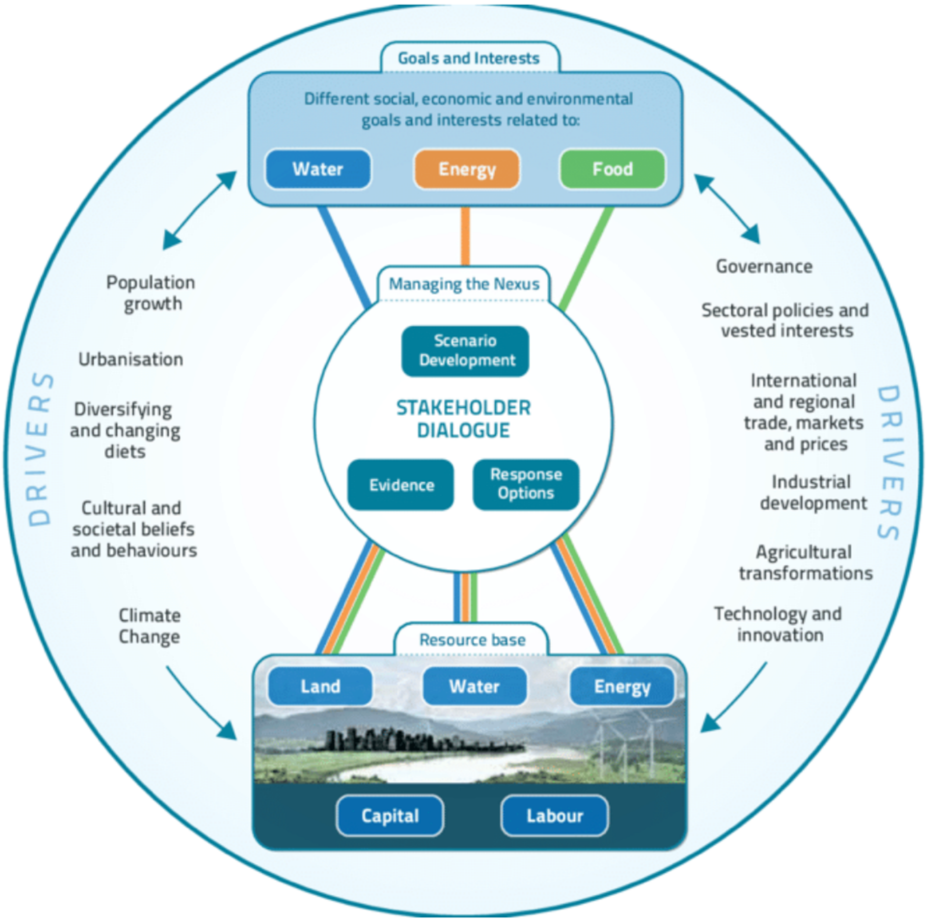


Figure 2: FAO approach to the Nexus

1.4. Aim and motivation of the thesis

1.4.1. Overall Objective

The final aim of the thesis consists of to create a system dynamics model, which is capable to conduct ex-ante analysis in electrification project for having a clear picture of the long-term sustainability and the positive effect on the rural communities in accordance with the 2030 Sustainable Development Goals.

The strategy selection in this field should be accompanied to an integrated approach which studies social dimensions of the problem. Knowledge about the synergies between technical and behavioral components, help to assess the fundamental dynamics, variables and policies that defines the electricity-development nexus and its evolution.

To sum up the work tries to demonstrate that successful electrification project does not only depend on an appropriate technical design tailored on the local context, but the different scenarios are identified on the base of the impact of such multidimensional dynamics that increase the effectiveness of specific actions.

1.4.2. Specific Objectives

The thesis aims to propose a general, adaptable and flexible energy demand model to be used at the community level, such as villages and rural areas. The objective is to help NGOs and/or Organization and Institutions in the field , in analyzing future energy planning finding also insights about synergies between different dimensions that will promote the energy-development nexus .

To carry out the main purpose of this research project, a system Dynamics based simulation model, has been adopted.

On one hand the starting model (Riva er al.,2019) was developed on a direct field research mission, this resulted in the creation of a complex causal model which can describe accurately the dynamics behind the electrification in a rural village, on the other hand this complexity can be a barrier for replicability. For this reason, one of the specific objectives of this study is to develop a more direct and simple use model.

The model replicability is tackled first by analyzing which inputs of the starting model must be defined for running a model in a totally different context. Considering the complexities and the large number of inputs required, the only way is to apply a simplification procedure.

Therefore, once the simplification and the adaptation of model structure, another section has been added. The model has been integrated with a new dimension which describe water supply system and its impact on the local context. The outcome of this last part has been made possible by the opportunity given by Aachen university. The novelty came from the necessity to create a more comprehensive planning procedure also considering the water food energy nexus.

1.4.3. Thesis Outline

After the *Introduction* chapter where it has been possible to have a fast overview of the problem to be addressed in the thesis, the work will be structured as follows:

In the *Material and Methodology* chapter, the approach used during the whole thesis is introduced, supported by a wide literature review. The selection of a specific method has been justified and its application has been described for each step undertaken to achieve the specific and main objectives. A classification of model parameters is used to understand which kind of parameters are needed to apply the model in another context, the categorization follows this structure: fixed, context dependent, free and scenario settings.In the *Results&Discussion* chapter, a quantitative and qualitative section of the model is developed using the system dynamics approach, to describe the dynamics between the nexus and the previously modeled part. The results are shown, and the validation phase is performed to give even more reliability to the model

The conclusion will recap the pillars of the work, adding some insights for possible future development .

2 Literary review

The complex relation between factors which determine and affect energy planning has received considerable attention in literature. In rural electrification most of the studies focus attention on cost recovery, technical optimization and the match between generation and electrical load.

In this context Hartvigsson emphasizes the inadequate number of appropriate future load development studies. According to his view, the optimization process for energy solution does not take into account feedback from driving dynamics, fundamental for long term sustainability [6]. As matter of fact wrong projection is the major cause of project's failure [7]. In accordance with Riva (2018), the long term sustainability of energy projects is achieved only considering uncertainty and the dynamic evolution of electrical demand along time.

Considering all the constrains cited, Hartvigsson (2015) states that small systems of generation , to be successful , need an accurate estimation of the load size and its characteristics , since it cost is highly dependent on the single user [8].

The electric load assessment can be done using two general approaches: top-down and bottom-up modelling. The top-down are implied in large groups prevision, it requires aggregated data sets and use mathematical method to obtain prevision . Its strength is the ability to capture dynamics when local data are not available, and this is a common problem when dealing with rural areas, but they can't capture specific social dynamics that could have strong impact on the final result, for this reason it works for large scale level. On the other hand, the second one starts from single appliances and its operation time, building up a system load for total users, tailored on the local context . The main difficulties are about data collection, it requires a big amount of information regarding human behavior which are not easily available [9].

Deeping the classification, Riva (2018) summarizes strengths and weakness of different long-term rural energy planning, the categorization is made according to the methodology they use to forecast energy demand . The identified approach are : fixed demand, arbitrary trends , extrapolation, system dynamics and input/output [10]. According to him, the only ones that consider the variation of demand over the time horizon are system dynamics and agent-based model. The chosen models are not only able to predict energy dynamics but are also capable to tackle the localcomplexities of rural region, the nexus among socio-economic aspect and energy use.

Riva discusses in [7] a comparative study between system dynamics and agent-based model. The latter consist in modeling social network archetypes in the simulation of diffusion processes which can impact the sizing of the off-grid system. This approach has three main difficulties: huge amount of data for the calibration and for the characterization of each single agent, knowledge of specific social structure and the possibility to extend result to other context.

As an alternative, system dynamics present a suitable technique since it calls for less detailed data and returns a more holist and structural construction for describe the complex network behind energy evolution and exogenous agents.

System dynamics has been recognized by literature as one of the most effective approaches to capture the impact of electrification on way of living. Firstly it give a support in defining a tool to map complex dynamics triggered by access to electricity E.g. environmental impact , energy use, income creation and the aggregated socio-economic indicators and their consequence on electricity demand. The second reason is the capacity to run long-term dynamics giving back a realistic future prevision [11].

Since the launch of SDGs in 2015 by UN, the integrative nature of that goals calls for combinative model to run simulations capable of measure sustainability progress. Collste et al. (2017) try to explain that goals, and the efficacy of the action made to carry out them, are interconnected [12]..

In 2016 The Millennium Institute , for the first time utilize system dynamics to create The Integrated Sustainable Development Goals (iSDGs) [13], a model to help policy makers and relevant stakeholders to understand the effect , cost and response of policy actions to meet SGDs target. The utilization of System Dynamic approach in iSDGs national planning confirms the hypothesis that SD's features run smoothly dealing with complex relations, time lags between positive and negative feedbacks and nonlinear connections. The capability to increase the knowledge about synergies between SDGs and thus deepening the human response to exogenous actions might explore expected outcome of different policy scenario. According to Collste et al. (2017) the use of integrated model must be done considering their limitations. There may be unexpected consequence in studying synergies, that are not in the scope of work boundaries. Holist and multidimensional tool for the sustainable development try to capture the synergies among factor, defined as the combination of different action resulting in outcome which is over the sum of individual effect [14]. These interactions are usually found between technological optimization, economical condition, social status, governmental framework, and natural resources. As reported by Pedercini at el.(2019) there are a series of criteria at which tools should respond in integrated analysis. First, the model should be multisectoral and so policy must be able to touch different areas. Second, each part of the model must have interconnected dynamics and the same endogenous key components, i.e., demographic and resources scheme, to have an adequate shot of policies implication. Third, the instrument used must be as near as possible to the real representation of policy application. Last, the model should ideally cover all the 17 SGDs to not miss dynamics through which synergies may arise.

It's evident how the interdisciplinarity of action made to achieve sustainable development needs tool to capture the causal relationship between policies and goals. The literature finds in System Dynamics model a valid instrument to identify those synergies. Remarkably, SD approach is particularly advantageous to understand policy effect, when a variation of it sets a series of changes in the cause effects loops, perturbating the model framework and its behavior [15].

WEF Nexus

The nexus between water, energy and food has been recognized recently by literature as one of the fundamental key aspect to achieve sustainable development [16], [17]. The nexus theoretical definition was first appreciated by the World Economic Forum (2011) [18], considering the energy, food and water management a challenge facing the world ,created by ballooning global population and the complexity of the modern society. Much studies originally focused the attention on clarifying the physical linkages between the three resources [19] while the actual trend is to incorporate environmental, economic, political and social dimensions [20]. FAO (2014), proposed a nexus approach to nature resources use within the context of social needs and economic development , aim to reducing poverty, sustainable agriculture and ecosystems and food security. Obviously the conceptualization of the water energy food nexus have become more complex, incorporating a multitude of drivers and dimensions . Therefore the need of development and use of analytical tools arose to address WEF interaction.

Three main types of approach have been used for modelling the interconnections of integrated WEF system : agent-based model, system of system model and system dynamics model. Agent based model create a series of agents how behave in different ways to simulate the real world, it requires a specific long term observation. System of system model matches different kind of holist systems, with the aim of optimization the behavior. System dynamics reflect the reality of the nexus , modeling the concept basing on flows and feedback loops , into a time evolution perspective [21]. In spite of the fact that all the three tools proposed are able to modeling integrated system between different dimensions , the system dynamics is recognized for the design and process of WEF nexus thanks to its capability to show long term characteristic and its elastic response to changes [22]. System Dynamics offers the possibility to investigate the behavior of complex relation between different factors , it can thus provide decision-makers with a strong contextual tool [23]. Simulation models have more potential on this front and allow to test the impact of scenarios on the WEF nexus. The analysis of this study, therefore, devotes itself to simulation models.

3 System dynamics

The current research introduces a system dynamics (SD) modeling according to the reasons expressed in the literary review.

Hence, in this chapter the system dynamics approach will be exposed since the knowledge behind the feedback relationship is essential to have a true representation of the complex nexus among the variables.

All the knowledge in this chapter is an extract of the already cited book *Business Dynamics: System Thinking and Modeling for a Complex World* by Jhon D. Sterman [24].

3.1. Fundamental of system dynamics

System dynamics is a method to improve education in complex system . It uses a multidimensional framework because it is focused in the behavior of nonlinear dynamics and feedback control to study human being as well as technical system and their intersection.

The backbone of the model is the use of feedback processes, which , along time delay, stock and flow construction , determine the dynamics of a system. The dynamics derive from the implementation of two type of feedback loops: positive and negative. The positive loops amplify what is happening in the system , they represent a self-reinforcing process and the own growth of the system. Negative loops counteract and oppose change, but it doesn't mean a criticism, in fact they are self-correction feedback. A simple example, eggs and chickens, clarifies the theory.

In the case of positive feedback , more chicken lay more eggs, which give rise in chicken population and so more and more eggs. The arrow indicate the casual relationship , the sign positive means that the effect is positive related to the cause: an increase in chicken population cause an a rise every day in number of eggs laid. Being a self-reinforcing loop it can be denoted with R . If in the entire dynamics this is the only loop Egg and Chicken will grow forever exponentially.

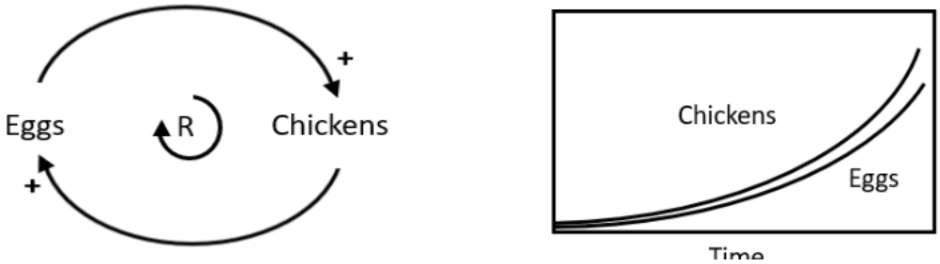


Figure 3: positive loop and its dynamics

Of, course , in reality this phenomenon can't grow forever. There is the need of this rise and it's created by negative feedback. As already said , negative loops are self-reinforcing . As matter of the fact that chickens growth can't be unlimited , negative loop balance the population as an antagonist. As for example: the more chickens there are , the more will cross road. Increasing the population will lead to an increase in risky road crossing , which then decrease the chicken population. The latter feedback is denoted with B as balancing feedback.

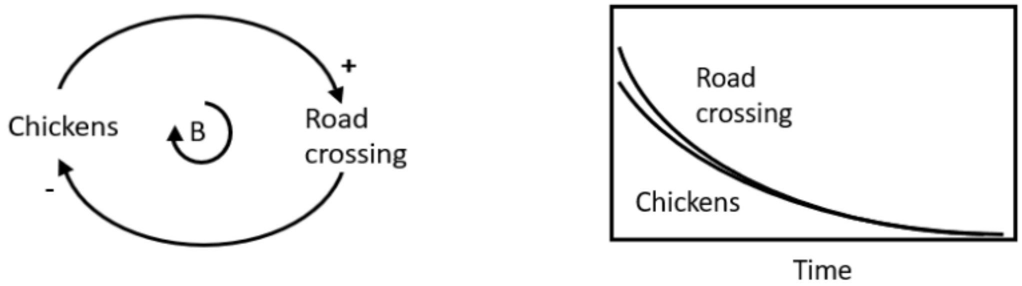


Figure 4: negative loop and its dynamics

The hole dynamic arise from the interaction of these loops; all system, independently from the complexity, consist of circuit of positive and negative feedbacks.

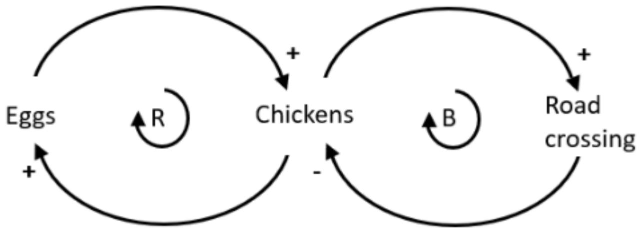


Figure 5: interaction of loops

3.2. Application of system dynamics

Modeling is a iterative and continual process of formulating hypothesis, testing and revision .The steps for modelling a system dynamics process follows this pattern:

- Problem articulation – once the boundary of the problem is selected , the main relevant dynamics that will be employed along the time horizon are chosen and at least the reference model is build.
- Formulation of Dynamic Hypothesis- the feedback structure is defined starting from the consequence of the endogenous dynamics on the feedback structure.

The development of a map able to describe boundaries, agents, feedbacks, and the aggregation level is fundamental to start the simulation model.

- Formulation of a Simulation model- starting from decision rules
- Testing- starts in the moment in which the first equation is write down. The model testing is made to obtain comparison to reference model , prove the robustness under certain extreme condition and make sensitivity analysis to stress the model behavior under uncertainty parameters, initial condition and different level of aggregation.
- Policy design and evaluation- the process ends with the policy design and evaluation, useful to draw scenario to improve the understanding of long-term dynamics behavior.

Modeling is a feedback process, not a linear list of action .During the ongoing design process constant interactions take place, questioning , testing and adjustments.

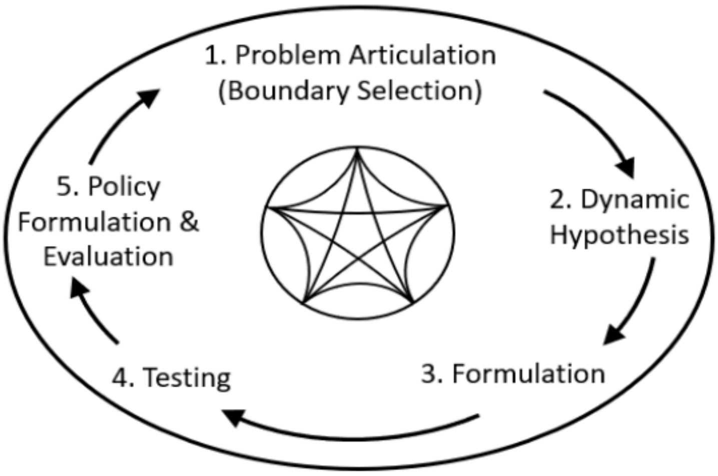


Figure 4: iteration steps of modelling

The iterative mechanism is shown in figure 6. The initial boundary selection as first step can affect the dynamics hypothesis evaluation an so on. The interaction can go back in every steps of the process , because this approach, and how it was thought , is not a one-shot activity. It’s an ongoing continuous process that relates real world and the virtual world of the model.

3.2.1. Problem articulation

The first one is the most important step of the modeling process, in fact a clear propose is the pivotal action that let the modeler to ask the questions that reveal if the model really address the problem. The purpose acts as the logical knife, providing the criteria to choose what can be neglected so that only the fundamental features are left. This is done through a participatory approach, the boundaries of the problem are established setting the reference model and the time horizon.

Reference model , made by a set of graph or any other descriptive way to show data, help to break out the short term event oriented and makes you begin to imagine how the problem might evolve in the future. To do it it's fundamental set the time horizon and define variable and dynamics important to describe the overall problem.

The time horizon should cover the temporal window able to capture the delayed effect of the potential policies. Cause and effect are not immediate, select a too short time horizon could influence the perception of the problem.

3.2.2. Formulating a Dynamic Hypothesis

Once the problem has been defined , modeler must develop dynamic hypothesis, characterizing the problem in terms of feedback and stock and flow structure.. In this phase the exogenous explanation of the problem is searched , rules witch arise from the outside , and answer the question *"What caused the exogenous variables to change as they did?"*. In order to communicate and represent the structure of the model there are different tool, such as , subsystem diagrams, model boundary diagrams, casual loop diagram, stock and flow maps.

- Model boundary chart- used to summarized the scope of the model, characterizes if the key variable are endogenous, exogenous and what are excluded from the scope. By explicitly listing the concepts and the dynamics that have been choose to exclude , it provides a warning about the limitation of the model.
- Subsystem diagrams- shows the architecture of the model along flows of materials , information and operation. It cover the aggregation level describing the agents and the number of different organization among it. Are usually simple and are used to transmit the hierarchical structure of large model.
- Casual loop diagrams- doesn't deal with the boundary and the architecture of the model. Here is represented how the variable are related showing the casual link with arrows and polarity.
- Stock and flow maps- causal loops are quantified by this ones. Stock represent the state of the system, they are integral accumulation variable , while flows are

the change of the state of the system and are computed as a differential equation.

- Policy structure diagrams- focus attentions on the causal structure and the time delays involved decisions and its information inputs.

3.3. Causal Loops Diagrams

As stated above causal loops diagrams (CLDs) are an important tool for the graphic representation of the feedback structure of the model. They are an exceptional instrument for a quick capture of dynamics hypothesis, can capture easily mental models and highlight the main feedback responsible for a problem. CLD consist in connecting variables by arrows and giving it a polarity (positive/negative) , specifying the kind of causal relation among it. Positive link means that if the cause increase, the effect increase *above what it would otherwise have been,* while if the cause decrease, the effect decrease *below what it would otherwise have been.*

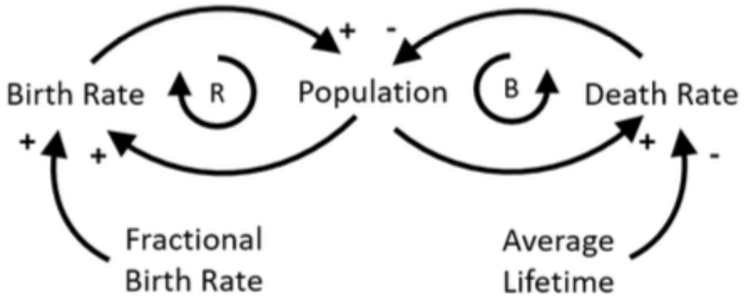


Figure 5: causal loop diagram

In figure 7 , increasing the fraction birth leads to the bird rate will be in number grater that that it would have been, and so the opposite ,decrease the average life time means that the death rate will rise above it would have been.

The polarities do not describe how the variable behave but only the structure of the system. They are in charge to designate the WHAT IF situation, which means to answer to the question: what would happened if the were a change in this variable? They do not show the reality of the situation but actually what would happen if the variable were to change. It's important to remember that an increase in a cause variable will not lead necessarily to an increase , for two reasons. First, the variable often are the sum of different inputs , and in order to know what actually will be the results it should have an overview of the whole change in input. Going back to the population example, the birth rate depends on population and birth rate . You cannot say that an increase in factional birth rate will surely rise up the birth rate without knowing if population is rising , falling or being constant.

The second reason, causal loop diagrams don't diversify if a variable represent a stock or a flow. In the previous diagram the population is a stock and it fractional increase come from the birth rate less the death rate . Birth rates, as it is formulate , can only increase the population , they can never reduce it. Likewise, a drop in death rate does not accounts as an increase in population.

3.4. Stocks and flows

Casual loops diagrams are fundamental to capture mental models and to communicate the results , despite that they suffer from a big limitation, their inability to capture the difference from stocks and flows. Stocks and flows are the pivotal notions of the system dynamics theory. Stocks are accumulation, are the level variable of the system and gives systems inertia and provide memory. Flows are states variables, the difference between inflows and outflows create delays in accumulation.

The stock and flow diagramming convention (Forrester 1961) [25]were based on a hydraulic metaphor, the flow of water into and out of reservoirs.

- Stocks are rectangles which suggest a container holding some material
- Inflows and outflows are represented by pipes pointing out or into the stocks
- Valves control the flow
- Clouds define the boundaries of the model

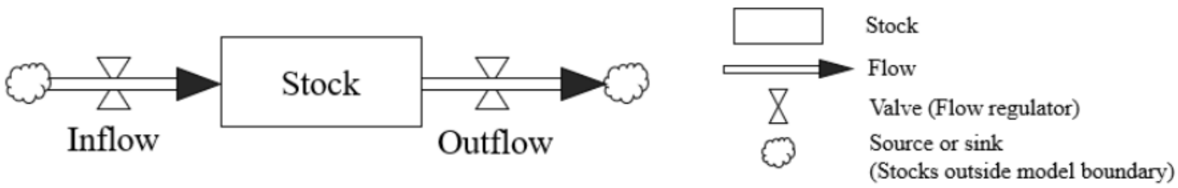


Figure 6: stock and flow diagramming notation

Thinking about the water metaphor , the quantity of water in the bathtub at any time is the accumulation of the water flowing in less the water flowing out through the drain. This is translate in mathematical terms , Stocks accumulate or integrate their flows; the net flow into the stocks is the rate of change of the stock itself. Hence this correspond to an integral equation:

$$Stock(t) = \int_{t_0}^{t} [Inflows(t) - Outflows(t)]dt + Stock(t_0) \tag{1}$$

Equivalently, the net rate change of any stocks , is the inflows less the outflows, defining a differential equation:

$$\frac{d(Stock)}{dt} = Inflows(t) - Outflows(t) \tag{2}$$

3.5. Fundamental Behavior of Dynamic System

The behavior of a system emerge from its structure. Different modes arise from the relationship between feedback and structure. These modes are growth, created by positive feedback; goal seeking , created by negative feedbacks; and oscillations, created by negative feedback with time delays.

3.5.1. Exponential growth

The exponential growth derive from a positive and so self-reinforcing feedback. The larger is the starting quantities , the greater is the increase. The particular properties of this behavior is that whatever it would be the quantity , the doubling time is constant. This is a direct consequences of the positive feedback: the net increase depends only on the size of the state of the system.

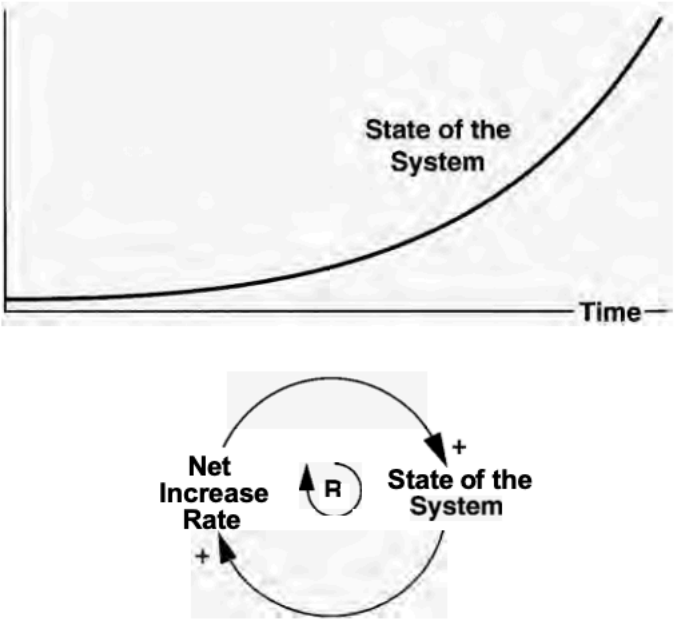


Figure 7: exponential growth

In figure 9 the exponential growth is explained in terms of feedback and polarities. The state of the system determines the net increase rate, and the latter adds to the state of system.

The linear growth indeed is quite rare. In fact it require the absence of feedbacks between state of the system and the net increase rate, because the increase rate needs to remain constant even if the state change. Often what seems to be linear in reality is exponential because the time horizon is to small to snap the acceleration.

3.5.2. Goal Seeking

While positive feedback generates amplification, negative feedbacks aim to bring the state of the system in line with a chosen state. In this case the state of the system is compared with a goal , and if there were any deviation during the reaching a corrective action is initiate. In every negative loop a process to compare the desired and the actual condition it incluted, hence corrective action. Sometimes the goals are under the control of the modeler, but other times the state of system is implicit and so out not under the control of decision maker.

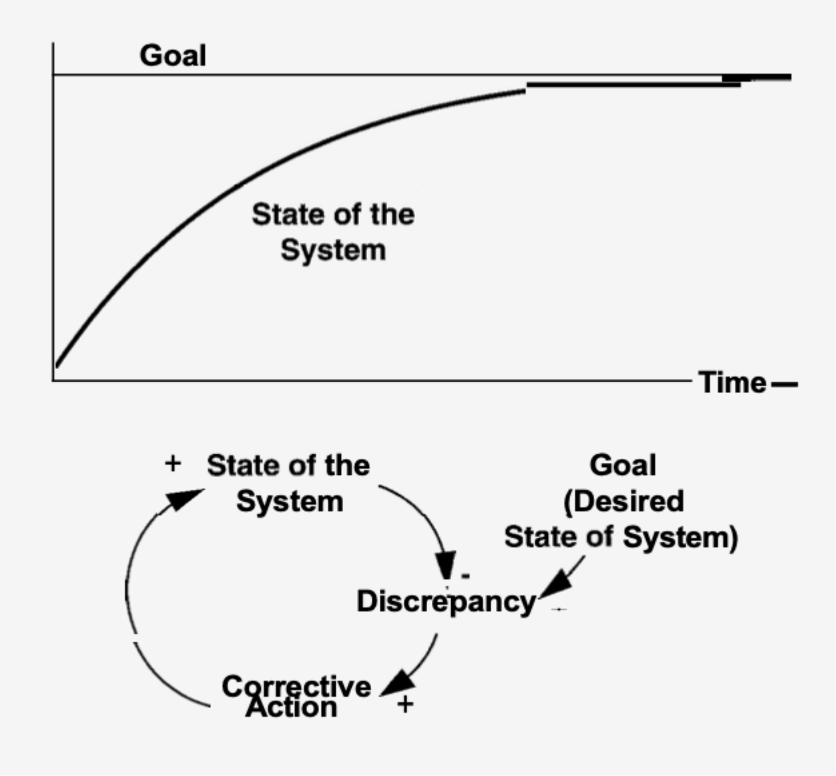


Figure 8: goal seeking, structure and behavior

The rate at which the state of the system approaches its goal fall as the discrepancy is reducing. The gradual approach arises because a large gap generates a large response.

For example, a cup of coffee cools through negative feedback until it reach an stable equilibrium with the room's temperature. The net flow of heat from the cup to the ambient air is larger when the delta in temperature is large.

3.5.3. Oscillation

As goal seeking, oscillation comes from negative feedback. The state of the system is compared to the goal and comparative action are taken to remove any discrepancy. The oscillation system is characterized by the tendency of the goal to overshoot, reverse and then undershoot, in a repetitive way. This behavior is due to the presence of significant time delay in the loop.

There are many variants of oscillation, including damped oscillation, limit cycles, and chaos; but every type of oscillation has inside negative feedback with time delay. The time delay can occur in any part of the negative loop, in perceiving the state rather than in initiating corrective actions.

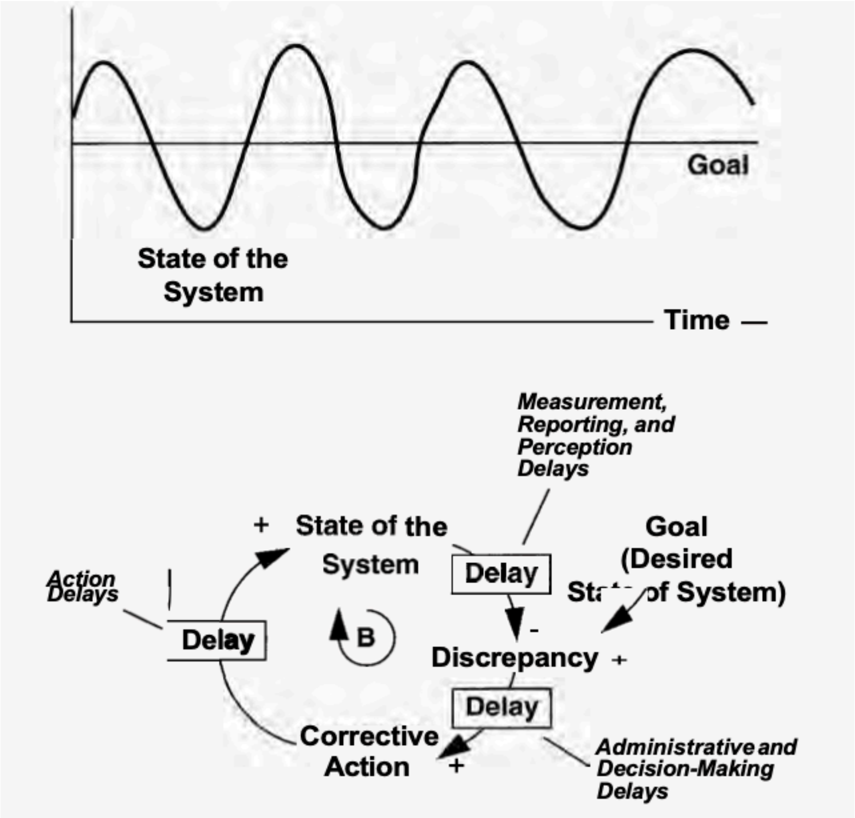


Figure 9:oscillation, structure, and behavior

3.5.4. Interaction of the Fundamental Modes

If the basic modes of behavior interact in nonlinear way with each other give rise to more complex patterns:

- S-Shaped Growth: it represent the concept of carrying capacity. In ecological point of view , the carrying capacity is the number of organism that it can be supported in a particular ambient , its determinate by the resource available. As the maximum value is reaching , the state of the system continues to grow , but a lower rate, until resource are scarce enough to stop the growth. This mode generate a S-shape growth only if two condition are met: negative loops must not include significant time delay and second, the carrying capacity factor must be fixed.
- S-Shaped Growth with Overshoot: it requires the negative feedbacks that constrain growth to act quickly as the carrying capacity is imminent. The time delay in the loop leads the state of the system to overshoot and oscillate around the carrying capacity.
- Overshot and Collapse: the second condition of the S-Shaped Growth, the fixed carrying capacity, sometime can fall when the ability of the environment is consumed by the population itself. In this case the consumption of the carrying capacity creates second negative feedback which limit the growth. In this case when the net increase reaches the zero the system does not reach equilibrium and it start decline.

3.6. Validation and Model Testing

The model testing is one of the most relevant stage of the modelling process, this is made to obtain comparison to reference model, prove the robustness under certain extreme condition and make sensitivity analysis to stress the model behavior under uncertainty parameters, initial condition and different level of aggregation.

Verification means to prove the accuracy of the model, while validation is done once the result can be properly derived from the initial assumption. By definition, no model can ever validate or verified. The only statement that can be verified or validated are pure analytic statements , derived by logical system.

The validation of a model is impossible , in the sense of the establishing truth, but many argue that its falsity can. Of course, since all models are wrong, all of them can be falsified by one test or the other. If validation is impossible and all models are wrong, why then do we bother to build them? The modeler’s responsibility is to use the best model for a determine scope in charge , despite its inevitable limitations. Tests helps to answer question about model purpose and boundary, physical and decision-making, and sensitivity analysis.

Boundary Adequacy Tests

This test consists in the definition the adequacy of the boundary chosen for the model. The first step is the boundary definition, then confirm that the list of the exogenous variables is complete. Once the model boundary is well established, an inspection of the important feedbacks must be conduct, to verify to not have omitted important relations. If the reviews of data reveals that a new structure included might matter, it should be added to the model. On the other hand, if additional structure demonstrates to have not a significant impact, it can be excluded, making the model smaller and easier to explain.

Structure Assessment Tests

The structure assessment test is used to define how the model structure match the reality. This kind of test focus the attention on the level of aggregation, the physical reality of the assumptions and the realism of the decision rules. The search is aimed to show violation of the physical low such as conservation of matter or more in general real stocks quantities, for example population or inventories, that cannot become negative. This is done by direct inspection of the equations. Subsystem diagram and stocks and flows maps help to expose the right level of aggregation, while partial model tests demonstrate the rationality of single decision. When excessive disaggregation does not result in relevant result for the purpose can be simplified or merged.

Dimensional Consistency

Dimensional consistency is at the base of the modeling. It is the step in which all the units of measure are subject to a consistency control. Dimensional inconsistency could reveal important mistake in the structure and dynamics understanding. Even if the model includes automatic dimensional analysis, the direct inspection of the equations and the single variables is the finest method.

Parameter Assessment

Before the parameter assessment is fundamental to make sure that every constant has a clear and real life meaning. After that the kind of estimation of parameter should be choose. The two possibility are : statistical data and judgment estimation. The first need the knowledge about how the principal regression techniques work , which tool is appropriate to do it and what are the limitation. The down side is about the numerical availability data, which means that often is impossible to have an estimation of all parameter. When this issue occurs the judgement estimation acts. The estimations of parameter is done when it is impossible the use of datasets through interviews, archival materials, direct experiences or workshops. In practice the use of one method doesn't exclude the other. When a direct knowledge of the dynamic modeled suggest a real important relation, it must be included , even if the numerical data has not been able to estimate it.

Extreme Condition Test

The extreme condition test stresses the model to respond to extreme input value. The robustness of the model is demonstrated by the realistic outcome under unrealistic value of input as zero or infinite. This test could carry out in two ways: by simulation or by a direct inspection of the model. The inspection should involve each rate equation and ask if the output is reasonable even when the input has been assumed extreme value. This test can reveal mistake that direct inspection has missed. When the output of an extreme input result in a unconvincing behavior , the source of the defect must be identify in the equation and then corrected.

Integration Error Test

The choice of time step and numerical integration method must be selected before modeling start. Whatever this two characteristic would be the model should not suffer its. The integration error test is conduct changing the integration method, it should be the first one to carry out , because an error in this step will lead a meaningless model. Likewise the time step test is done by cutting the time step and run the model again, if the results change in a consistent way this means that the time steps was too large.

Behavior Reproduction Tests

In order to testing the ability of the model to reproduce the behavior of the system the most used tool is the descriptive statistics to assets the point-by-point fit. It computes some measure of error between a data series Xd and the model output X at every point for which data are available and then makes the average over a relevant time horizon. , the coefficient of determination, is the widely measure reported. It measures the fraction of the variance in the data, if it means that the model replicates the exact data series, while if it means that the model output is constant. The limitation in this case came from the fact that the behavior test cannot show if a model is correct or not. It could be many models that replicate the date well but it can never be showing through this check if the behavior was generated by a particular correct structure.

Behavior Anomaly Tests

Data lack often means the impossibility to established the strength of important relations. The behavior anomaly test examine the importance of the structure whether anomalous result arise when relations are cancelled out or modified. Loop knockout analysis is a method used to search anomalies. In this test a target relationship is zero out. It became particularly effective when it is used together with the extreme condition test, impossible behavior under extreme conditions evidence the fact that the relation is important to be not included. In alternative anomalies can be studied with a test that replaces disequilibrium structure with simplified one to prove the importance of certain disequilibrium formulation

Family Member Tests

The family member test investigate whether the model is able to generator behavior of other cases in the same class. The more different the instances of a system a model can replicate the more general the theory it comprises. This test is useful when the class of the system the model handles include a wide range of behavioral patterns.

Surprise Behavior Tests

The discrepancy between the model behavior and the expected output reveal that among the mental and the formal model there are glitch. The surprise behavior test is passed once the model which previously generated an unexpected output , now reflect the reality of the system. It requires a particular attention on the analysis of different performance , along with the behavior of all variables, not just the major ones. At this point the sources of the unexpected behavior should be tracked down.

Sensitivity analysis

The sensitivity analysis aim to test the robustness of your conclusions and how they change if the assumption are varied over the plausible range of uncertainty. There are three types of sensitivity:

- Numerical sensitivity : a change in assumption cause a change in the numerical value of the results. All models show it.
- Behavior mode sensitivity: a change in assumption change the behavior of the model. For example when it cause a change from an s-shaped growth to an overshoot behavior.
- Policy sensitivity: prevail when a change in assumption modifies the outcome of a policy.

The sensitivity analysis is not just a variation of the parameters, it requires consideration about the boundary of the problem, the change in the level of aggregation and a change on the way of making decision. First it must be done the identification of a range of uncertainty in which parameters are tested. In order to not underestimate the uncertainty a good rule is to test over a range at least twice as wide as statistical or judgment opinion suggest.

One common method to carry out sensitivity analysis is the definition of the best and worst scenarios. In the best (worst) case scenario you set the values of all parameters and relationships to the values most (least) favorable to the outcomes you desire or the policies you want to test. Outcome from best and worst scenario are not the most favorable. Monte Carlo simulation instead, generate dynamic confidence intervals , and randomly draws a value for each parameter form different distribution.

System improvement test

System improvement test ask if the modelling process helped in improving the system. A positive outcome of the test is the identification of policy which lead to an upgrading. Assessing the impact of a model is a tough work because when new policies are implemented it takes a long time for their effects to manifest. The issue is worsen by the other variables and conditions which change at the same time, confusing effort to link results to new policy. The key methods for the modeling assessment are prospective evaluation, use of multiple data source and the adherence to proper experimental protocols.

- Prospective evaluation is more effective than retrospective one. Discussion if the process will be successful is part of the initial problem definition phase.
- Multiple data source are needed to measure all the dimensions to assess the extend which any changes in performance can be attribute to the intervention.
- Experimental protocols must be design, and this comprise the creation of control and treatment groups.

4 Methodology

4.1. System Dynamics framework

Given the variety of cause-effect relationships, feedback loops, and time delays within the electricity-socioeconomic support implementation that is the topic of the study, System Dynamics modeling framework was judged to be the most appropriate technique for the modeling exercise.

Modeling is a feedback process rather than a simple list of actions. Iterations, ongoing questioning, testing, and refinement are all constant processes for models. Figure 10 appropriately illustrates the modeling approach as an iterative cycle. The boundaries and extent of the modeling effort are determined by the initial objective, but what we discover during the modeling process may change our fundamental knowledge of the issue and the intention behind our work. Any step may be iterated from to another step (indicated by the interconnections in the center of the diagram).

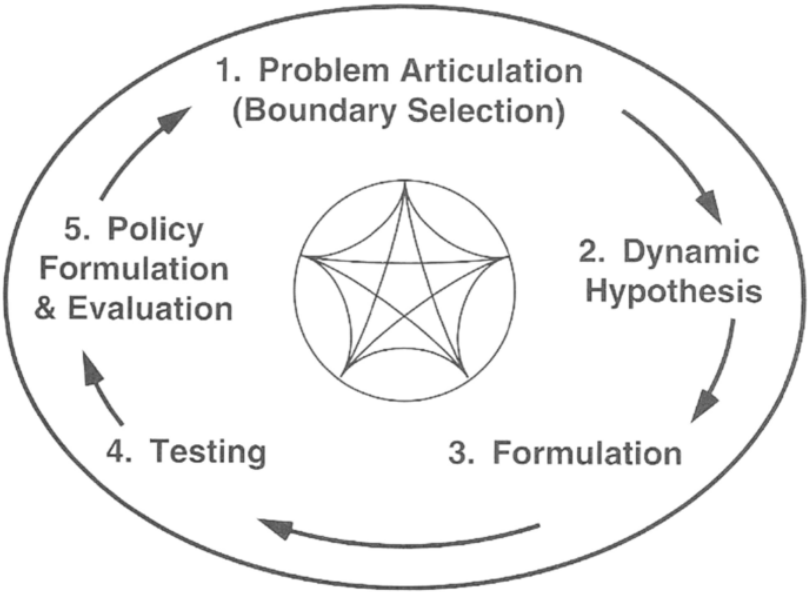


Figure 10:Iterative modeling process

The capacity of the model to be replicated in various contexts, making the application as generic as feasible, is the primary challenge to be addressed starting with the problem formulation. This step is completed by first analyzing the original model that served as the foundation for this thesis. The need to reinterpret some dynamics emerged as a result of the extreme condition and the boundary adequacy test. In order to examine the influence of the other two agents, food and water, made accessible by the electrification project, new subsystems have been introduced to the description of the water-energy-food nexus.

The results of this first analysis have led to the formulation of a new issue articulation that now concentrates on the pertinent feedback linkages between the three dimensions of the nexus. The iteration process continues and goes back to the problem formulation each time a new factor must be considered. Throughout the iterative process, the testing phase is ongoing. In fact, several tests will be carried out at each stage of the process, and depending on the outcomes, it will either go on to the next phase or occur a different stage.

4.2. Model adoption and replicability assessment

4.2.1. Presentation of the model

The thesis relies on a System Dynamic-based model, developed by Politecnico di Milano, validated for the Ikondo village, in Njombe region of Tanzania. The aim of the original model is to assess a long-term electricity load forecast to also guarantee a techno economic feasibility study for the installation of off-grid in rural area. Other than this output, the tool can simulate non-linear relation between electricity access and socio-economic development. Riva (2018), states that in rural electrification field, the demand planning in most of cases is handle as linear dynamic, unable to consider the exogenous and endogenous contribution, leading to a less reliable grid design. For the purpose of a more appropriate approach model to study the nexus between energy and development, the former doctoral researcher of Politecnico di Milano, Fabio Riva, modeled a system dynamics approach [26]. The work done could be summarized as follow:

I. Description of the dynamics hypothesis that are the basis of the relation between electricity access and utilization and rural development. This hypothesis has been modeled as casual loop diagrams to give a clear idea of their link and shows the differential roles of the reinforcing and balancing feedback loops.
II. Transformation into equations and mathematical expression of the casual loops, formulating the model structure. The model aims to reproduce the evolution of the energy demand along the time window, testing the behavior of it on historical data series of the studied village. The final pattern accounts for 123 constants, 260 auxiliary equations and 80 integral equations.

The final structure of the model account for 11 sub model: *IGAs formation and Income, Market demand, Market production and revenues, Agricultural production and revenues, Population, Time savings, Education, IGAs electricity connections, HHs electricity connections, Household appliances diffusion* and *Electrical Energy consumptions*

In particular IGAs formation and Income, Market and Agricultural production and revenues sub model will be described below.

IGAs formation & Income

The financing mechanism of IGAs arises from three different mechanisms:

I. Emulation: people who ask for a loan without a previous market analysis but just emulating who open a business.
II. Market inspection: a proper market analysis is done before the opening of a new activity. The investigation is based on the number and the type of new income generating activities potentially needed in the market.
III. Financial availability:
    i) access to microcredit
    ii) self-financing

The dynamic of IGAs formation is slowed down by a delay which occurs for material procurement and authorization, and a second delay caused by the bankruptcy of a fraction of them.

$$\begin{cases} IGAs(t) = \int_t \big(setting - up\ of\ new\ IGAs(t) - bankrupty\ rate\ of\ IGAs(t)\big) \cdot dt \\ setting - up\ of\ new\ IGAs(t) = \dfrac{Financed\ IGAs(t)}{Time\ for\ setting - up\ the\ IGA} \\ Financed\ IGA(t) = \int_t \big(financing\ IGAs(t) - \ setting - up\ of\ new\ IGAs(t)\big) \cdot dt \end{cases} \tag{3}$$

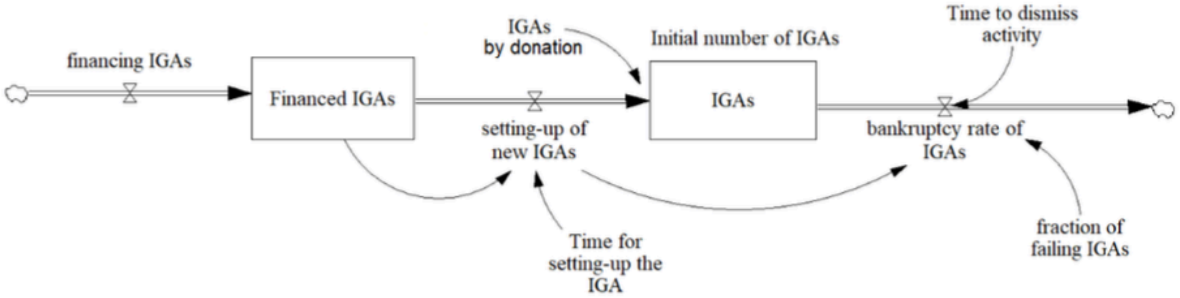
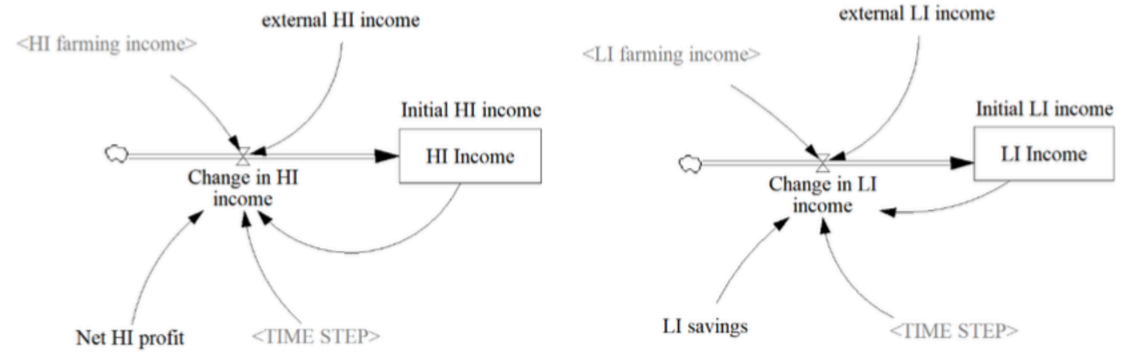


Figure 11: IGAs formation process

People's income is directly responsive to the cost of opening an IGA. For both HI (high income) and LI (low income) households the income represents the financial availability, which each time unit Δt (1 week) increases or decreases based on financial flows. For both households the income come from the summation of agricultural revenue and external remittances. For HI HHs the income has also a net income flow from profit due to business activities while LI HHs tents to save part of the income for self-financing.

$$\begin{cases} \displaystyle\int_t \frac{dHI\ Income(t)}{Change\ in\ HI\ Income(t)} = \int_t dt \\ Change\ in\ HI\ Income(t) = \dfrac{(external\ HI\ income(t) + Net\ HI\ revenues(t) + HI\ farming\ income(t) - HI\ Income(t))}{\Delta t} \\ \displaystyle\int_t \frac{dLI\ Income(t)}{Change\ in\ LI\ Income(t)} = \int_t dt \\ Change\ in\ LI\ Income(t) = \dfrac{(external\ LI\ income(t) + HI\ farming\ income(t) - LI\ savings) - LI\ Income(t)}{\Delta t} \end{cases} \quad (4)$$



Market & agricultural revenues and production

The economic dimension of the supply of good and services is driven by the number of the local activities and their productivities. The representation of production relies on the commonly named "production function" , which related an output Q of a production process to quantities of inputs The Cobb-Douglas is a particular production function , it is proportional to the product of n terms representative of the inputs of the production , each one to the power of their output elasticities λ_i.

Figure 12: HI and LI dynamics

$$Q = A\prod_{i=1}^{n} X_i^{\lambda_i} \tag{5}$$

In this case the Cobb-Douglas expresses the market production of the local IGAs as the production between income availability and education level, each one powered of the corresponding elasticity, which measures the responsiveness of the output Q on a change in . The mathematical formulation of the production function and its input factors are shows in the following equations:

$$\begin{cases} HI\ capital\ effect(t) = \left(\dfrac{HI\ Income(t)}{Initial\ HI\ Income}\right)^{\varepsilon - IGAs\ income} \\ I\ education\ effect(t) = \left(\dfrac{I\ education\ level(t)}{Initial\ education\ level}\right)^{\gamma - edu} \\ A_{market} = Reference\ factor\ productivity \cdot (1 + electrification\ effect(t) + \vartheta - capacity\ building\ elastcitiy) \\ electrification\ effect(t) = fraction\ of\ EE - reliant\ IGAs(t) \cdot \beta - el \end{cases} \tag{6}$$

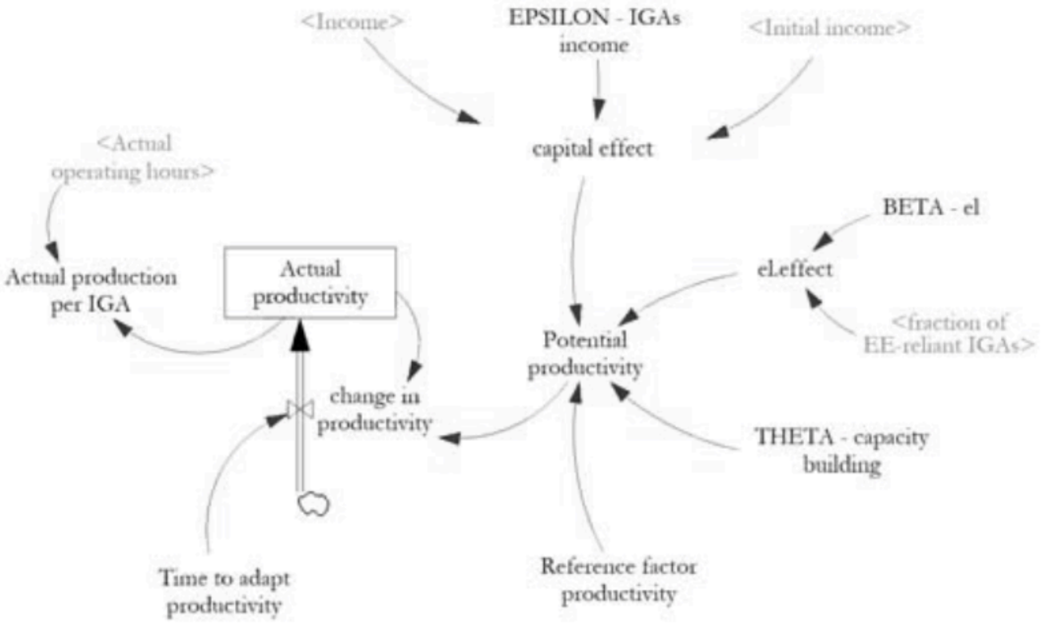


Figure 13: market production dynamics

To sum up the market dynamics, the demand is based on the household's expenditure which is represented by a fraction of the total weekly expenditures that it's the difference between 100% and the fraction of income spent for food, education, healthcare, and electricity. The market supply is defined by the product of number of IGAs, productivity and operating hours. The latter factor represents the working time of each IGA, based on the market demand and the household's available time. If the difference in *Total market demand* and *Total market supply* is positive, so the market is unbalanced, this condition drives a potential change in the IGAs production. In other word the controlling factor between supply and market demand defines the quantity of goods sold in the market, the revenues from it, and the household's profit. As for the productivity of the local market, the farming revenues relies on a Cobb-Douglas formulation. The farm productivity depends on three main input elements:

I. *Financial resources.* The high propensity to invest in farming activities is directly related to the availability of earning.
II. *Education.* The increase of the education level leads to increase people's farming productivity.
III. *Time.* An increase in available time due to nighttime at home lighted by electricity, allows to invest more time in preparing products.

Other relevant dynamics

The total electricity consumption of the whole community results from the summation of the electricity demand of household and IGAs.

$$Total\ electricity\ demand(t) = Total\ HHs\ electricity\ demand(t) + Total\ IGAs\ electricity\ demand(t) \tag{7}$$

For the domestic use of electricity the *Total HHs electricity demand in* each time step Δt is given by the summation of the two income groups (HI and LI HHs), which it's computed as the summation of the product between the number of connected users (*Connected HHs),* the number of appliances owned (*Appliances),* the nominal power *(Electric Power),* the functioning time (Functioning *time for appliances),* and the power plant reliability (*El Reliability).*

$$\begin{cases} Total\ HHs\ electricity\ demand(t) = \sum_{j=1}^{2} Connected\ HHs_j(t) \cdot HHs\ electricity\ consumption(t) \\ HHs\ el.\ load = \sum_{i=1}^{6} Appliance_i(t) \cdot ElectricPower_i \cdot Functioninig\ time\ for\ appliance_i(t) \cdot El\ Reliability \end{cases} \tag{8}$$

For IGAs, the *Total IGAs electricity demand* is the summation of the electric consumption of the two different class of business activities (*EE-reliant IGAs and the other*); which is given by the product between the number of each type of IGAs (*Connected IGAs),* the associated energy consumption (*IGAs electricity demand*), and the power plant reliability (*El Reliability*).

$$\begin{cases} Total\ IGAs\ el\ demand(t) = \sum_{j=1}^{2} Connected\ IGAs_j(t) \cdot IGAs\ electricity\ demand_j(t) \cdot El\ Reliability \\ \int_t \frac{d(Connected\ IGAs(t))}{IGAs\ connection\ rate(t) - bankruptcy\ of\ connected\ IGAs(t)} = \int_t dt \\ IGAs\ connection\ rate\ (t) = IGAs\ to\ be\ connected(t) \cdot affordable\ connections\ by\ IGAs(t) \end{cases} \tag{9}$$

As already defined above the main agents of the model are the High-Income Households who manage both productive and agricultural activities and, Low-Income Households who rely only on agricultural revenues. The evolution of the households is defined by the population dynamic. The population growth has a S-shape behavior starting from an initial value (i*nitial population),* growing at a constant rate (*maximum fr population growth*) until the equilibrium is reached (*Population Carrying capacity*).

$$\begin{cases} \int_t \frac{d(Population(t))}{chamge\ in\ population(t)} = \int_t dt \\ change\ in\ population(t) = \left(1 - \frac{Population(t)}{Popultaion\ Carrying\ capacity}\right) \cdot Population(t) \cdot maximumfr\ population\ growth \end{cases} \quad (10)$$

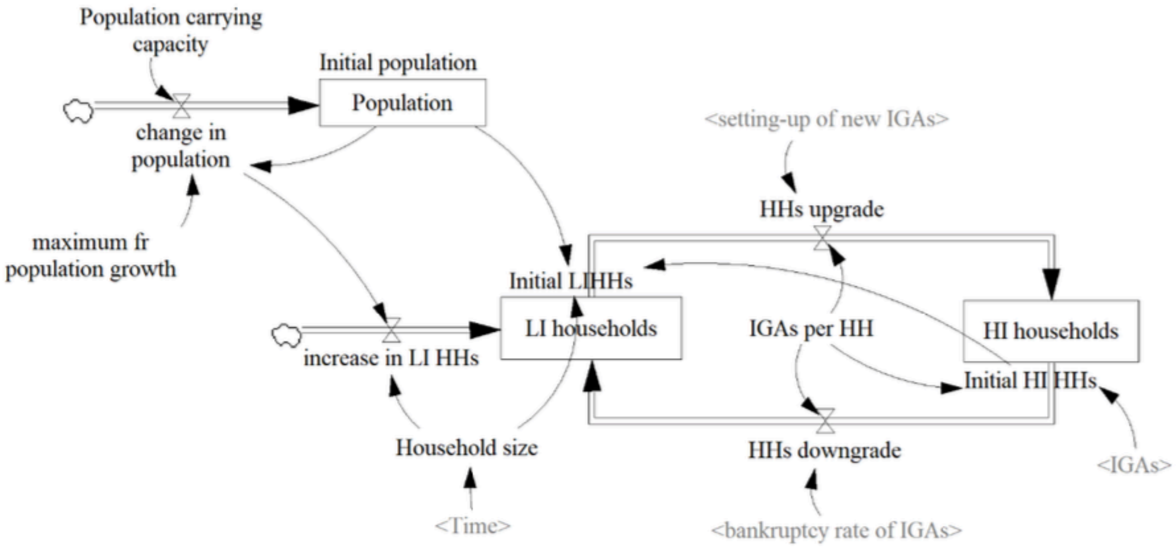


Figure 14: Population and Household dynamics

4.2.2. Extreme condition test

The original model develop by Riva has the aim to simulating the electricity demand in the long term in a rural area of Tanzania and reporting the interdimensional effect due to the access of electricity. Specifically, it has been calibrated on historical data trend of Ikondo village. The simplification phase allows to condense essential structures of large-scale models to bring out relevant dynamics, to increase model understanding, making the structure more functional in different context application [27] .Even if the system dynamic approach deals with accurate simulation which reflect the reality of the problem, its complexity makes it difficult the deep understanding of the structure except for those who made it. According to Eberlein (1989) and others (Saysel & Barlas, 2006), these complexities could be eliminated, because a smaller model continue to simulate the right behavior on condition that it keeps the pivotal correlations and feedbacks [28]. The model simplification is not only aimed to a faster reading of the model by other, but also it makes the model more general, moving from a context-specific case to a more universal and flexible to replicability.

For the model simplification purpose, the most appropriate method turns out to be the *extreme condition test*, already citated in section 3.6. The simplification is carried out removing the feedbacks resulting irrelevant to the outcome (Eberlein,1989) or in the fragmentation of the problem in smaller part to set apart their results [29].

The stressing test amplify the condition at which the model is submitted. In particular, the formal procedure starts by turning off a variable at once, confining the effect on the model. Thus, a ceteris paribus simulation is done on every block of the structure with the purpose to find quickly flaws.

Following the Riva model (2019), Grimoldi (2020), a master's degree student from Politecnico di Milano, conducted the extreme condition tests checking the results with real feedbacks collected during a field study. The testing phase and the subsequent confirmation revealed the dynamics from the original model that have a strong impact on the electricity access and those that can be overlooked [30].

4.2.3. Generalization of the system dynamics model

With the aim of propose a more general, adaptable, and flexible energy demand model and to provide a learning tool for policymakers to improve their understanding of long-term dynamics behavior of water, food and energy system, the boundary of the original model must be modified to consider additional parameters that can most affect the system or its sub-system. The *boundary adequacy tests* assess the appropriateness of the model boundary for the purpose at hand. This test consists of modification of the model to include plausible additional structure, making constants and exogenous variable endogenous. If additional structure has a significant impact on the behavior of the model, then it must be included. In this specific case review of the relevant literature and archival materials suggest some processes that should be made endogenous (Sterman,2000).

WFE nexus model in literature

The system dynamics approach model of the WFE nexus consists of inter-linked modules for modeling *population, water, agriculture,* and *energy* sub-system and their relations.

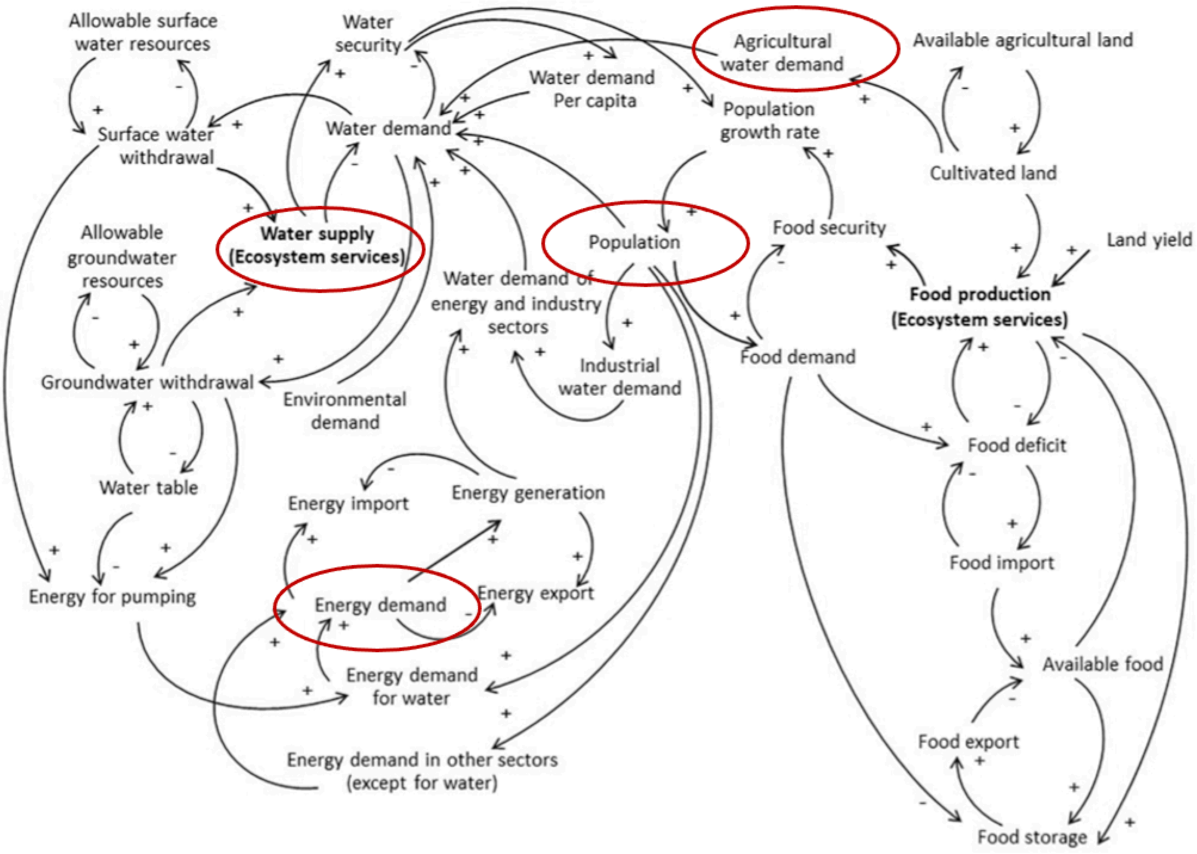


Figure 15: general WFE nexus from Zeinab et al.

The first example came from a field study based on Gavkhuni basin in Iran, conduct by Zeinab et al. from 2001 to 2010 [31].The model counts for three main sub-system which are water, energy, and food-land. These are the principal dimensions studied in the purpose of nexus modeling.

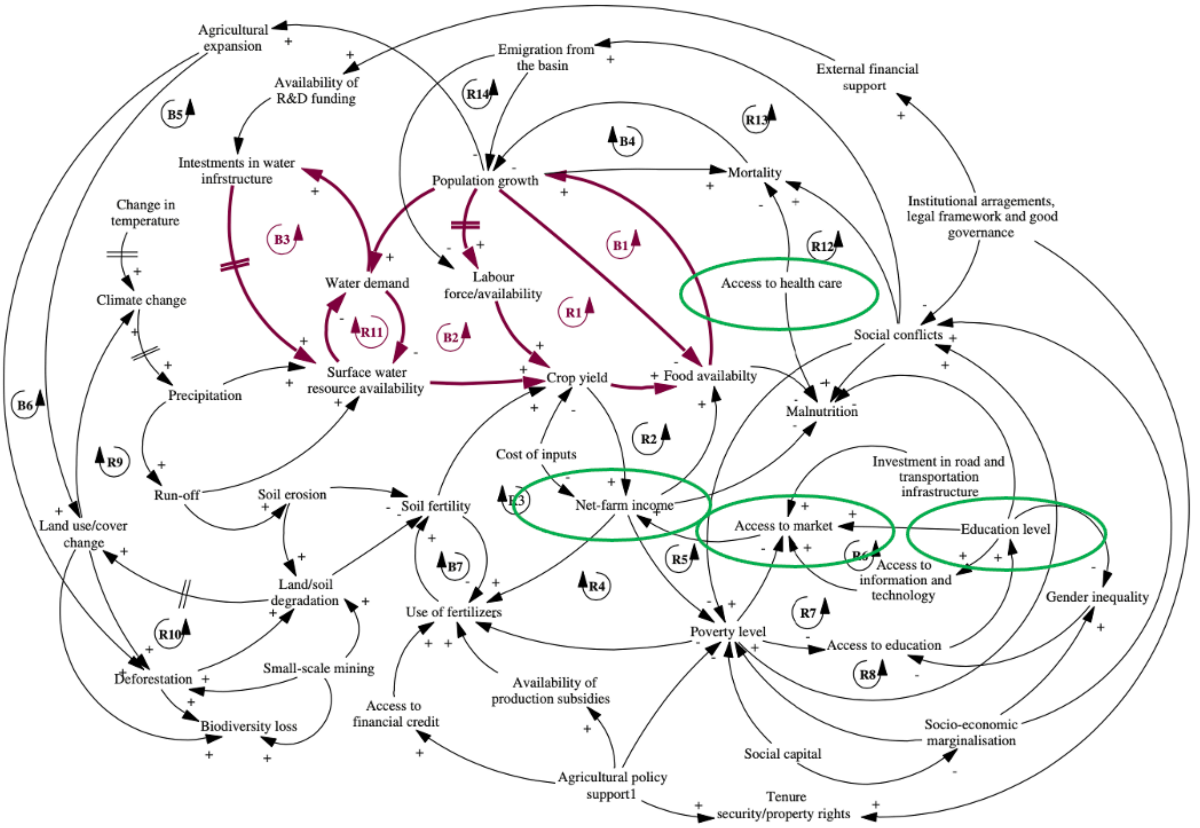


Figure 16: conceptual model for Volta River Basin from Kotir et.al

Additional dynamics in this case have been included, such as *education level, healthcare, access to market* and *Income.* For example, in the conceptual model shown above, population leads to an increase in labour force, and subsequently crop yield growth. As yield increases, it rises the food availability and thus population growth is strengthened [32].Population is the driving force for water demand sector because it directly determines the domestic consumption, and indirectly impacts other water demand and uses.

The water sub-sector is typically differentiated in demand and supply side. Kotir et. al represent the water demand subsector basing the calculation on water demand for agriculture , which means the consumption of water due to irrigation system, domestic and industrial use. Typically the domestic demand is a function of the population [33].Agricultural water demand shall account for on high fraction of the total demand for example 70%, because it would typically include irrigation, feedstock, and goods preparation [34] .

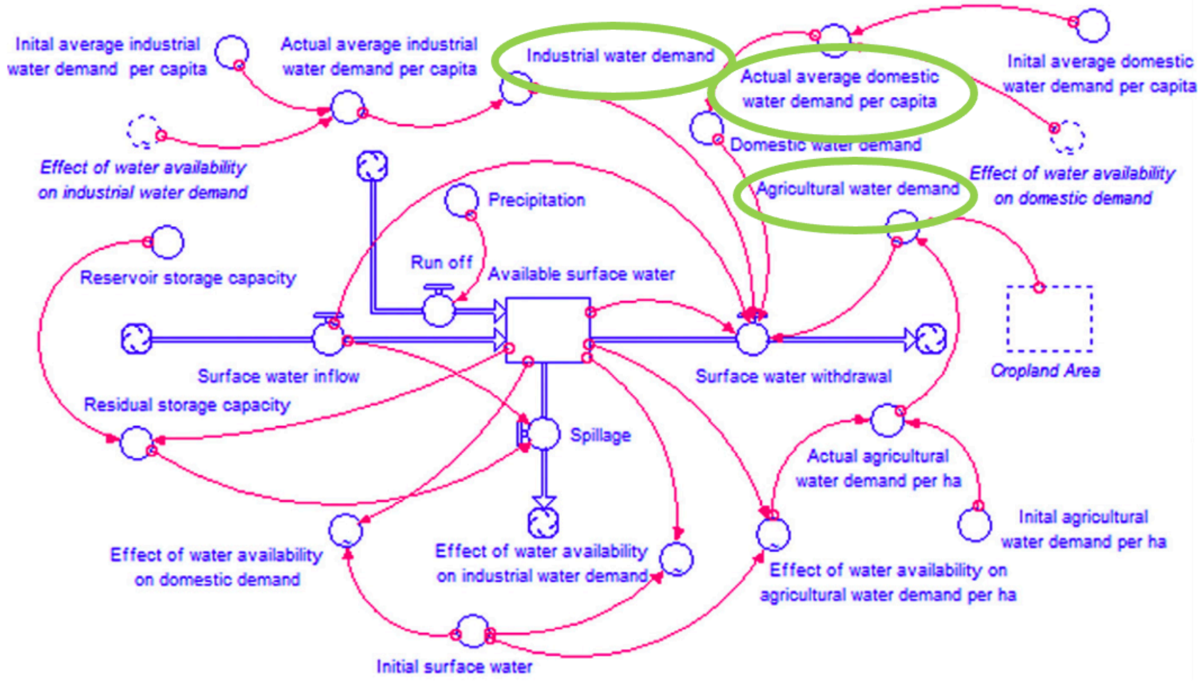


Figure 18: water demand sub-sector from Kotir et. al

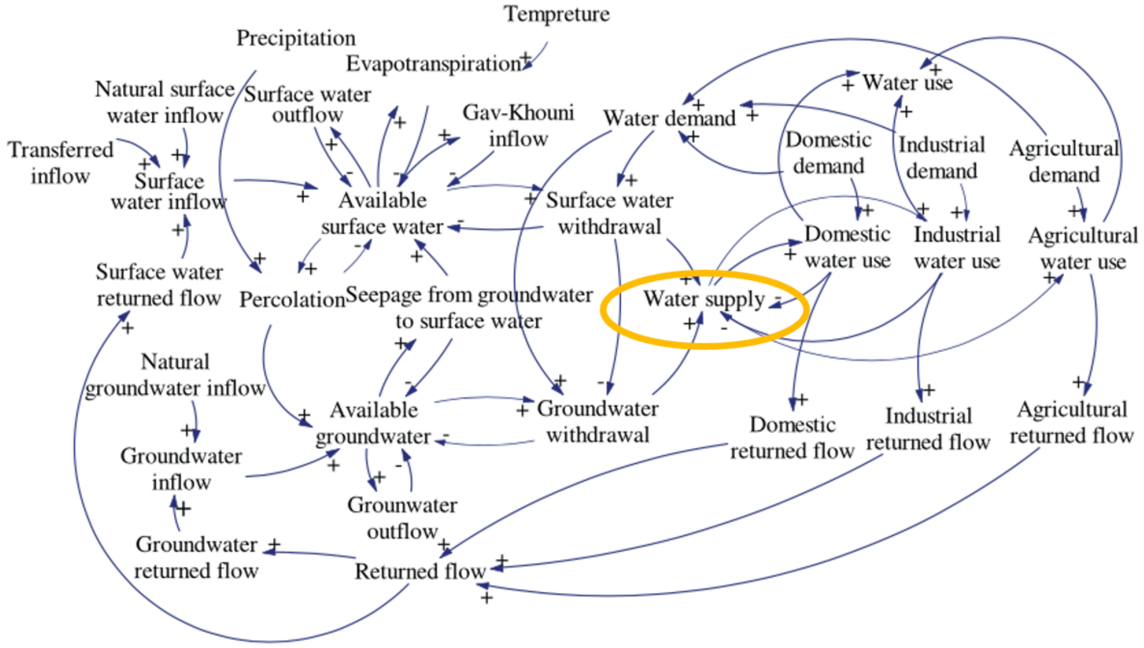


Figure 17: water supply sub-system from Gohari et. al

On the supply side the water resources can come from surface water (i.e., natural rainfall, rivers, streams, lakes) or groundwater resources. Surface water availability is governed by factors including, precipitation, runoff, surface water inflows and outflows, groundwater discharge, evapotranspiration, and infrastructure conditions

[35].Other states that the water demand is not driven by population growth but instead by the state of the socioeconomic development, which is in force of impact directly on domestic's utility and in migration effect [36].The water residential utility can be also assumed as the combination of per capita water use, added value from water use, and national economic growth rate. A fasten economic growth in a water satisfied area, will naturally lead to a more rapid development, which will rise the job opportunity and fostering water use also in other sectors.

4.2.4. Conceptualization of the system dynamics model

The findings from literature and the outcomes from testing provide the pivotal information to complete the simplification process by reducing context specific, large, and parameterized model structure of an existing dynamic problem to a general, reduced, and agile one. The results achieved in this step have been conceptualized in <casual loop maps and then in the next section will be formalized in mathematical formulation of the model.

These steps of simplification have been conceptualized through the iterative redefinition of the original dynamical hypothesis, integrating the outcomes from the tests executed previously.

4.2.5. Formulation of the system dynamics model

Once the *extreme condition test* and the *boundary adequacy test* have been performed, considering one dynamic at time it's possible to do adjust, changes and additions to the original model structure by verifying step by step the consistency of the unit of measure, running the *Dimensional consistency test*. Moreover, a different level of aggregation can be simulated executing the *Structure assessment test.*

4.2.6. Classification of the input parameters

As the part of the main purpose of replicability and creation of clear guideline for the model application in different context, different parameter classification of the input data is necessary to correctly define their value in application of diverse electrification project.

To use the simplified model in other different context and countries some of the total input data need to be initiate. They have been classified in four different categories to know how to approach it:

I. Fixed parameters
II. Context dependent parameters
III. Free parameters
IV. Scenario settings parameters

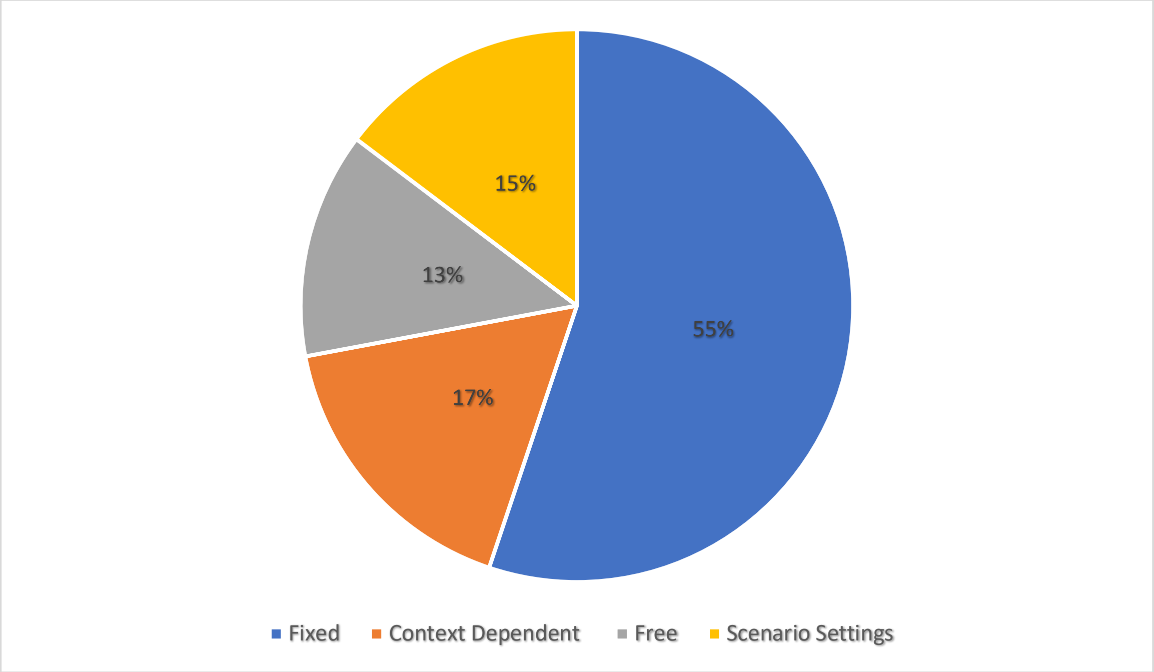


Figure 19: Parameters distribution depending on its category

Tables in Appendix A- Characterization of parameters defines each one of the subdivisions, contains:

I. Name of parameter
II. Unite of measure (UM)
III. Minimum and maximum value they can reach in the model
IV. Source from which the parameter is obtained
V. Commentaries and meaning. This column shows some additional information or description about the parameter useful for future works.

Fixed parameters

This category defines which model parameters would be left fixed even if the context in which the model is applied is different. This category includes the DUMMY ones, which are in charge of active or deactivate the use of some dynamics, some engineering facts such as the conversion of the units of measures kWatt to Watt, and data previously calibrated on Matembwe village. The latest citated class of parameters are considered fixed because only a long and deep field study on new context could substitute it. Some examples of it are the Cobb-Douglass input function, the time delays to appreciate new technology or services and data about social contagion of wiliness to pay. They have been defined after a consequence of model calibration conduct in preceding studies [37].

Context dependent parameters

Parameters which belong to this category are the ones who change every time the model is applied in a different context. Depending on their meaning, they are obtained by different sources. It can be recognized three main sources: references from the own village or more commonly countries' database, such us The World Bank Database, direct observation of the phenomenon, and data from other research work related to similar area o village. Example of this kinds of data are income, local currency, population growth rate, and share of income spent for medical or education expenditures.

Free parameters

In this case the choice of the parameter is left to the modeler depending on the type of simulation that he wants to run. The modeler has the possibility to arbitrarily choose some parameters such as fee tariff, operation time , duration of the simulation or price to cost factor.

Scenario setting parameters

Are those parameters that by changing them generate new scenarios for policy evaluation.

4.3. Impact and effectiveness evaluation of the project

4.3.1. Identification of the SDGs target

Electrification and water access project are mostly focus on the issue of sustainability in all human activities. This is carried out through a diverse set of standards, frameworks, and metric related to what is defined as a threshold to got. Thanks to the Agenda 2030, a general pattern to achieve common objective has been settled. The goals, along with their target and indicators, provide a detailed dashboard for the transition to sustainable development. Nowadays, countries are called upon to translate policy definition into long-term visions with clear target . There is a general emphasis on developing a solid framework of indicators and the classification data needed to monitoring process of the SDGs and inform policy [38].

The use of SGDs for impact evaluation is not a novelty , in fact as already mentioned in the literary review, the Millennium Institute created a policy simulation tool design to help policy makers in the policy evaluation toward achieving the SDGs.

For definition SGDs are described as integrated which implies that the goal, and impact and effectiveness of the policies addressed to achieve them, depend on each other. This is the reason why, in this work, the outcome of the different simulation scenarios will be presented with the use of SDGs indicators definitions. The choice to show results in this way came from one simple motivation: the easy understanding of SDGs' targets from policy makers' view unlike huge raw data output from simulation software, which are not useful and easy reading for who is not a technical expert.

In this thesis the model will focus on the following SDGs (data from [39]):

SUSTAINABLE DEVELOPMENT GOAL 3: ENSURE HEALTY LIVES AND PROMOTE WELL-BEING FOR ALL AT ALL AGES

The 2030 Agenda recognizes the importance of good health to long-term development and the interdependence of the two. It considers expanding economic and social disparities, rising urbanization, and climate-related risks. SDG 3's goal of eradicating poverty and reducing inequality will need universal health care. However, the globe is falling short of the health-related SDGs. Both between and within countries, progress has been inconsistent. The countries with the shortest and longest life expectancies are separated by 31 years. While some nations have achieved significant progress, national averages conceal the fact that many others have fallen behind. To address inequities and promote good health for all, multi-sectoral, rights-based, and gender-sensitive methods are required.

Figure 20: SGD 3

Target 3.8: Achieve universal health coverage

SDG INDICATOR 3.8.2.: Household expenditure on health

Definition: Portion of population with large household expenditures on health as a share of total household expenditure or income.

SUSTAINABLE DEVELOPMENT GOAL 6: ENSURE ACCESS TO WATER AND SANITATION FOR ALL

More than 40% of people are affected by water shortages, a frightening proportion that is expected to climb as temperatures rise. Despite the fact that 2.1 billion people have improved their water cleanliness since 1990, every continent is experiencing declining drinking water resources. Water stress is affecting an increasing number of countries, and rising drought and desertification are exacerbating the problem. At least one out of every four individuals is expected to face chronic water shortages by 2050. By 2030, we must invest in enough infrastructure, sanitation facilities, and hygiene promotion to ensure that everyone has access to safe and inexpensive drinking water. Water-related ecosystems must be protected and restored. To ensure universal access to safe and inexpensive drinking water, more than 800 million people who lack basic services must be reached, and the accessibility and safety of services for over two billion people must be improved.

Figure 21: SDG 6

Target 6.1: Save and affordable drinking water

SDG INDICATOR 6.1.1.: Safe drinking water

Definition: Portion of population using safely managed drinking water services.

A safely managed drinking water services is defined as one located on premises, available when needed and free from contamination.

SUSTAINABLE DEVELOPMENT GOAL 7: ENSURE ACCESS TO AFFORDABLE, RELIABLE, SUISTANABLE AND MODERN ENERGY FOR ALL

Between 2000 and 2018, the percentage of people with access to electricity climbed from 78 to 90%, while the number of persons without access to electricity decreased to 789 million. However, as the world's population grows, so will the demand for inexpensive energy, and an economy based on fossil fuels is causing significant climate change. If we are to meet SDG 7 by 2030, we must invest in solar, wind, and thermal power, improve energy productivity, and ensure that everyone has access to energy.

In all countries, expanding infrastructure and improving technologies to offer clean and more efficient energy would boost growth while also benefiting the environment.

Figure 22: SDG 7

Target 7.1: Universal access to modern energy

SDG INDICATOR 7.1.1.: Access to electricity

Definition: Portion of population with access to electricity

This is measured as the share of people with electricity access at household’s level. It comprises electricity sold commercially, both on-grid and off-grid.

SUSTAINABLE DEVELOPMENT GOAL 7: PROMOTE INCLUSIVE AND SUSTAINABLE ECONOMIC GROWTH, EMPLOYMENT AND DECENT WORK FOR ALL

Despite the long-term effects of the 2008 economic crisis and global recession, the number of employees living in severe poverty has decreased considerably over the last 25 years. The middle class currently accounts for more than 34% of total employment in emerging nations, a figure that has nearly quadrupled between 1991 and 2015. However, as the global economy recovers, we are seeing slower growth, greater disparities, and a shortage of employment to keep up with an expanding workforce. More than 204 million people were jobless in 2015, according to the International Labour Organization. The Sustainable Development Goals (SDGs) encourage long-term economic development, increased productivity, and technological innovation. Encouragement of entrepreneurship and job development, as well as effective efforts to end forced labor, slavery, and human trafficking, are essential. With these goals in mind, the objective is for all women and men to have full and productive employment, as well as respectable job, by 2030.

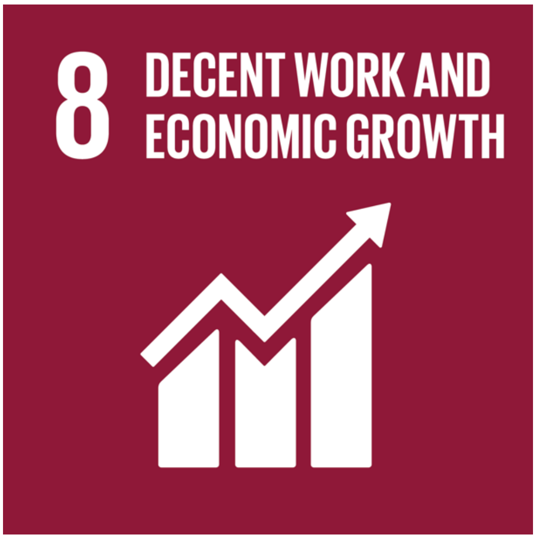


Figure 23: SDG 8

Target 7.1: Sustainable Economic Growth

SDG INDICATOR 8.1.1.: GDP per capita growth rate

Definition: annual growth rate of real GDP per capita

This is measured as the annual percentage growth in gross domestic product (GDP) per capita based on constant local currency.

4.3.2. Policy testing

Reference has been made to the assessment phase of the PCM (Project Cycle Management) in order to pinpoint the major variables in the model on which the policy testing will be conducted.

It is vital to note that the project cycle management, which includes the planning, identification, formulation, execution, and evaluation phases of a project, uses the guidelines created by the staff of Aid Delivery Report to promote sound management practices and wise decision-making (European Commission, 2004). These standards support the methodology for project evaluation employed by the majority of NGOs, international organizations, governments of developing countries, and funders [40].

Looking at PCM's *evaluation phase* in Figure 22, the *efficiency, effectiveness, relevance, impact, and sustainability* indicators serve as excellent descriptions of a project's results and attainment of its goals.

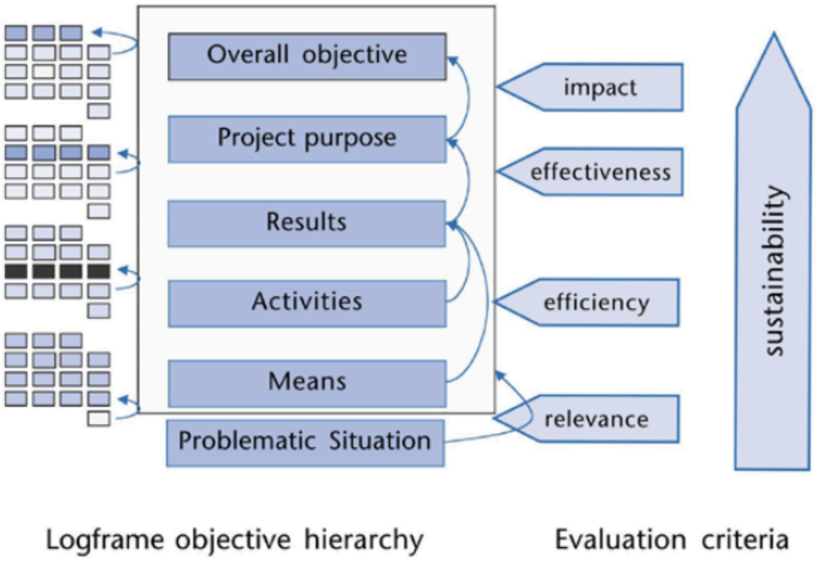


Figure 24:Evaluation phase of Project Cycle Management framework

The model variable selected for policy testing are the follow:

- Income
- Fraction of income spent for medical expenditure
- Affordable connection by IGAs

The impact evaluation of the different scenarios on the SDGs that were mentioned in the previous paragraph is reflected in these variables.

It is interesting to test and examine how the modification of these policy effects the model behavior and its cause-and-effect chains once the validated model has been established and the key control variables have been determined.

In comparison to the Full Intervention scenario, when every policy actively participates, the impact of the enacted policies is examined.

Control variables (0–1) will be used to individually offset the stocks, flows, and auxiliary variables. This method is based on the simulation that Saleh proposed in his paper, which uses trial-and-error to determine the appropriate rules and a set of recommendations for a successful electrification project execution [41].

The results of any particular policy test are inherently reliant on the existence of additional complimentary activities that pass through their causality to the model correlations. Furthermore, it is critical to remember that the impact of policies is not simply the sum of each one's individual effects [42],since they influence one another through endogenous linkages between variables, resulting in a balanced effect. This implies that each policy testing's results reflect a relative impact rather than an absolute one.

The study's goal is to demonstrate the importance of supporting measures for an electrification program and water facilities improvement to be successful. In order to assess how the impact of such a complicated electrification project may boost its efficacy and success, a variety of scenarios where various interventions are addressed will be critically examined and studied.

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5 Case study

5.1. Burundi overview

Burundi has one of the smallest populations in Africa and one of the smallest countries overall [43]. It is a landlocked nation in Southeast Africa's African Great Lakes area, bordered to the east by the United Republic of Tanzania, north by Rwanda, south by the Democratic Republic of the Congo (DRC), and west by Tanganyika Lake. It lies near the equator in latitude and longitude 3°30' S and 30°00' E in the southern hemisphere.

Figure 25: Map of Burundi

Burundi has an underdeveloped manufacturing sector and a lack of resources. Because of this, the economy is mostly dependent on agriculture and breeding, which together account for slightly over 30% of GDP and provide jobs for more than 90% of the population. Due to a paucity of resources, the country's main exports, which make up 90% of its foreign exchange revenues, are coffee and tea. Exports make up a minor portion of the GDP. Presently, Burundi continues to be incredibly reliant on help from bilateral and multilateral donors; foreign aid accounts for 42% of Burundi's GDP, the second-highest percentage in Sub-Saharan Africa [44]. Due to this unfavorable condition, the nation ranks fourth from the bottom in the world in terms of GDP per capita and twenty from the bottom in terms of HDI [45]. With more than 90% of the population living on less than US $2 a day, Burundi is still regarded as a Low Developing Country (LDC) [46].

One of the sub-Saharan African nations with the poorest rate of electricity availability is Burundi. Only 10% of the country's ten million residents had access to electricity as of 2021, one of the lowest percentages in the whole globe [47].

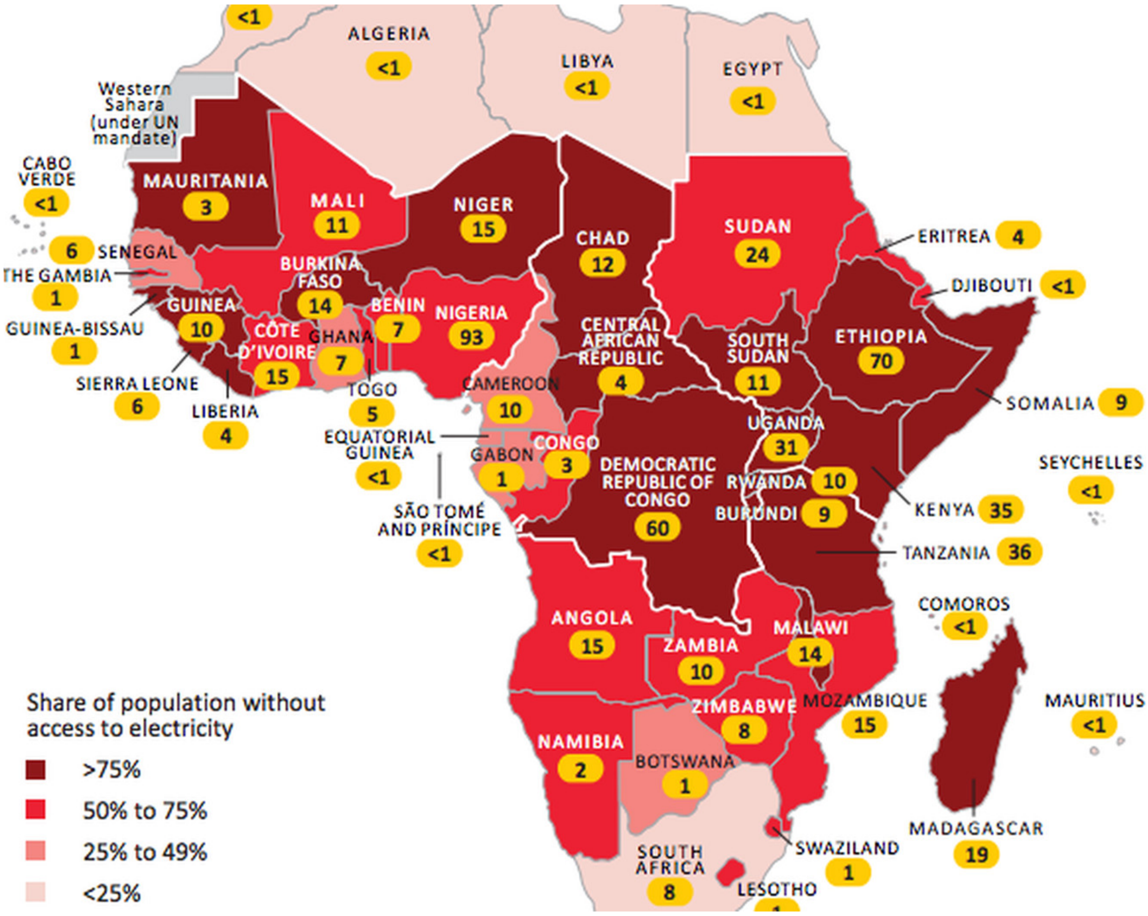

Figure 26: Access to electricity

Table 1 summarizes the main points of Burundi's energy assessment, with data from 2020 provided by the International Renewables Energy Agency (IRENA) [48].

Country	BURUNDI
Total Primary Energy Supply	66 006 [TJ]
Rate of renewables	86%
Energy self-sufficiency	85%
Electricity generation	994 [TJ
Access to electricity	11%

Table 1:Burundi's energy indicators

5.2. Rutana case study

The village of Rutana is the target context of this thesis. It is located in a small outpost in southern Burundi. The little town is not electrified, save from a few homes with solar panel solutions and the health center, because it is remote from a high voltage system. High-voltage wires closest to you are around 20 kilometers distant. A elementary and secondary school with 400–700 pupils both exists. In the heart of the town stands a large church. There is a dry season and a mountain climate with roughly 1500 mm of annual rainfall. Normal temperatures range from 15 to 25 degrees Celsius, and the weather is often dry. A little stream nearby supplies water even during the dry season, and the flow appears to be at least 200 liters per second most of the time.

Figure 27:solar home system

Figure 29:coal for cooking

Figure 28: unsafe generator

6 Results and simulation

6.1. Model adoption and replicability assessment

6.1.1. Highlights from extreme condition testing

The extreme test condition has been performed focusing on the Grimaldi's instruction, the examination has been conducted step by step on macro structure of the model as shown below:

Setting-up of Income Generating Activities

The initial IGAs donated to the local people by CEFA, though have a significant role in the market stimulation they have only an instantaneous effect on the model. Moreover, the choice to eliminate it was since that was a complementary activity based on the Matembwe example and so it was not coherent to the model generalization process.

Market & Agricultural Revenues and Productivity

The education effect on the productivity both in farming and business sectors results to be irrelevant. The reasons are related to the fact that if on one hand the electricity access improve the education level and quality, on the other hand the rising in primary education level accomplishment doesn't affect the electricity demand.

There is not the evidence of creation of competition in the market due to electrification effect, access to electricity impacts on the productivity but it is neutralized by the supply-demand dynamics without evident impact on the final output.

Time savings

In the market and agricultural productivity, the time proved to be an irrelevant factor to enhance productivity. It seems that time managing is not a constrain element for investment or productivity. Additional confirmations came from literature, in particular Baldwin (2015) who evidences the lack of a feedback between the rising in operating hours thanks to nigh lighting and the increase in productivity and so income [49].

6.1.2. Conceptualization of the system dynamics model

The reshaping of the main causal loops described in the previous chapter have been adapted to the introduction of the water-food-energy nexus.

<u>First causal loop – IGAs formation and income</u>

The figure 20 displays the mechanisms behind formation and investment in new business and how this is facilitated by access to electricity and accessible financial instruments such as loans and microcredits. The increasing number of new IGAs in the market leads to a market saturation of the demand, activating the crowding effect which balances the demand and supply of certain goods. The additional time gained

from the use of electricity at home can be invested in setting up new income generating activities.

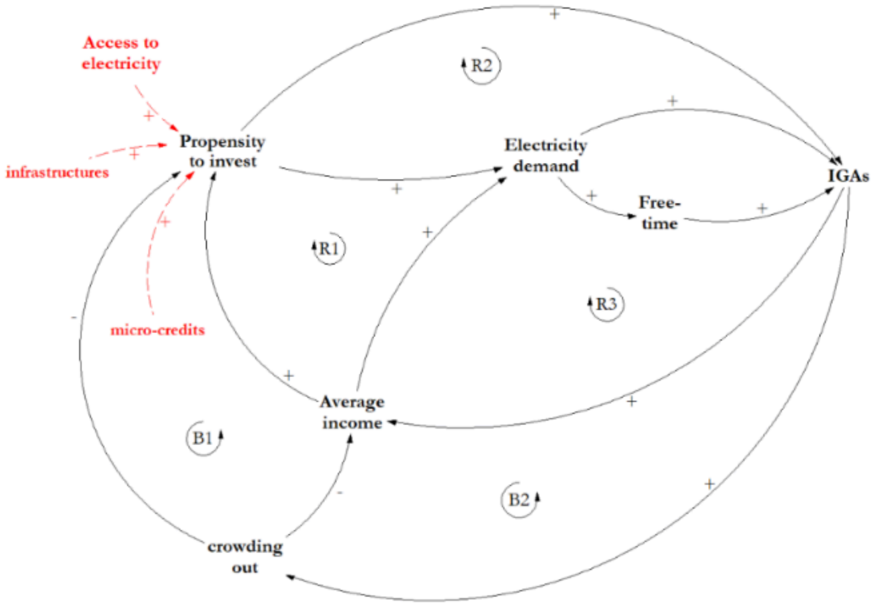

Figure 30: Original causal loop about IGAs and Income

As mentioned before, since the time is not a biding constrain for opening a new business activity, its dynamic has been simplified and so eliminated. The reshaping of the original CLD due to water availability introduction are described.

- R3) *Availability of capital → Electrical demand→Water supply→IGAs formation→Income→ Availability of capital*
  The Access to clean and safe water can help to increase the productivity of farming activities, stimulating the market demand, and increasing the number of firms.
- R4) *Availability of capital →Electrical demand→Water supply→People's health→Income→ Availability of capital*
  The consumption of clean water decreases the health disease, this improve can result in positive feedback on energy use. An improved health status reduces the time spent being sick and money for health services, increasing households' financial capacity.

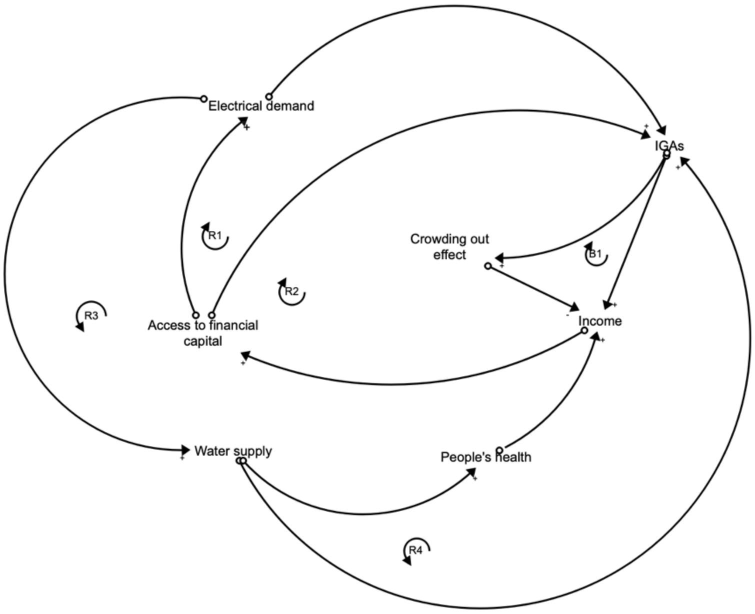

Figure 31:modified causal loop about IGAs and Income

Second causal loop – Market production and revenue

The figure 22 shows the effect of electricity access in the market supply, increasing the demand and attracting also external demand. The increase of the demand side of the market is the driving force of it, the rise in demand reduces the competition which in turn encourages more production and so the supply side. The use of electrical devices and machineries increase the productivity, which in turn in increase the supply of goods, sales, and revenue, the higher the income the higher the fraction of it spent for energy services. The capacity building is one of the most relevant elements to increase productivity of the exiting IGAs, which has the effect of increasing the competition, lowering the total market revenues. Its role is pivotal in supporting entrepreneurs' social skills and network to access new market and technical skills to innovate to sell products.

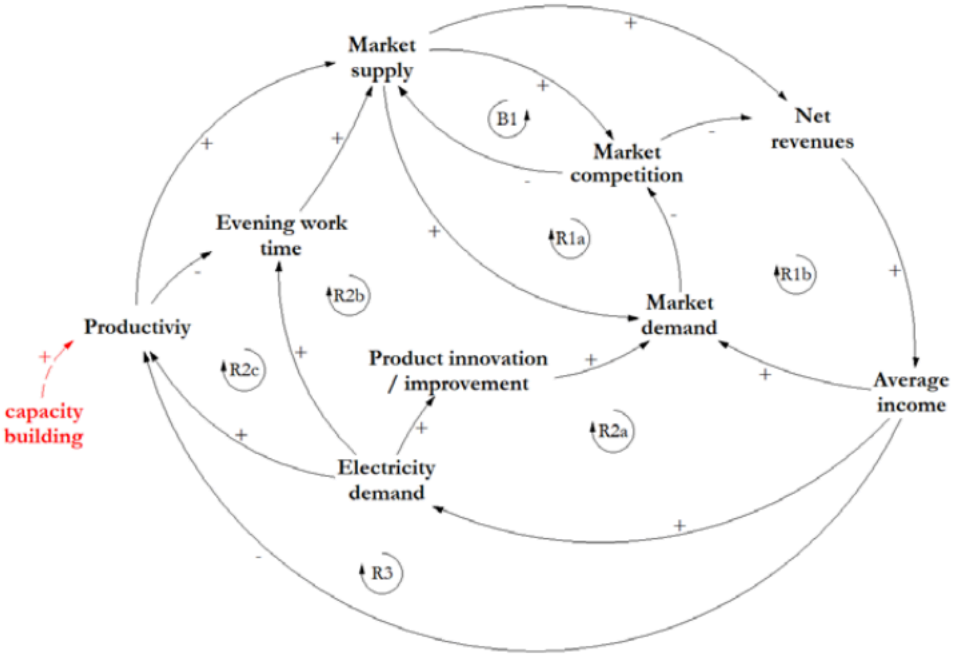

Figure 32: Original causal loop about market production and revenue

The original causal loop diagram has been modified as shown in figure 23.

- R4) *Water supply→Market supply→Income→Water supply*
  The availability of water increases the number and size of crops, market supply increase both in amount and quality of good rising market revenue and so the share of income spent for water facilities.
- R5) *Water supply→Electrical demand →Water supply*
  The increase in water supply leads to an increase in energy demand

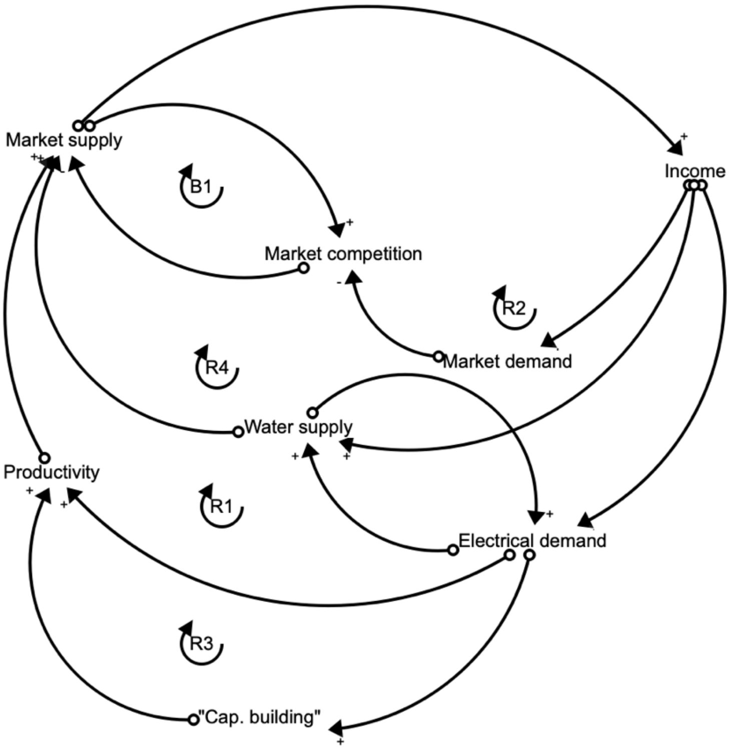

Figure 33: Modified causal loop about market production and revenue

Third causal loop – Farming activities

Since the water availability is a pivotal factor for the improving of farming activities an additional CLD has been conceptualized in order to describe the fundamental feedback relations activated by the introduction of the new water dynamic.

- R1) *Electrical demand→Farming productivity →Income from farming→Income→Electrical demand*
  Electrical lighting allows people to continue farming activities in the night (e.g., shelling) and the use of farming machinery like electric mills enhance their production to sell and the income that can be reinvested again in the activity.
- R2) *Market supply →Income from farming →Income→Market demand→Market supply*
  The increase of market supply as result of electrification leads to positive feedback on farming activities too, attracting also external consumers. This give rise to income, market demand and supply.
- R3) *Water supply→ Electrical demand→Farming productivity →Income from farming→Income→Water supply*

There is a similar effect to electrification due to the water supply. The availability of water increases the electrical demand which consequently allows to produce more goods and as a result incomes increase.

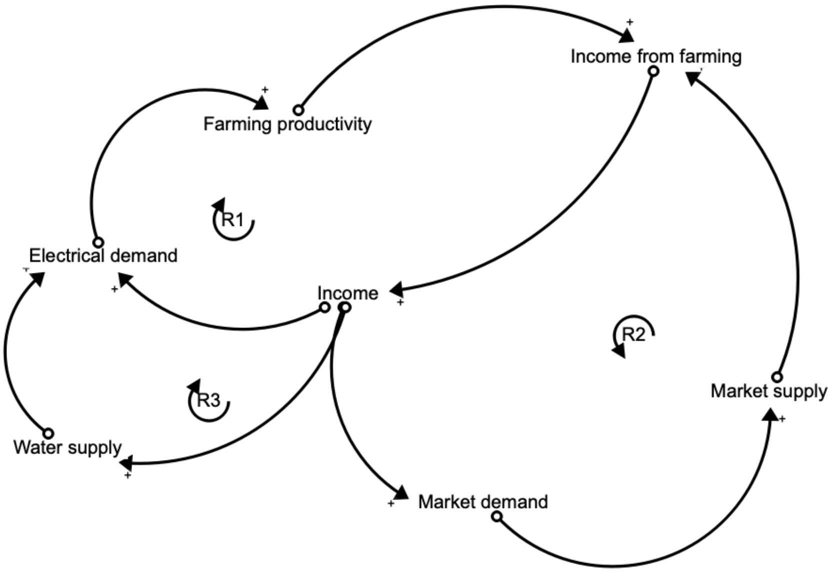

Figure 34:New causal loop about farming activities

<u>Fourth causal loop-Water demand and supply</u>

The driving force of the water subsystem is the population growth. It influences both the direct demand of water and the food demand. Since the water in this model is modelled such a finite resource, it supply the water for domestic and agricultural sectors basing on the water resource available at any time t. The increase in the demand will lead in an increase in supply thanks to the amplification of the infrastructure. The food gap is filled increasing the yield thanks to the additional cultivated land irrigated.

- B1) *Water demand→ Water availability*
  The high is the demand the lower will be the water available
- R1) *Population growth→Water Demand→Water infrastructure→Water Availability →Food production→Population growth*

The increase in population is the driving force of the water demand, the increase of community leads to an increase in the demand which needs more water infrastructure to rise the food production to feed the population.

- B2) *Food production→Food deficit*
  The highest is the production of food from agriculture to feed the population, the lower will be the food gap deficit
- R2) *Available land→Cultivated land→Food production→Food deficit→Cultivated land→Available land*
  The land available in the local context, thanks to the agricultural water facilities, became cultivated land to the production of food to fill the gap of food demand.
- B3) *Available land→Cultivated land*
  The relentless demand for fields for food production diminishes the residual availability of land

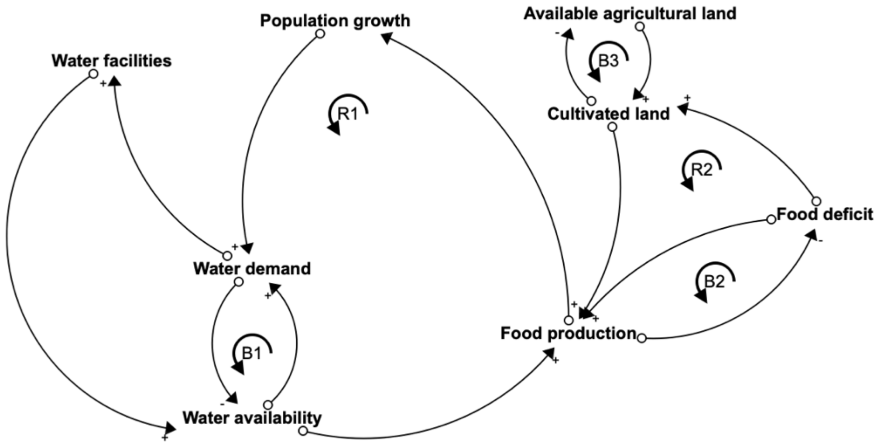

Figure 35:Water supply and demand casual loop

6.1.3. Formulation of the system dynamics model

Considering the dynamics highlighted in the updated causal loops, the new version, in which changes, and adjustment have been proposed, is formulated as follows.

Households' definition

However, first of all, it is important to present the main agents of the model: the households. In the first example of the model conceptualization (Riva, 2019) the household had been characterized by the distinguishment between High-Income Households, who run both productive and farming activity, and Low-Income Household, who rely only on agricultural revenues. Even if this classification results a faithful representation of reality, the diversification of the input data needed for the categorization of the two-income level, results difficult due to data scarcity. In fact, in on one hand the decision of having one household's representation leads to lose some interesting differentiation such us distinctive expenditure or consumption habits, on the other hand, the simplification allows to an easier data collection and model utilization.

The *Structure assessment test* result on positive feedback on the household categorization simplification, in fact by comparing the two model, the original one by Riva (2019) and the new one, utilizing the Average Income as a control variable, both test's results show a similar behavior. The average income has a more smoothed variation just because is evaluated as a mean value.

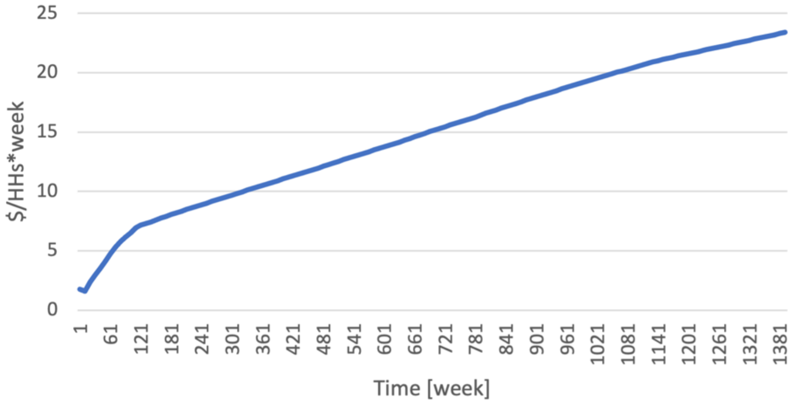

Figure 36: Average income output

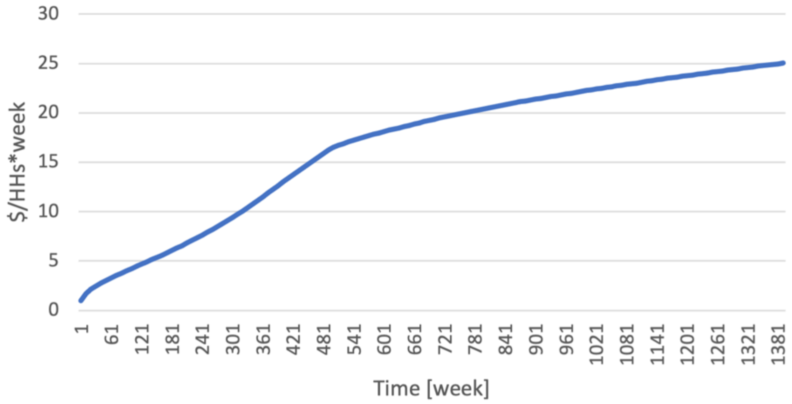

Figure 37: Income output

The same results are provided by the comparison of the *Cumulated community electricity demand*. The first graph shows the electricity demand output from the model in which there is the differentiation between HI household and LI households, while the second one is the results of the households' aggregation.

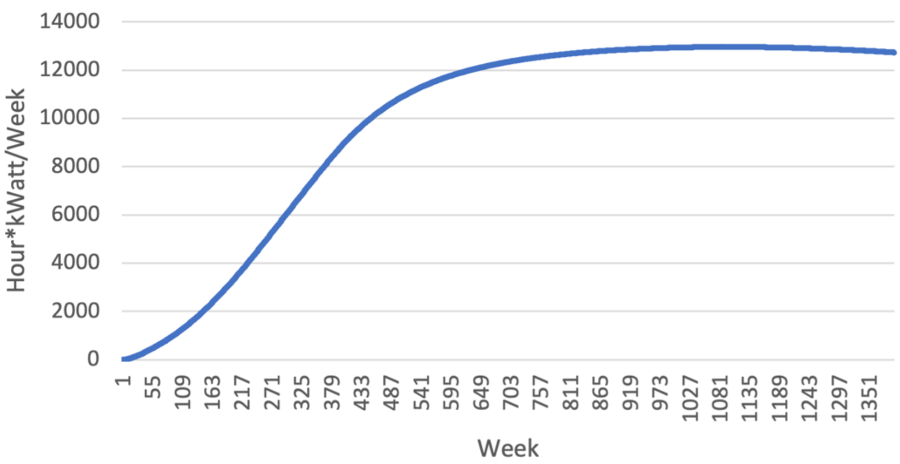

Figure 38:Comulated community electricity demand output from original model

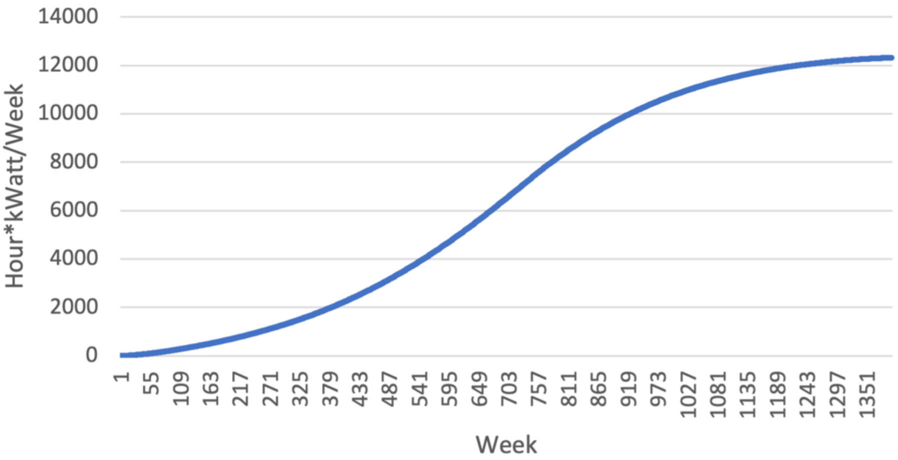

Figure 39:Comulated community electricity demand output from the new version of the model

IGAs creation and income

As discussed, beforehand, the creation of a unique household profile led to eliminate the difference in credit access by population. In fact, if the different financing mechanisms were distinguished for high-income household and low-income households, now the available capital for setting up new IGAs comes from a fraction of population who access to microcredit while the remaining part tents to make savings. In addition, as stated by Grimoldi, and sequentially verified by the conduction of the *extreme condition test,* the electrification effect and the time-based propensity have been shown irrelevant dynamics in setting up of new business decision and so in the new model they are no longer present.

Population

The population growth dynamic is modeled as *"Lump-sum" model.* Population is formulated through one single stock, and the single flow represents the process of reproduction, migration, and mortality [26]. The resulted behavior is the S-shaped growth, which reach the equilibrium given by the carrying capacity factor. With the aim of make the model applicable in different context the carrying capacity factor is calculated starting from initial population.

$$\begin{cases} \int_t \frac{d(Population(t))}{change\ in\ population(t)} = \int_t dt \\ change\ in\ population(t) = \left(1 - \frac{Population(t)}{Population\ capacity\ carrying}\right) \cdot Population(t) \cdot \max fr\ population\ growth \\ Population\ capacity\ carrying = Initial\ population \cdot (1 + Annual\ population\ growth\ rate)^{Year} \end{cases}$$

(11)

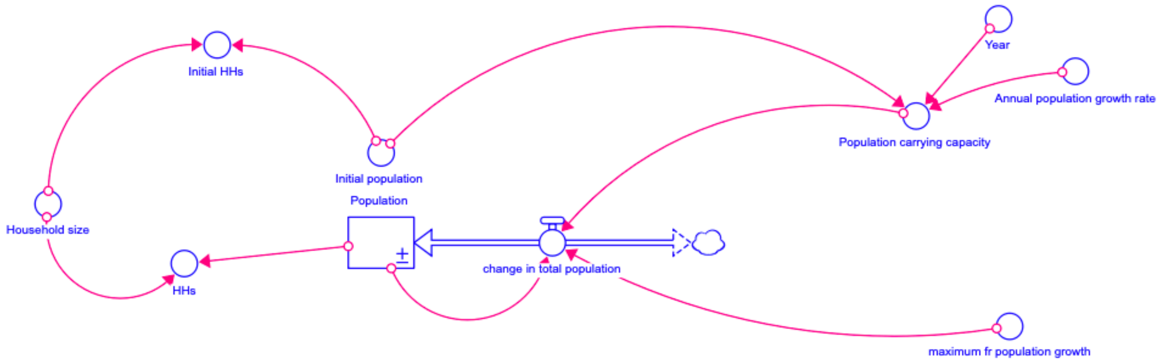

Figure 40: Population stock and flow diagram

Water supply and utilization

The model structure of the dynamic of water supply and demand is dived in three main subsystems: water supply, water demand, and energy. The interest in the water-energy-food (WEF) nexus suggests that these sectors are intimately connected acting as one complex system, this is the reason why the three dimensions of the nexus should be simulated together [50]. Pumping, treating, and distributing water, as well as treating wastewater, need energy, whereas water is necessary to produce crops. Water, energy, and food requirements/demands often arise at the same time in many regions, putting them in competition for limited resources. At the same time, these resources are under enormous strain, and demand for each is expected to rise significantly until the middle of the century.

Water demand subsystem

Local demand for water is driving by the population growth variable. Demand is based on per capita water consumption within each time unit Δt. In accordance with literature the demand has been divided in domestic water demand, and agriculture water demand. The third sector always citated in papers, which is the industrial one, in this case will not be considered because the model represents a small village in rural areas.

Water demand subsystem- Domestic Water Demand

Safe and secure water is essential to poor people's survival and health, however meeting basic needs can play a wider role in poverty reduction and improving livings. The domestic use of water dynamic is affected on two mains factor: income and reliability.

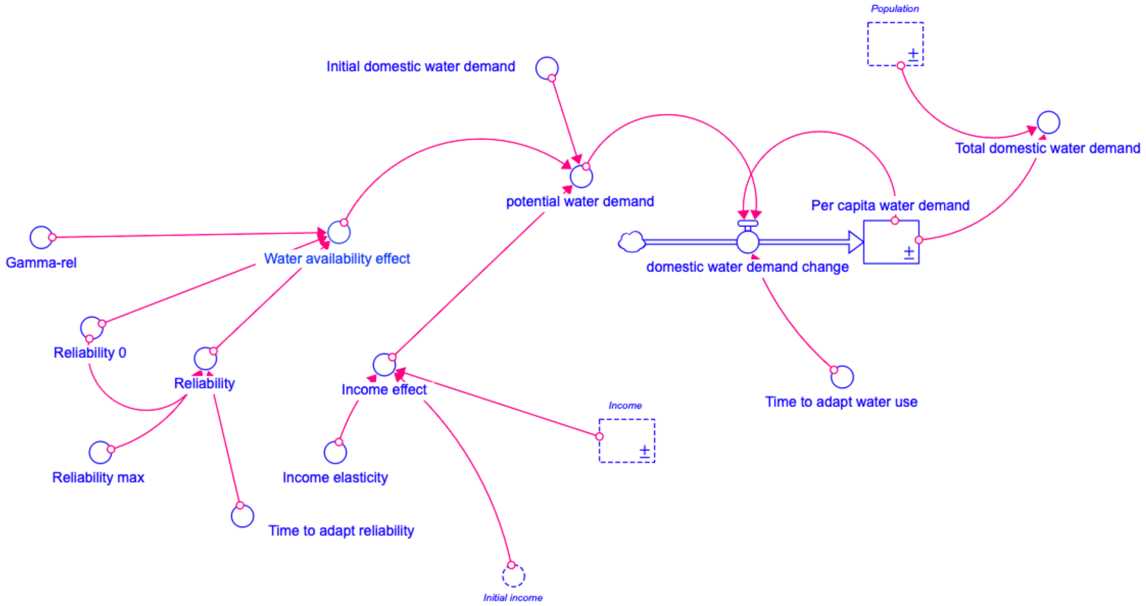

Figure 41: Stocks and flows of Domestic Water Demand

$$\begin{cases} \int_t dPer\ capita\ water\ demand(t) = \int_t Domestic\ water\ demand\ change(t)dt \\ Domestic\ demand\ change(t) = MAX\left(0; \dfrac{Potential\ demand(t) - Per\ capita\ demand}{Time\ to\ adapt\ water\ use}\right) \\ Potential\ domestic\ demand(t) = Initial\ domestic\ demand \cdot Water\ availability\ effect(t) \cdot \\ \qquad Income\ effect(t) \end{cases} \quad (12)$$

The income effect on the water demand positively, the beneficial impact of household income on water consumption is intriguing because there are some reasons to believe that wealthier people use less water: wealthier people live in newer homes, which are more water-efficient than older structures; and wealthier people, who tend to be more educated, have more environmentally conscious attitudes [51]. However, concerning rural areas context, there are reasons to believe that prosperity will lead to increased water use because wealthy people consume more goods and services, and environmental ideals are not necessarily tightly linked to behavior [52] .The *Income effect* is a time-varying inputs where *ε-Income* expresses the output proportionality in relation to a change in the input. The World Bank Research, during field studies, found out that the income elasticities of demand for enhanced water services were universally low—0.15 in Brazil, 0.14 in India, 0.07 in Zimbabwe, and 0.06 in Kenya—when they could be estimated (which was not possible in all of the studies due to the difficulties of obtaining income data). According to these findings, a 10% increase in household income would result in a 1% increase in the likelihood that a household would opt to use the enhanced water system. Overall, the data imply that, while household wealth is important, it is not the most important factor of demand for better services [53].

The previous citated study focused also on the variability of the households' willingness to pay based on the quality of the service. Households are often ready to pay significantly more if the water from a better source is reliable, which means that reliability is a crucial factor to take in consideration. Studies from India and Pakistan show that the increased reliability in water services lead to an increase in connected household to the system because there is willing to pay much more if the water from an improved source is reliable.

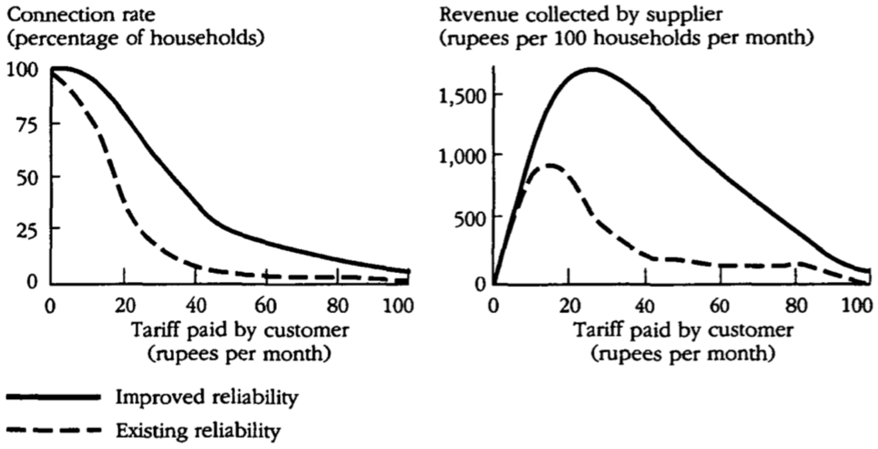

Figure 42:How reliability of supply affects willingness to pay for piped water

$$\begin{cases} Income\ effect(t) = \left(\dfrac{Income(t)}{Initial\ income}\right)^{\epsilon-income} \\ Water\ availability\ effect(t) = \left(\dfrac{Rel(t)}{Rel_0}\right)^{\gamma-rel} \\ Rel(t) = DEALAY(Rel_{max}; Time\ to\ adapt\ reliability; Rel_0) \end{cases} \quad (13)$$

Like the income effect, the reliability ones consider the γ-rel elasticity which suggest the proportionality between the increase in the improving of the system and the water demand for domestic purpose. The time-varying variable *Reliability(t)* is computed as a delayed function which returns a delay for the output after a variation of the input. In simple terms we estimate that the reliability will increase starting from the *Rel_0* value to the maximum value *Rel_max.* The output of the stock *Per capita water demand* is computed as m^3 of water per capita per week. The final result is multiplied for the *Population(t)* variable, returning the *Total Domestic Water Demand.*

Water demand subsystem- Agriculture Water Demand

The water demand for agricultural use is strictly related to the food poverty definition. Although the fundamental reasons of poverty differ by farming system, water shortages and competitiveness in many countries represent a threat to future progress in poverty reduction. In fact, most places of prolonged poverty are characterized by a scarcity of water. However, in both absolute and relative terms, many irrigated areas with large-scale continue to be home to significant numbers of poor people. This is due to injustice in access to land and water resources, as well as low productivity as a result [54]. Starting with the notion of *Unbalanced food demand*, the entire demand for agricultural water is calculated. The water required arises from an *unbalanced food demand*, which is turned into a perceived requirement for more cropland because of fluctuating yield sizes to meet the food need. Water's importance in establishing food and nutrition security in order to promote human nutrition and health cannot be overstated. Water is critical to food and nutrition security because of its connections to all areas of economic food access.

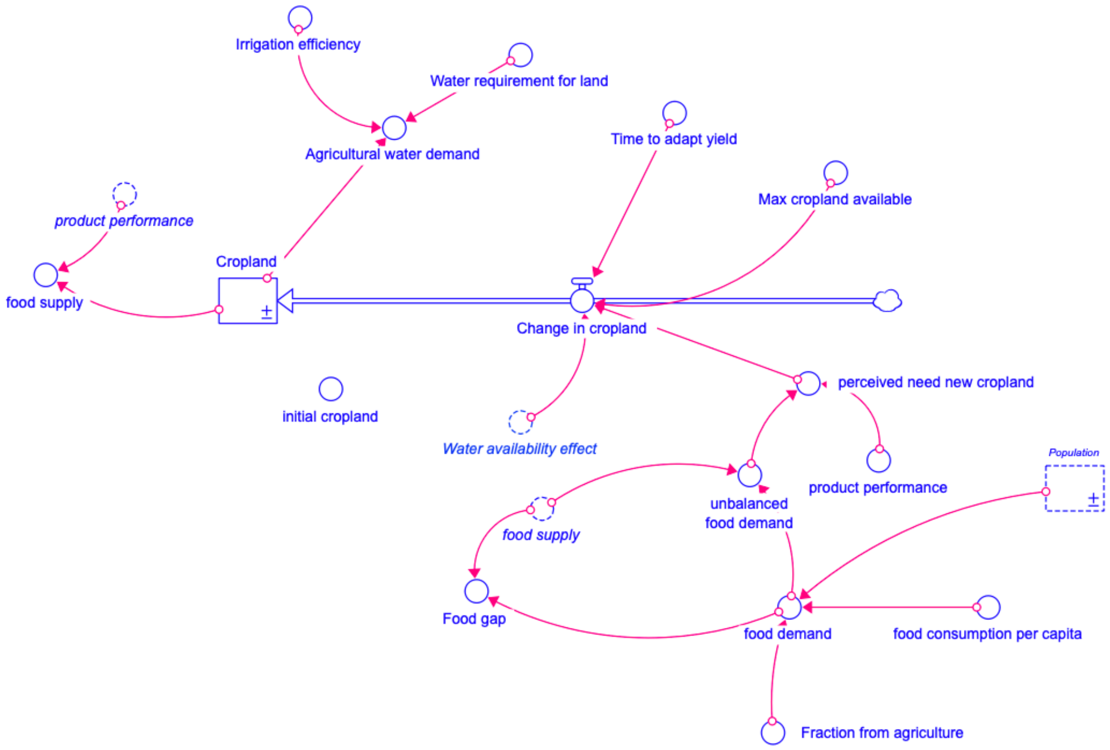

Figure 43:Stocks and flows of Agriculture Water Demand

$$\begin{cases} \int_t d\big(Cropland(t)\big) = \int_t Change\ in\ cropland(t)dt \\ Change\ in\ cropland(t) = MIN\left(Max\ crop\ available; MAX\left(0; \frac{Perceived\ new\ cropland}{Time\ to\ adapt\ yield} \cdot Water\ availability\ effect(t)\right)\right) \\ Perceived\ need\ new\ cropland = unbalanced\ food\ demand(t) \cdot product\ performance \end{cases} \tag{14}$$

The maximum crop available is a limit figure for crop expansion that varies depending on the situation in which the model is employed. Food security refers to the gap between supply and demand for food resources. Variations in population and per capita food intake are used to determine *food demand*. The *product performance* variable, a metric that calculates yield productivity in kilograms per hectare, is used to assess the perceived requirement for new cropland.

$$\begin{cases} Unbalanced\ food\ demand(t) = food\ demand(t) - food\ supply(t) \\ Food\ demand(t) = Food\ consumption\ per\ capita \cdot Population(t) \cdot \\ \qquad Food\ from\ agriculture \\ Food\ supply(t) = Cropland(t) \cdot product\ performace \end{cases} \tag{15}$$

The food demand time dependent variable is derived from the proportion of total food consumption per capita that is based on plants, as measured by the *food from agriculture* parameter. Looking at Figure 32, the average share of plant-based food is around 82% [55]. The various concerns surrounding nutrition, food sources, and motivations for food choices argue for a multidisciplinary approach to addressing nutrition security in poor rural households. Agriculture has a part in human nutrition by providing food. It also plays a role in boosting nutritional diversity and providing consumers with more options. Agriculture can also boost household incomes, allowing families to purchase more healthful foods.

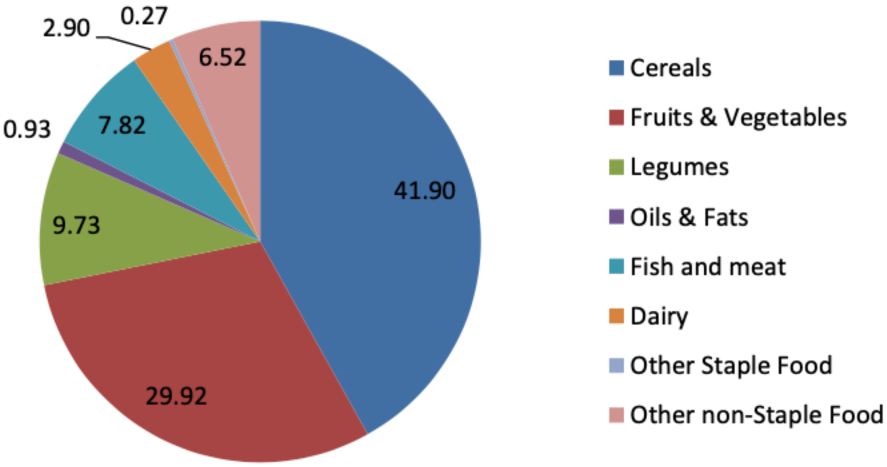

Figure 44: Rural food consumption share

Finally, the overall agricultural water requirement is calculated as follows:

$$Agriculture\ water\ demand(t) = Water\ requirement\ for\ land \cdot \frac{Cropland(t)}{Irrigation\ efficiency} \tag{16}$$

Where the weekly water requirement for a unit of land extension is represented by the water requirement for land.

Water supply subsystem

The component of this sub-system are desalinated water, groundwater, and surface water. The systems dynamic model models current and future water supply by considering factors including population increase, agricultural and domestic water demand, and the portfolio mix of surface water-dependent dams, groundwater, and rain-independent desalinated water supply.

Water supply subsystem-Desalinated water

Desalination plants are rain-independent supply sources that could help ease water scarcity and ensure a more stable supply. Large investments are currently being made in long-distance water conveyance and desalination projects in order to secure water supplies in the future, based on estimates of growing demand. It has been highlighted that future water supply sources will become increasingly expensive and energy heavy, as most locally available, less expensive, and more energy efficient choices have already been fully utilized [56].

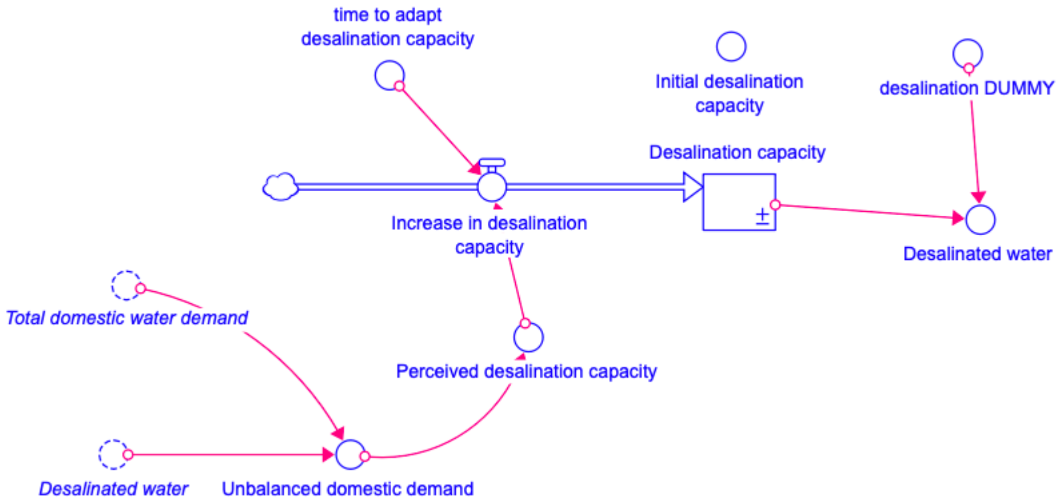

Figure 45:Stocks and flows diagram for desalination capacity

Starting from an initial desalination capacity, the increase in the size of the infrastructure come from the unbalanced domestic demand for fresh water, in fact as an assumption the domestic need is covered by the desalination supply. Starting with a small desalination capacity, the infrastructure will grow in size over time to meet the rising household demand for fresh water, assuming that the desalination water supply can meet the domestic demand.

$$\begin{cases} \int_t d\big(Desalination\ capacity(t)\big) = \int_t Increase\ in\ desalination\ capacity(t)dt \\ Increase\ in\ desalination\ capacity(t) = MAX\left(0; \frac{Perceived\ desalination\ capacity(t)}{Time\ to\ adapt\ desalination\ capacity}\right) \\ Perceived\ desalination\ capacity(t) = Total\ domestic\ demand(t) - Desalinated\ water(t) \end{cases} \quad (17)$$

Water supply subsystem-Surface water

Any body of water above earth is considered surface water, which includes streams, rivers, lakes, wetlands, reservoirs, and creeks. Despite being saltwater, the ocean is classified as surface water. The hydrologic cycle, sometimes known as the water cycle, involves the transportation of water from and to the Earth's surface. Surface water bodies are fed by precipitation and runoff. Water bodies, on the other hand, lose water due to evaporation and seepage into the ground. The amount of surface water accessible is computed here, taking into account the competition between surface water and hydropower generation.

$$Surface\ water\ available(t) = MAX\big(0; Surface\ water - Water\ demand\ for\ electricity\ production(t)\big)$$

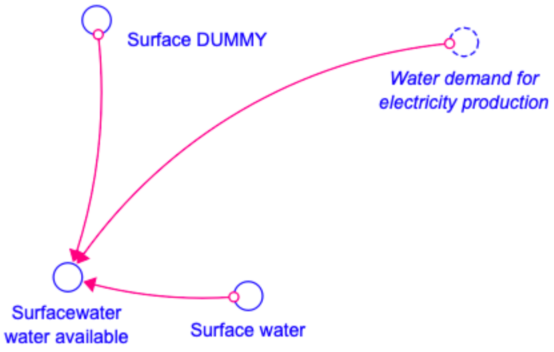

Figure 46:Surface water dynamics

The need for efficient, egalitarian, and long-term water resource management to meet the needs of many sectors is pressing, especially in locations where water supplies are depleting. Along with this comes the desire to gain a thorough understanding of the importance of water in its various applications. Understanding the value of water in its alternative uses is critical for fostering informed debate on water management and allocation, identifying the basis for making 'agreeable' trade-offs, identifying the potential for improvement, and establishing links with water allocation options, particularly in agricultural-based economies, where agriculture competes with other sectors and where water re-allocation decisions may involve large transfers of water from the sector generating the highest water demand such as hydropower generation [57].

Water supply subsystem-Groundwater

Groundwater is the primary supply of drinking water in Africa, and its usage for irrigation is expected to rise dramatically in the face of rising food shortages. As the African droughts demonstrate, many surface water sources are vulnerable to high temporal and geographical changes. Groundwater, on the other hand, accounts for nearly all the world's fresh water supply. This source is normally quite clean, and unlike surface sources, it is not affected by climate extremes. The task at hand is to develop the groundwater supply [58]. Because groundwater requires higher energy input for extraction, the dynamics of groundwater have been modeled in a supplementary fashion to those of surface water.

$$\begin{cases} \int_t d(Groundwater\ capacity) = \int_t Increasing\ Groundwater\ usage(t)dt \\ Increasing\ Groundwater\ usage(t) = MIN\begin{pmatrix} Max\ possibile\ groundwater\ extraxtion; \\ Unbalanced\ agriculture\ demand(t) \end{pmatrix} \\ Unbalanced\ agriculture\ demand(t) = Agriculture\ water\ demand(t) \\ \qquad -Agriculture\ water\ supply(t) \end{cases} \tag{18}$$

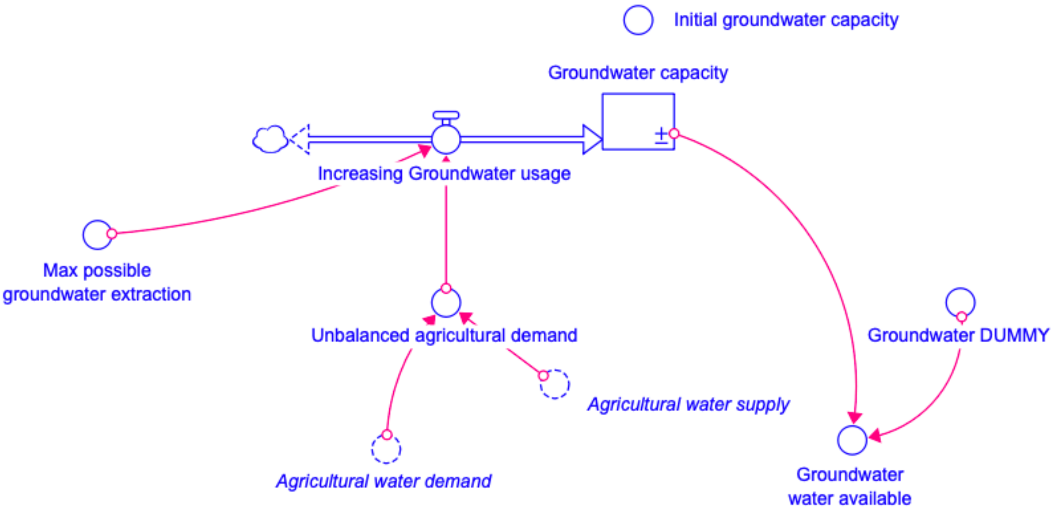

Figure 47:Groundwater supply dynamic

Households' medical expenditure

As seen in the IGAs creation and Income causal loop, improved health due to access to clean water aids in the reduction of health disease, which decreases money spent on medical services, hence boosting households' financial capacity. This dynamic is particular important in case of rural African context. Out-of-pocket expenditures, which are the most common method of paying health care in Sub-Saharan Africa, have hampered the region's efforts to achieve universal health coverage (UHC) and the Sustainable Development Goals, (indicator 3.8.2."the portion of population with large household expenditure on health as a share of total households' expenditure or income"). Any health-care expense that puts a household's financial ability to meet its basic necessities in jeopardy is classified as catastrophic, which does not always imply high health-care expenses. Even little health-care costs might be financially catastrophic for low-income families. This is because, in comparison to wealthier households, practically all their available resources are consumed for basic requirements, and they are thus less able to cope with even extremely low health costs [59].

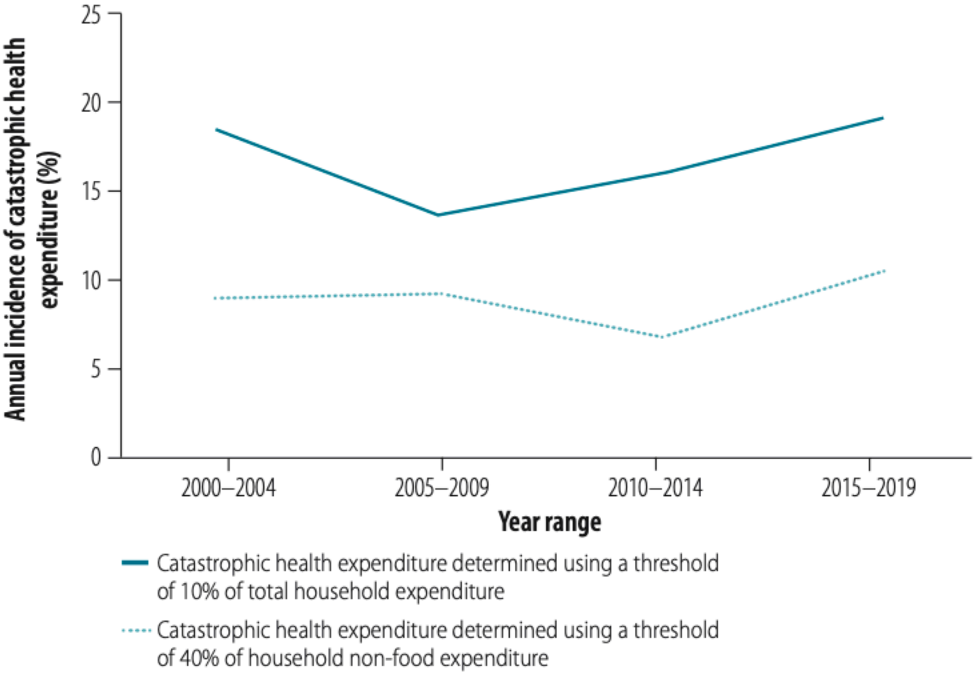

Figure 48: health expenditure in SSA 2000-2019

Focusing the attention on the positive effect of water access to health status, a study conducts in a remote rural area in the north-eastern parts of Limpopo Province in South Africa, used diarrhea incidence as an indicator to quantify the impact of the reliability of water delivery systems on community health improvements. After the intervention, showed a marked decrease in illness indicating a 57% reduction. The implementation of better water infrastructure appears to be linked to a decrease in diarrheal illnesses in communities. The health impact, on the other hand, was most noticeable in the community with the most trusted system [60].

Health-care spending is no longer a fixed parameter; instead, it is treated as a time-dependent variable that is dependent on the reliability of water domestic facilities and the percentage of domestic water supply. The following are the equations:

$$\begin{cases} fr\ income\ for\ medical\ expenditure(t) = Initial\ medical\ expenditure \cdot \\ \left(1 - water\ effect\ on\ medical\ expenditure(t)\right) \\ Water\ effect\ on\ med\ exp(t) = DELAY(\max med\ expenditure(t) \cdot fr\ decrese\ illness \cdot \\ Water\ availability\ effect(t) \cdot Domestic\ gap(t); Time\ to\ adapt\ reliability) \end{cases} \tag{19}$$

Irrigation effect on agricultural productivity

In the original model the farm productivity depends on three main factors:

1. Financial Resources
2. Education
3. Time

The introduction of the water supply subsystem emphasizes the importance of assessing the impact of irrigation on productivity. In fact, the implementation of a dependable irrigation system has a two-fold effect: an increase in productivity and a diversification of crop yields, both of which have a direct impact on farming income. Crop diversification refers to the practice of producing multiple crops at once. It's also concerned with the transition from subsistence to commercial agriculture, The greater the household's income from crop production, the greater the tendency to diversify into crop production [61] .Improved yields, decreased crop loss, improved cropping intensity, and greater farmed area may all contribute to higher production. The usage of water is enhanced when it is available on a regular basis [62] .

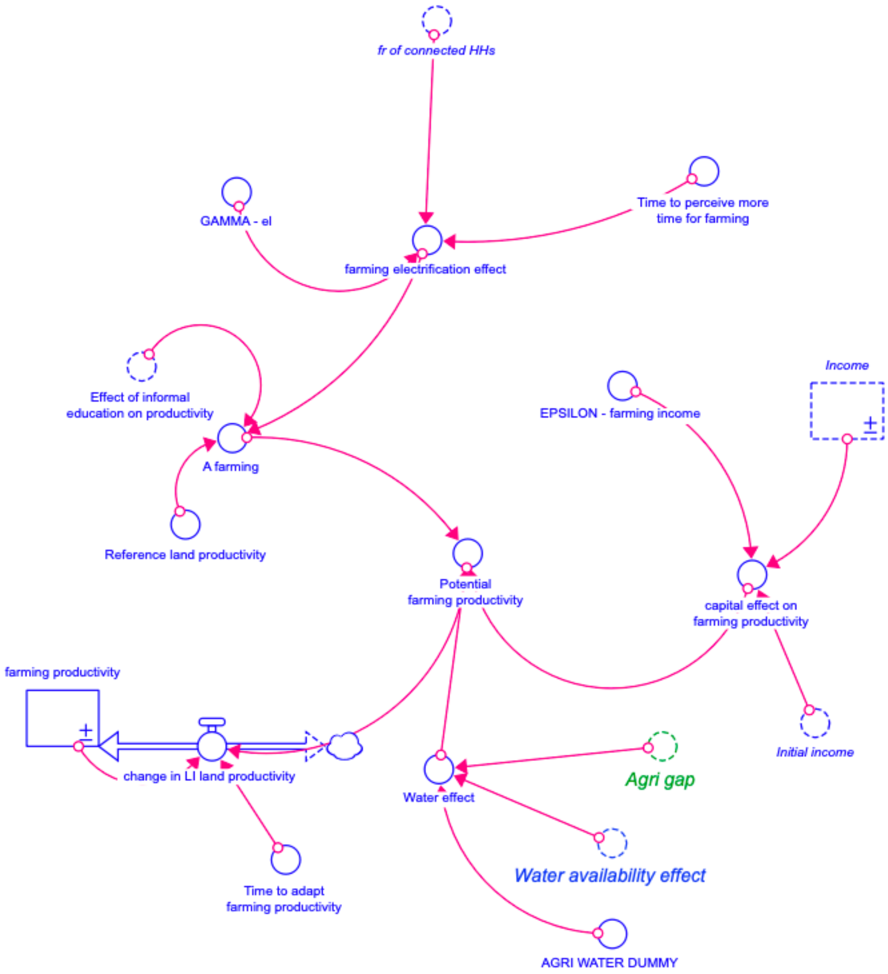

Figure 49:Potential farming productivity

As for the productivity of the local market for modeling farming productivity, the model uses a Cobb-Douglas formulation.

$$Potential\ farming\ productivity(t) = A_{farming}(t) \cdot Capital\ effect\ on\ farming\ productivity(t) \cdot Water\ availability\ effect(t) \quad (20)$$

Electricity subsystem

Hydropower, diesel generators, and solar power plants are all examined in terms of energy supply. The electrical consumption of irrigation networks drives the agriculture sector's electricity needs, the volume of residential water consumed is also taken into account when calculating electricity demand. Pumping for groundwater abstraction and the desalination process are two sources of electricity consumption on the supply side of the water infrastructure.

Electricity subsystem-Demand side

The sum of the direct and indirect embodied energy necessary to generate a specific unit volume of water is stated as the energy consumed for water abstraction, treatment, and distribution in pressurized water distribution systems. Indirect energy is defined as the off-site administrative energy and chemical consumption, whereas direct energy is defined as the onsite energy for the operation, water treatment, and distribution of water in terms of electricity and fuel. The embedded energy demand, which is calculated using life-cycle assessments, input-output analysis, or process-based hybrid techniques, varies depending on whether the water is supplied by groundwater, surface water, or reclaimed water. Depending on the well production, the height over which the water is raised, and the efficiency of the pumping systems, direct energy usage for delivering ground water is estimated to be 20–30% greater than that for supplying surface water per unit of water delivered. The pipe features, the treatment technique, the quality of raw water, and the distance from the source are the key factors of direct energy in surface water delivery alternatives. Estimates of total direct and indirect energy consumption for various water treatment procedures are given in terms of the amount of energy required (kWh) to generate one unit volume (1 m3) [63].

The evaluation of the power required for each equipment is calculated as follows:

$$Electricity\ demand\left[\frac{kWh}{week}\right] = water\ pumping\ efficiency[-]\cdot Energy\ intensity\left[\frac{kWh}{m^3}\right]\cdot water\ flow\left[\frac{m^3}{week}\right] \tag{21}$$

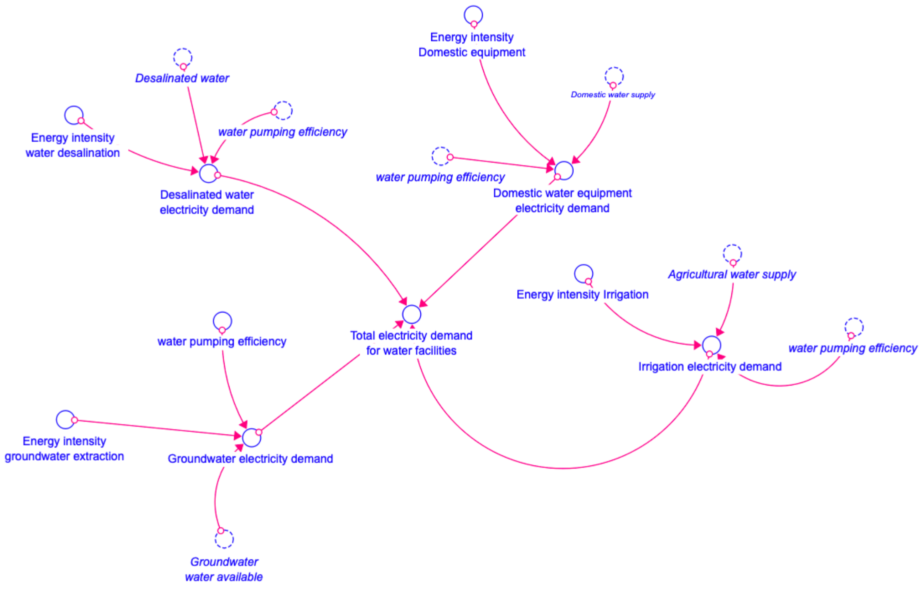

Figure 50: Energy demand

Table 2: Energy consumption for water supply

Water type	Energy intensity kWh/m^3	Reference
Groundwater	1.1-2.4	[64]
Irrigation	0,09	[65]
Domestic equipment	0,006	[54]
	Desalination process	
MSF	10.5-13	[66]
BWRO[1]	1.0-2.5	[66]
SWRO[2]	4.5-8.5	[66]

For the desalination process three different technologies are taking into consideration, this is because many of the various combinations of RES-driven desalination systems may not be practical under specific situations, therefore not all of them are feasible. There are various elements to consider while choosing a desalination method that is appropriate for a certain application, including as [67]:

I. The amount of fresh water required in a particular application in combination with the range of applicability of the various desalination-processes.
II. The effectiveness of the process with respect to energy consumption.
III. Suitability of the process for solar-energy application.
IV. The sea water treatment requirements.
V. The capital cost of the equipment and imported material.
VI. The land area required, or could be made available, for the installation of the equipment.
VII. Robustness criteria and simplicity of operation,
VIII. Low maintenance, compact size, and easy transportation to site.
IX. Acceptance and support by the local community with minimum change to social sphere,
X. Organization at local level with relatively simple training.

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[1] BWRO: Brackish water reverse osmosis

[2] SWRO: Seawater reverse osmosis

Two technologies offer around 80% of the world's desalination capacity: multi-stage flash (MSF) and reverse osmosis (RO). MSF desalination units account for more than 40% of the world's desalination capacity. MSF is made up of a series of stages with decreasing temperature and pressure. It works by generating vapor from seawater or brine as a result of a quick pressure drop when seawater enters an evacuated chamber. Because of the following benefits, low temperature MED is getting wider favor for smaller and medium capacity desalination facilities. [68]:

- Lower energy consumption
- Higher heat transfer coefficient
- Compactness
- High product water quality
- Reduced pre-treatment

Other desalination procedures, on the other hand, do not entail phase changes. Reverse osmosis (RO) and electrodialysis (ED)/electrodialysis reversal are membrane processes (EDR). Membrane technologies, particularly RO, are expected to continue to gain market share from thermal desalination, with membrane-based capacity accounting for 59 percent of total new capacity [58].

6.2. Model testing and validation

In Charter 3 (Paragraph 3.6), the theoretical explanation of the validation phase is reported following the Sterman guidelines, in this section it is shown hoe it has been implemented in this model. An important consideration is that not all tests were performed because of the nature of the model.

Boundary Adequacy Test

The first test consists in the evaluation of appropriateness of the model boundary and if important dynamics and loop have been omitted. This step was performed temporarily to the model building. The model purpose in this case asks for a more general and comprehensive structure, and so the literary review reveals a missing point to the objective achieving. The water and food sub-system have been added to fill this gap.

Structure Assessment Test

This test reveals if the model is consistent with the knowledge of the real system, it focuses on the level of aggregation, the conformance of the model to bas physical realities and the realism of the agents behaves. This analysis was performed during the modelling phase. Direct inspection of the equation disclosed the conservation rules’ validity. System diagrams, causal loop diagram, and stock and flow have been implemented considering the hypothesis assumed. The level of aggregation for the household’s definition has been changed following this test in section 6.1.3.

Dimensional Consistency Test

As Sterman declares, the dimensional consistency test should be among the very first you do. As matter of the fact, during the model definition, the units of measure have been specified for each variable and, a direct inspection of the equations has been conducted. Stella Environment software include auto dimensional analysis, which it was used as a further confirmation of the dimensional consistency.

Parameter Assessment Test

This test is performed through judgmental and numerical estimation, it checks the real life meaning of the variables in the model. As reported in Chapter 4 (Paragraph 4.1.6), all the data input, both exogenous and endogenous, are collected and classifies in a critical way. Proceeding in this way, all the data are accompanied by a brief description, this ensures a clear significance. Some of them are estimated through historical estimation form Riva’s model, other came from literate or numerical estimation.

Extreme Condition Test

This test tries to discuss the model's outputs for various input values, up to the most extreme ones. The more sensible values were used for this test, and the model's reaction was assessed by changing those parameters, ceteris paribus, within a feasible physical range. The model response's consistency with predictions was confirmed. The model was stressed to the lowest/highest achievable value until the occurrence of dynamics not considered in the model limits. Whenever a value must resemble an infinite number, it is arbitrary put to . Several conditions were tested, the most significant are here reported:

Fraction of feasible HHs market supply
Min: 0
Meaning: simulation of a market able to satisfy t 0% of the local HHs demand.
Max:1
Meaning: simulation of a market able to satisfy 100% of the local HHs demand.

Figure 51: Extreme condition on fraction of
feasible HHs market supply

The minimum shows extremely few IGAs are formed, only enough to meet the demand from outside sources and the supply chain of other IGAs. The response of the maximum simulation displays a higher number of IGAs formation, due to a higher market demand but also a higher market competition. These findings show that establishing access to electricity is particularly suited for a local context that has the resources to possibly meet all local market demand. On the other hand, a very remote community with few resources wouldn't develop only by having access to electricity; instead, it would need supplementary activities to secure enough productive inputs and resources.

Internal migration effect
Min:0
Meaning: no migration effects
Max:→
Meaning: all the HHs can potentially affords the connections
The minimum doesn’t show a sensible changes respect to the base case value. The response of the maximum in the simulated horizon, every household is connected. The entire demand for market products and services is decreased along with a reduction in the number IGAs as more individuals are required to pay for energy.Because it

enables individuals to diversify their consumption of products and services, this argues that a gradual pace of household power access is more sustainable.

Initial external market demand
Min:0
Meaning: closed economy.
Max:0,3
Meaning: market with high trading level.

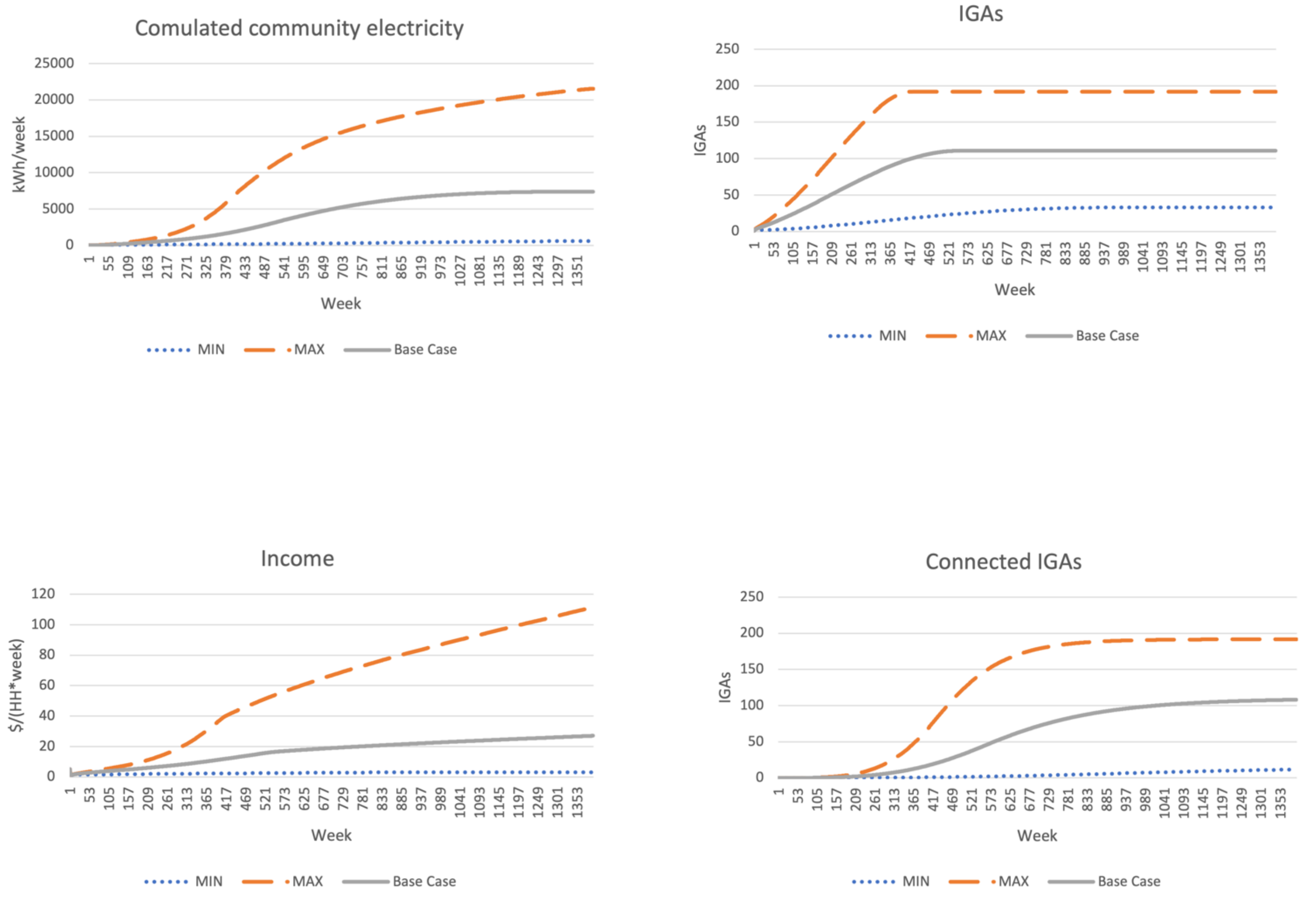

Figure 52: Extreme condition on initial external market demand

The initial market demand's minimal value denotes a poor economic performance, with the village's revenue remaining extremely low and connection and power consumption reflecting this. The maximum condition demonstrates a growth in IGAs, income, and electricity use—all indicators of significant economic success. These findings support the idea that the impact of electricity would be less on a local economy the closer it is to another. This shows how crucial it is to supplement electrification with other initiatives to increase remote settlements' accessibility (e.g. improvement of roads and communications).

Integral Error Test

This phase is carried out to make sure that altering the time step or the integration method will not materially alter either the behavior or the outcomes. The "cutting-in-half" test was used to determine whether the time step was adequate It consists in selecting a first-tentative time step Δt1, simulating the model with a Δt2 obtained by cutting the time- step in half and the checking if the results change substantially. If not, Δt1 is appropriate; otherwise, the iteration continues with Δt2. . The first tentative time step was chosen to be one-fourth (viz. 0.25), the size of the model's lowest time constant (viz. 1 week), in accordance with Starman's rule of thumb (Sterman 2000). The values of the 4 variables were analyzed at the conclusion of the simulations to see if the results are sensitive to changes in the time-step. In specific, the iterative "cutting-in-half" technique was carried out up until the Δt-error term ξ condition indicated in the following equation was satisfied. The first iteration verified that the time-step of 0.25 was suitable (Table 2).

$$\xi = \frac{X_{t=FINAL,dt} - X_{t=FINAL,{dt}/{2}}}{X_{t=FINAL,dt}} \leq 5\% \quad (22)$$

Table 3:Δt-error term for the main 4 output variables of the model.

Variable	ξ
Total connected HHs	0,03%
Cumulated community electricity demand	2,33%
Domestic Gap	0,33%
Total water demand	0,53%

The aim of the second part of this validation test is to determine whether the behavior persists even when the integration technique is changed. The traditional Runge-Kutta technique, often known as a "RK4", with fixed and automatically adjusting increments, is used to compare it to the Euler method. The RK4 approach enables the computation of a more accurate integration in contrast to the Euler integration, which assumes that the derivates (i.e., rate) are constant throughout the finite time-step Δt. The numerical approximation of the integral at time t+dt is determined by the value of the level at time t plus a weighted average of four increments, where each increment is the product of the time-step Δt, a weight coefficient wi , and an intermediate evaluation ki of the derivate ("rate") .

$$Y_{t+dt} = \int_{t}^{t+dt} x \cdot \Delta t = Y_t + \Delta t \cdot \left(\sum_{i=1}^{4} w_i \cdot k_i\right) \quad (23)$$

At the conclusion of the simulations, the values of the same four variables of the previous test were examined, and the error term was compared to the Euler technique. Table 30 demonstrates that the model has acceptable error margins of approximately 5% and is not overly sensitive to changes in the integration approach.

Table 4:dt-error term for the main 4 output variable of the model.

Variable	ξ
Total connected HHs	0,14%
Cumulated community electricity demand	2,8%
Domestic Gap	0,1%
Total water demand	1,4%

Behavior Reproduction Test

To conduct the Behaviour reproduction test, Sterman suggests some statistical measures to include descriptive analysis. He also recommends trend comparison between the model output and the actual, or better the historical, data by formulating a linear, quadratic, or an exponential trend. The historical data fitting do not always confirm the model must be correct. There may be many models that replicate the data well, but it can never show that the behavior of the reality was generated by any particular structure. According to this theory, this test cannot be performed in this case because it is an ex-ante simulation test, the time horizon is referring to the future 20 years, thus the output of the model is a prediction of what might happen.

Behavior Anomaly Test

Due to data restrictions, statistical methods are frequently unable to determine the significance or strength of crucial relationships or formulations. Behavior anomaly tests look at how important these structures are by asking if abnormal behavior occurs when the relationship is changed. The goal of this research is to develop a general model capable of simulating the behavior of various local contexts. However, the absence of data from various case studies prevents an accurate test of the simulation's response to changing contexts. The test was carried out solely by increasing the population size from a beginning population of 3000 to 30000 persons.

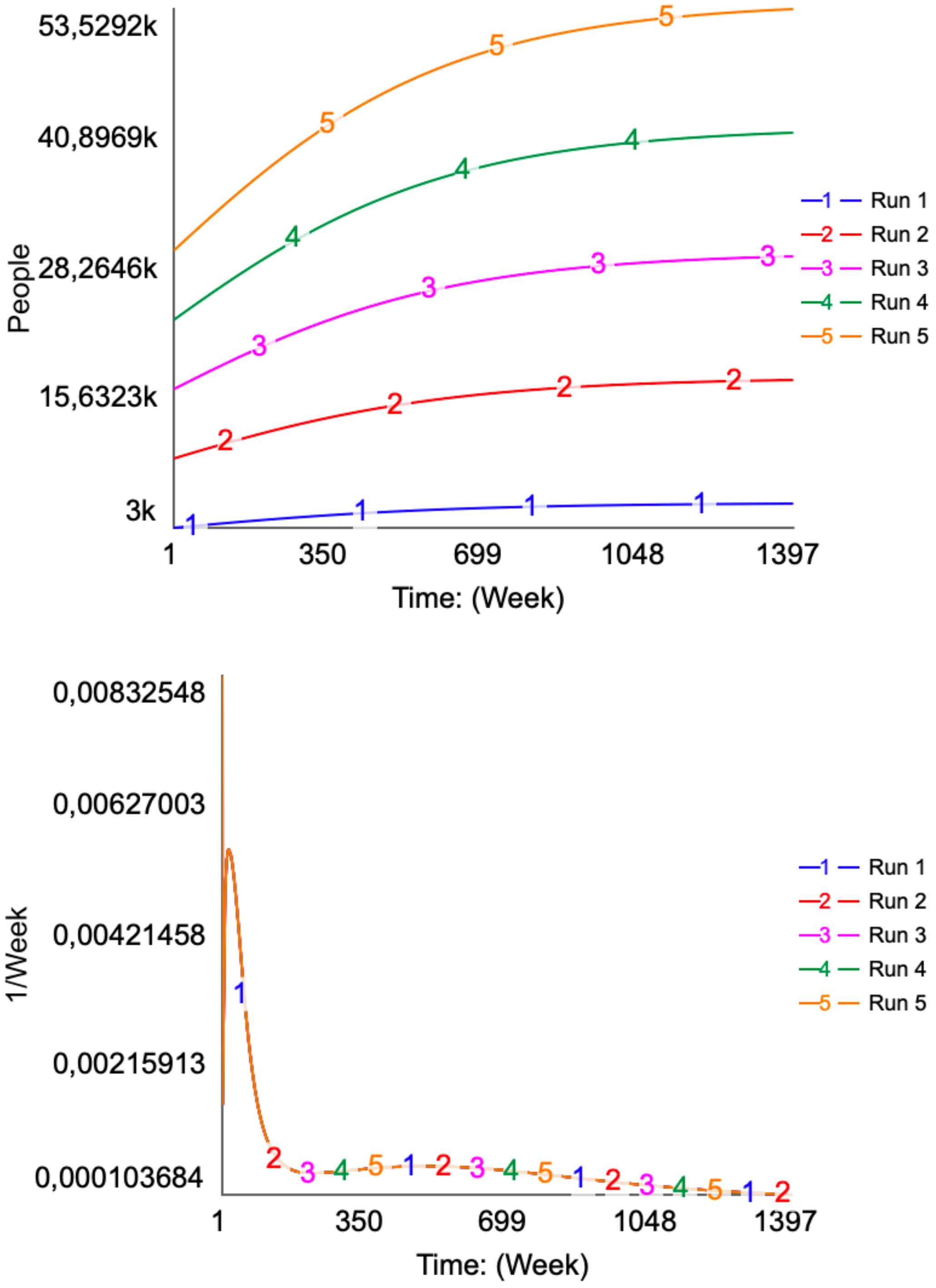

Figure 54:Trend in HHs connection for the different villages size

It's clear that increasing the village size has the same effect on the trend in home connection. This means that the model can replicate a variety of scenarios. As a result, the initial model's restriction has been overcome without unexpected results.

Family Member Test

The family member test determines whether the model can create behavior for other instances in the same class as the system it was designed to emulate. The more instances of a system that a model can represent, the more general the theory it represents. When the class of systems the model addresses comprises a wide range of alternative patterns of behavior, the family member test is especially useful. Any model that can only demonstrate one mode of behavior should be regarded with caution. In the case under investigation, this validation test was not carried out. Nonetheless, some qualitative examples can be provided. As far as the electricity access project is concerned, another important aspect could be modeled: the access to clean fuel for cooking. The use of solid fuels for cooking is a major cause of indoor air pollution-related mortality and illness. Transitioning from ancient methods of cooking and heating to more contemporary, cleaner ones is the most obvious strategy to reduce indoor air pollution from solid fuel burning. Transitioning to non-solid fuels such as natural gas, ethanol, or even electric technology can be one way to achieve this. For this new case, new information about cooking habits have to be found; it is also necessary to identify the major obstacles and drivers that influence the adoption fraction.

Surprise Behavior Test

The surprise behavior test aims to find flaws between the model behavior and the expected output, in the formal model, in the mental model, or both. For the test to be effective the model behavior must be analyzed closely, looking at the comportment of all variables not only the major indicators. The way to do that is carefully document the mental models prior the modeling effort. This test has been conducted during the model building, whenever a partial simulation gave unusual results.

Sensitivity Analysis Test

In this validation test, the findings are tested for robustness when a variety of uncertain assumptions are changed. As stated in Chapter 3, it must be carried out on variables that are both highly unclear and likely to have an impact. The variables on which the sensitivity analysis must be used must first be specified. Finding the range of uncertainty through online research, publications, and studies is the next step.

Table 5:Range of uncertainty

Variable	MIN	MAX	UDM	SOURCE
Irrigation efficiency	34%	42%	-	[35]
Income elasticity	0,06	0,15	-	[47]
Product performance	1,196	1,450	$kg/_{m^2}$	[69]
Water requirement for land	0,0768	0,1152	$m^3/_{(week \cdot m^2)}$	[70]
Efficiency of delivery networks	85%	65%	-	[71]
Willingness to pay	0,112	0,2	-	[72]
El Reliability	0,9583	0,9995	-	[26]
Fr change in external market demand	0,4484	0,4956	-	[26]
Reference Factor productivity	0,3534	0,3906	-	[26]
Fr of feasible HHs market supply	0,6	0,9	-	[26]

Some variables' confidence intervals have already been supplied by the source, among this there are: *irrigation efficiency, Income elasticity, willingness to pay, El reliability, fr change in external market demand*, *reference factor productivity*, and *fr of feasible HHs market supply.* For *the* remaining part the range of uncertainty has been computed by changing the actual value of a ±5%.

To perform the test is needed to explain the weight of some parameters in the real world, understanding the meaning of their variation.

Table 6: Parameters’ variation discussion

Parameter	Discussion
Income elasticity	The likelihood that a household would opt to utilize the water system would rise by around 1% for every 10% increase in household income. Simple terms, the higher the elasticity, the greater the amount of water used by households.
Product performance	A more productive farming method increases the amount of food produced per m^2 of farmed area as product performance values rise.
Fr change in external market demand	This parameter indicates the quality and entity of the commercial trading for both food, and non-food goods and services. Low value means a more close economy, while the higher one simulates a market with higher trading level.
Reference Factor productivity	Fundamental concepts in microeconomics include productivity and "marginal product." The idea is closely tied to the market's dynamics of supply and demand, which apply to rural regions as well. The local market competition and consequently the number of IGAs would alter depending on whether IGA production increased or decreased.
Fr of feasible HHs market supply	This parameter takes into consideration a fundamental dynamic: the greater the local consumer purchasing power, the less family spending is required to meet local market demand.

To determine the worst/best values for each variable that produce the least/most favorable policy result, sensitivity analysis is conducted on each parameter. They are reported in the table below. Then, four runs are performed, with two representing the best scenario and the other two representing the worst situation. A comparison between the base case and complete scenario implementation is done for each best and worst situation.

Table 7:Worst and best case

Variable	WORST	BEST	UDM
Irrigation efficiency	34%	42%	-
Income elasticity	0,060	0,150	-
Product performance	1,196	1,450	$kg/_{m^2}$
Water requirement for land	0,115	0,077	$m^3/_{(week \cdot m^2)}$
Efficiency of delivery networks	65%	85%	-
Willingness to pay	0,112	0,2	-
El Reliability	0,958	0,999	-
Fr change in external market demand	0,4484	0,4956	-
Reference Factor productivity	0,353	0,391	-
Fr of feasible HHs market supply	0,600	0,900	-

It is crucial to emphasize that combining the worst/best values of each element does not necessarily result in the worst/best scenario.

The results are shown in the following graphs:

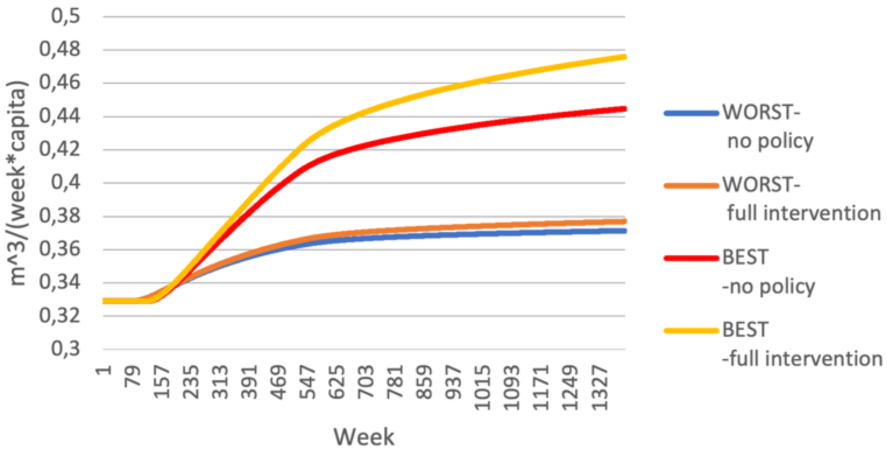

Figure 55: Per capita water demand

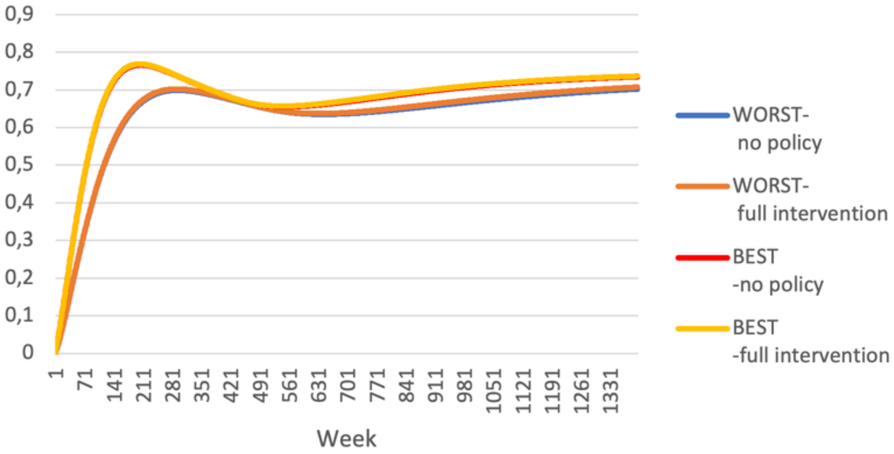

Figure 56:Fraction of connected HHs

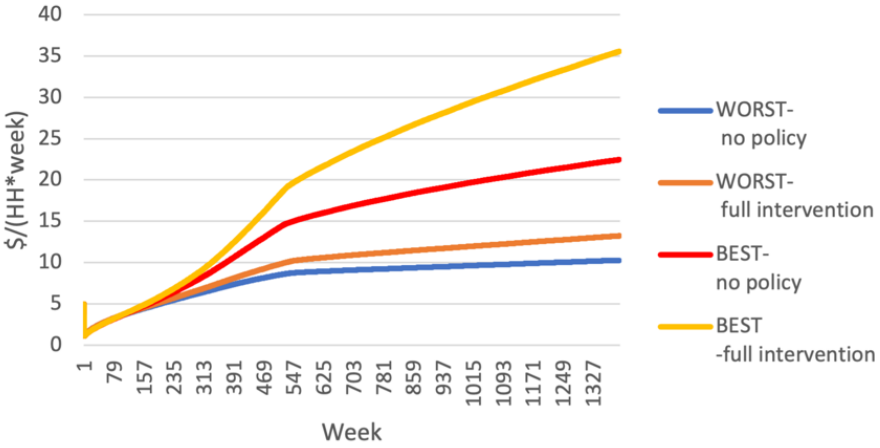

Figure 57:Income

The domestic water consumption is significantly lower in the worst scenarios compared to the best case, as seen in the graphs. This is a result of poor service quality; in reality, in the worst situations, the difference in water demand level compared to the scenario with no policy implementation is only 1,5%, while in the best case, the implementation of the policy results in an increase in *per capita water demand* of around 7%. Additionally, the long-term trend is the same since population increase, which is constant in all scenarios, is the key factor influencing the *per capita water demand* variable.

Looking at the *Fraction of connected households*, this tells us that the water policy implications do not have an impact on the households' electricity connection rate because the difference in connections is only noticeable between the two best and the two worst circumstances.

In the worst circumstances, the variations in *Income* levels are the most noticeable. This is because access to water improves farming output and lowers healthcare costs, which together contribute to a rise in income.

It is clear how the results in *Income*, the F*raction of Connected Households*, and *Per Capita Water Demand* attain their higher values when all the selected variables for the sensitivity analysis display their maximum value.

System Improvement Test

A modeling's ultimate purpose is to address a problem. This test examines whether the modeling method aided in the improvement of the system. The process of identifying the policy that led to improvement entails measuring the influence of a model, which is a challenging task. Because it takes a long time for new policies to take effect, the approach should include a long-term experimental protocol. This test cannot be implemented because this model is only a simulation of alternative policies.

6.3. Model application: Burundi case study

The village of Rutana serves as the thesis' intended backdrop. With the method employed in this study, the model can simulate the ex-ante dynamics related to the availability of water and energy in a rural community. To do this, the data categorization covered in chapter 4 describes the kinds of inputs that must be provided in order to represent a certain context.

The crucial endogenous dynamics must then be determined for the case study after the model's pertinent variables have been identified. In this way, actual findings about the influence of the policy's execution are tested, showing the positive effects on the village's socioeconomic dimension. Different sources provided the information that was needed to define the context. In Rutana, a field study has been set up to examine the model behavior through household interviews and additional data come from literature. The Table 8 shows the context related input data.

Table 8: context dependent parameters

PARAMETER	UM	VALUE	SOURCE
Annual population growth rate	-	0,03	World Bank Data, 2018
Food consumption per capita	Kg/(capita*week)	10,36	Zeinab Ravar, "System Dynamics modeling for assessment of water-food-energy resources security " 2020
Fr if initial HHs to be connected	-	1,00	Local observation
Fr income for education expenditure	-	0,10	A comparison of real Households consumption expenditures and price levels in Africa,Africa Development Bank, 2012
Households size	people/ households	4,80	United Nations , Database on Households size and composition 2019
Initial Income	$/HH*week(or month)	4,60	World Bank Data
Initial domestic water demand	m^3/(week*capita)	0,33	Mehdi Rahmani, *Ain Shams Engineering Journal,* 2022.
Initial fr income for food expenditure	-	0,43	A comparison of real Households consumption expenditures and price levels in Africa,Africa Development Bank, 2014

Initial fr income for medical expenditure	-	0,25	sdg-tracker.org
Initial fr of HHs close to the grid	-	0,06	Local observation
Initial population	people	3.000,00	field study/setted by modeller
Internal migration effect	-	1,18	calibration parameter from previous model
Investment for a new IGA	$/IGA	1.500,00	The Global Competitiveness Report, World Economic Forum 2019
Local currency to USD	$/currency	0,00	currency exchange, Jan 2022
Max cropland available	m^2	200.000,00	Local observation
Max fraction income for health expenditure	-	0,40	sdg-tracker.org
Max Groundwater extraction	m^3/week	500,00	Local observation
Power EE-IGA	Watt/IGA	15.940,00	Local observation
Power notEE-IGA	Watt/IGA	60,00	Local observation
price to cost factor	-	3,00	settled by modeller
Surface water	m^3/week	10.000,00	Local observation

Time for setting-up the IGA	weeks	0,57	The GlobalCompetitiveness Report, World Economic Forum 2019

6.4. Impact and effectiveness evaluation of the project

6.4.1. Policy testing

In order to evaluate the success of an electrification project, their application, and implications for water supply management for the domestic and agricultural sectors within the case study, various policy scenarios were designed and simulated over a period of 20 years (i.e., between 2022 and 2042).

First, the baseline run, or the *Energy scenario* was run over the simulated period. Over the course of the simulation, the baseline run, or the Energy scenario, was first executed. This scenario made the assumption that the village's socioeconomic situation is mainly attributable to the installation of electricity. The results of the model simulation demonstrate how closely connected supplementary measures, such as financial access and exogenous capacity building, are to the attainment of social and economic growth related to access to energy. The Scenario 1, *Domestic Water*, represents the availability of domestic water because of the electrical connection. The goal is to show that improved access to energy not only improves the socioeconomic situation of the population, but also makes it possible to enhance other services like domestic water supply, which has a positive impact on both health and again socioeconomic conditions.

The effect of cropland growth within the communities is simulated in Scenario 2: *Cropland Expansion* by an irrigation network driven by electricity. To address the problem of water losses brought on by inefficient infrastructure, this scenario also considers the need that an increase in farmland must be matched by an increase in the effectiveness of the water delivery network. Therefore, scenario 2 models the impact of farmland development on the availability of water resources, water demands, and agricultural output. To show a comprehensive intervention scenario, the impacts of the preceding scenarios are added to the consequences of this scenario, which was built on the underlying premise that the present cropland area would expand.

When the dynamics associated with certain activities are eliminated from the model, the efficacy and impact of the electrification project will be thoroughly examined. Following that, the different scenarios are displayed, comparing the results of various circumstances in terms of *income, affordable connection,* and *fractional income for medical expenses.*

Income

The effects of the project's electrification measure the achievement of social and economic development along with the access to electricity in the area is clearly stated by the *Income* variable.

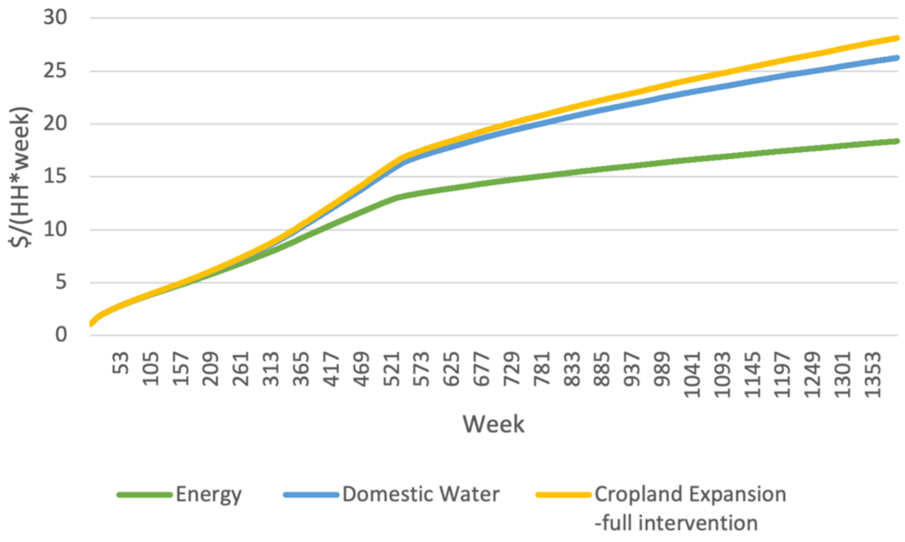

Figure 58: Policy testing on income

Table 9:Policy testing on income

Domestic water	Cropland Expansion-Full intervention
+43%	53%

These results indicate that, despite the only energy scenario brings an increase of the income thanks to the setting-up of new business that raises living conditions, increases income, and perhaps improves human welfare, on the other hand the access to drinkable and safe water and subquently the irrigation implementation, they sharply increase the income already growing by the percentage shows in Table 5. This is due to the dual impact that access to water has on the generation of income. Higher levels of water availability will result in lower health care costs, and more productive agriculture will result in higher farming revenue. The percentage variation of the outcome has been computed at the final time step comparing to the Base case (Energy scenario).

Affordable connection

The effectiveness of the electrification project measures the achievement of the electrification rate in the rural area, well expressed by the *affordable connection* variable. This variable is interesting because in this thesis the attention has been focused on the 7th SDG whose target is to "ensure access to affordable, reliable, sustainable and modern energy for all". This variable is computed knowing how much money would be necessary for households to invest in being connected to the grid, compute then the ratio between households that will spend the money for the grid connection over the total number of households.

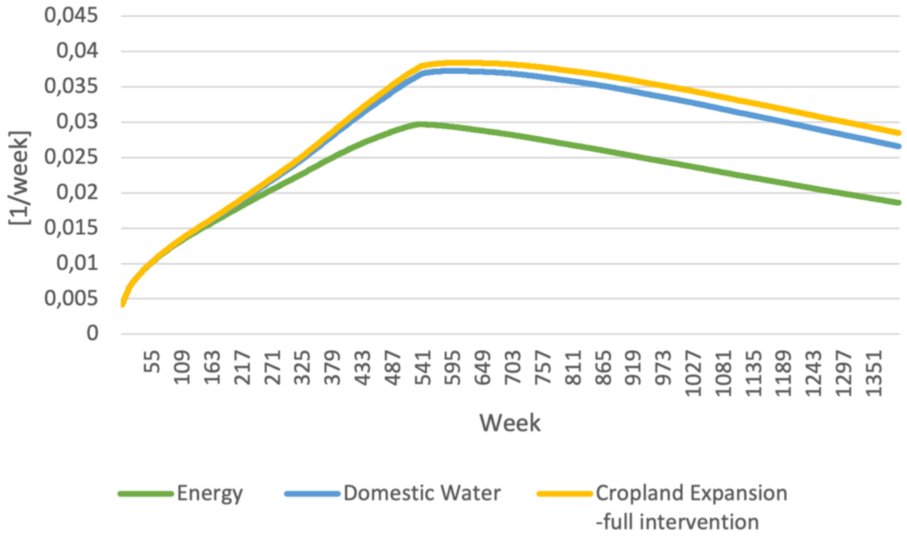

Figure 59: Policy testing on affordable connection

The effect on the income of the policy implementation seen in the previous analysis are reflect in this one. The higher the income, the higher will be the portion of households who can afford the connection cost. The reversal of the trend which occurs more or less at half time window it is due to the fact that the connection rate will slow as when an innovation introduction happens.

Fractional income for medical expenses

Access to clean water improves health, which lowers the incidence of sickness and lowers the cost of medical care, improving household finances. For low-income families, even little medical expenses might have disastrous financial repercussions. This is because all of their resources are used to meet their fundamental needs, making them less able to handle even incredibly low health expenses. The fractional income for medical expenses has been used as an indicator to assess the influence of the dependability of water delivery systems on changes in community health, drawing attention to the beneficial impact of water availability on health status. A decrease in diseases in communities seems to be associated with the implementation of better water infrastructure.

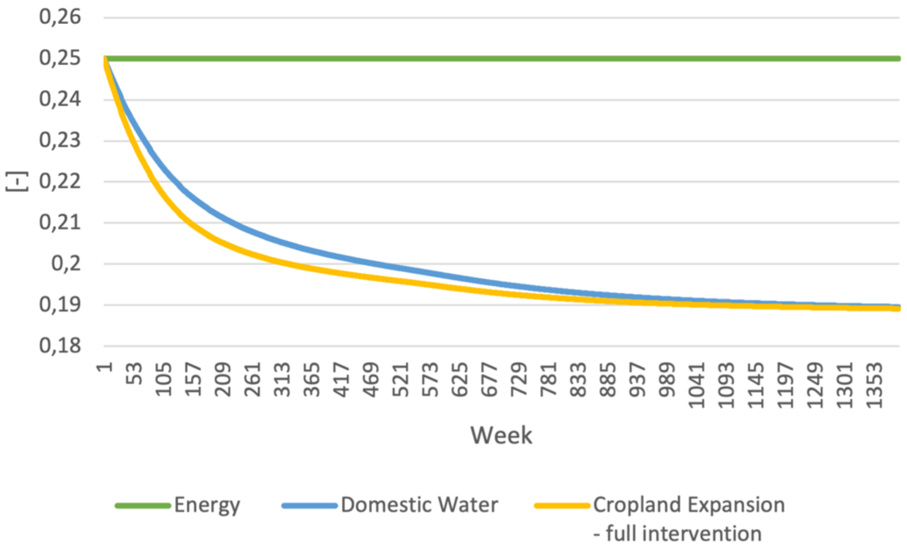

Figure 60: Policy testing on fractional income for medical expenditure

The percentage of income allocated for medical expenses in the Energy Scenario is expected to remain constant throughout the simulation's time span. This is attributed to fact that in the base case is not considered any intervention for health status-related issues. In the long term, the outcome is the same in both the domestic water scenario and the crop expansion scenario, but the last, after the transitory, it reach first the regime value . The delivery network efficiency is increased during the whole intervention, which reduces the time needed to attain the ideal value.

Regarding the electrification project's impact, the results from all of the scenarios demonstrate that achieving a social and economic development related to access to electricity is highly dependent on the complementary actions that have been implemented; obviously, the concurrent application of all complementary activity is essential for achieving the expected impact of the electrification project, such as in the Full Intervention scenario.

However, considering that they are essential pillars in a rural community, agricultural water distribution networks should receive special attention. They stand for the basic elements that will support sustainable production and stimulate the expansion of a self-sustaining social and economic development. Additionally, the home water supply is crucial in both the social and economic spheres. It starts the revenue, accelerating the rate of electrification and its beneficial effects.

The results of policy testing give a list of essential complementary activities to pair with electrification programs in order to maximize their favorable effects on rural populations and water supply.

6.4.2. Identification of the SDGs target

The 17 Sustainable Development Goals (SDGs) and their objectives are "integrated and indivisible" by definition, therefore every action taken to implement the 2030 Agenda must take this interrelationship into account. Lack of knowledge of the connections between various components of sustainable development is one of the obstacles to accomplishing these goals; as a result, effort is needed to map these interactions and communicate them to policy makers. A more democratic process and the achievement of desired results may result from improved communication and awareness of the effects of energy initiatives. Tools that make it easier to get information on how particular energy projects may impact the local and global attainment of the SDGs are urgently needed in light of the shown of linkages between energy and the SDGs. These resources will help stakeholders have the critical conversation about the essential steps to enhance the social, environmental, and economic consequences of energy projects. For these reasons, the thesis's ultimate goal is to demonstrate the influence of model simulation on the SDGs' target as well as the quantitative data gained from the simulation.

The energy access leads not only the achievement of the SDG 7, in fact the grid relaying on new, efficient, and reliable technology, resulting in synergies with infrastructure (9.4), energy (7.1, 7.3), and resource efficiency targets (8.4, 12.2). Possible synergies with poverty (1.1, 1.2, 1.4) and economy targets (8.3, 8.5, 8.6) come from the expectation that the project would generate employment, which will boost the local economy. As a project developer, the goal is to carry out the plan in a just and transparent manner, with extensive stakeholder participation and public education initiatives, creating synergies with equity aims and maybe having a beneficial social impact (5.1, 5.5, 10.1–10.3, 16.7). Due to the availability of energy and its potential health implications, significant trade-offs relating to water access have been discovered putting in place suitable resource delivery network systems addressing on sanitation and health (3,.1,3.8 ,6.2 ,6.3) that will simultaneously aim to improve food security through increased productivity and production from resilient agriculture practices, that help maintain ecosystem (2.4).

The table below shows the outcome of the SDGs’ target after the project implementation, compared to the national level.

Table 10: SDGs' indicators

Indicator	Project	National Level
3.8.2. Households' expenditure on health (fraction of income)	18%	22%
6.1.1. Proportion of population using safely managed drinking water	98%	55%
7.1.1. Proportion of population with access to electricity	72%	11%
8.1.1. Annual growth rate of real GDP per capita	2,8%	1,6%

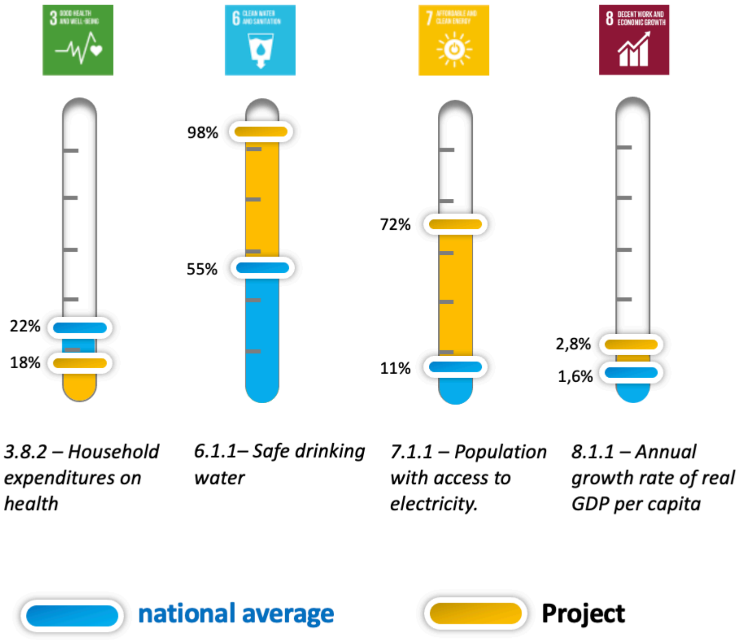

Figure 61: SDGs dashboard

7 Conclusion and future developments

7.1. Conclusions

A system dynamics-based simulation model created for long-term electricity demand estimates in rural environment has been used to achieve the major goal of this research project. To create a more straightforward and flexible model for use in other scenarios, the complexity of the case specific, substantial, and parameterized model structure was specifically addressed via a simplification method. As a result, the model's structure and behaviour have been validated by testing the simplified model against the different kind of validation: direct structure tests, structure-oriented test, and Behaviour pattern test. To assess how the impact of complicated electrification projects may boost their efficacy and success in rural contexts, it has now been feasible to use a policy testing where multiple scenarios are taken into consideration.
Several results have been discussed which have been reported below:

1. The model employed is a System-Dynamics model, which offers a modelling technique that aids in a more thorough understanding of the system and its associated causation. It is a method that aids in managing intricate systems like the nexus between growth and power. High levels of uncertainty, potent nonlinear events, complex diffusion processes, or time delays can have an impact.
2. A characterisation of the parameters is used to address the replication problem. The model has a total of 136 fixed parameters that need to be started. These parameters' value may vary from project to project, thus in order to make acquiring them easier, they have been divided into four categories.
3. The elimination of several dynamics and feedback loops from the model structure is a consistent value addition, increasing the model's usability and flexibility in addition to the reduction of parameters almost equivalent to 23% of the total parameters.
4. It also paves the way for further generalization of the System-Dynamic model for long-term electricity demand projections and its implications on the water energy food nexus. The validation helps to increase confidence in the simplified model framework and allows for testing the ability of the model structure to reproduce the behaviour on a different context.

5. According to the results of the policy testing, electrification and the establishment of a water supply distribution network that is adapted to local demands are crucial to fostering self-sustaining socioeconomic growth. Another key finding is that having access to clean water is significant for both social and economical reasons since it increases income, which in turn accelerates the rate of electrification and its beneficial effects.
6. The impact of model simulation on the SDGs' aim and the quantitative information obtained from the simulation have both been proven. Energy availability is a key factor in achieving SDG 7, but it also contributes to infrastructure and resource efficiency goals because the grid relies on modern, dependable technologies. The anticipation that the project will produce employment, which will strengthen the local economy, suggests potential connections with poverty and economic aims. Significant trade-offs regarding water access have been discovered due to the availability of energy and its potential health effects, leading to the establishment of suitable resource delivery network systems addressing on sanitation that will simultaneously aim to improve food security through increased productivity and production from resilient agricultural practices, that help maintain ecosystems.

The overarching goal of the thesis and outline, which would be the complementing measures in support of water, energy, and food programs that guarantee not only access to electricity but also sustainable growth, has been accomplished in this way.

In order to maximize the electrification project's beneficial effects on rural communities, policy testing allowed for the establishment of best practices, minimal requirements, and supporting activities. This suggests that in order to ensure the long-term viability of electricity access initiatives, future electrification programs might build on these results to determine the most important issues to address.

7.2. Future works

The debate presented above leaves certain unresolved questions and potential for future advancements, which are covered in this section. Future phases in the research would take into account further simplifying the model to concentrate just on the core dynamics, making it easier to use right away and more adaptable for usage in many scenarios. This should also eliminate the structure's dependence on the starting circumstances and offer up research projects aimed at expanding the model to various larger sizes. The planning of sustainable energy for cooking and heating requirements is another major obstacle to energy access in underdeveloped nations, hence it is proposed to extend the model to the thermal energy carrier.

A crucial element of the food-energy-water nexus is the battle for water between the food and energy industries. In order to understand how competing water uses for crop-specific irrigated agriculture and fuel-specific power production affect local water shortages for the population under both the current and a warmer climate, additional synergies should be research to describes competing water uses .

Bibliography

[1] IEA, "Energy Access Database," [Online]. Available: https://www.iea.org/energyaccess/database/. . [Accessed May 2022].

[2] L. H. Helene Ahlborg, "Drivers and barrieries to rural electrifiction in Tanzania and Mozambique -Grid-extension, off-grid, and renewable energy technologies," 2014.

[3] OECD, "Water Risk Hotspots for Agriculture, OECD Studies on Water," OECD , Paris, 2017.

[4] IEA, "World Energy Outlook," Paris, 2010.

[5] FAO. [Online]. Available: /http://www.fao.org/energy/water-food-energy-nexus/en/. [Accessed May 2022].

[6] M. S. G. C. Elias Hartvigsson, "Rural electrification and capacity expansion with an integrated modeling approach," 2018.

[7] E. C. C. P. Fabio Riva, "Towards modelling diffusion mechanisms for sustainable off-grid electicity planning," Energy for Sustainable Development , 2019.

[8] J. E. E. A. a. S. M. E. Hartvigsson, "Assessment of load profiles in minigrids: A case in Tanzania," in *50th International Universities Power Engineering Conference (UPEC)*, 2015.

[9] E. &. E. J. &. A. E. &. M. S. Hartvigsson, "Using system dynamics dor long term bottom-up electric load modelling in rural electrification," 2016.

[10] A. T. F. G. E. C. Fabio Riva, "Long-term energy planning and demand forecast in remote areas of developing countries:Classification of case studies and insights from a modelling perspective," Energy Strategy Reviews, 2018.

[11] E. C. Fabio Riva, "System-dynamics modelling of the electricity-development nexus in rural electrification based on a Tanzanian case study," 2020.

[12] D. P. M. &. C. Collste, "S.E. Policy coherence to achive the SDGs: using integrated simulation models to assess affective policies.," 2017.

[13] M. Institute, "iSDG Model Documentation," 2016. [Online]. Available: https://www.isdgs.org/isdg. [Accessed May 2022].

[14] S. A. D. C. a. H. H. Matteo Pedercini, "Harvesting synergy from sustainable development goal interaction," 2019.

[15] N. P. L. Ogano, "Analysis of policy options for projects in the electricity sector in Sub Saharan Africa: a system dynamics approach," *The South African Journal of Industrial Engineering,* 2017.

[16] J. W. L. P. Alex Smajgl, "The water-foof-energy Nexus: Realising a new paradig,," *Journal of Hydrology,* 2016.

[17] E. B. B. B. J. M. D. J. H. N. P. K. M. A. N. F. V. O. J. C. B. H. S. D. Y. I. Eloise M. Biggs, "Sustainable development and the water-energy-food nexus: A perspective on livelihoods," *Enviromental Science & Policy,* 2015.

[18] W. E. Forum, "Water security: The Water-Food-Energy Climate Nexus," Washington D.C., 2011.

[19] W. M. E., "Thirst for Power: Energy, Water, and Human Survival," Yale University Press, 2016.

[20] S. K. B. d. V. Maryam Ghodsvali, "Review of transdisciplinary approaches to food-water-energy nexus: A guide towards sustainable development," 2019.

[21] P. L. Z. L. J. Z. D. L. L. X. Maoyuan Feng, "Modeling the nexus across water supply, power generation and enviromental system using system dynamics approach:," 2016.

[22] C. Robinson, "Dynamical systems: stability, symbolic dynamics, and chaos," 1998.

[23] M. &. L. S. &. H. M. &. I. S. &. F. E. &. E.-S. A. Zomorodian, "The state-of-the-art system dynamics application in integrated water resources modeling," *Journal of Enviromental Managment,* 2018.

[24] S. John, Business dynamics : systems thinking and modeling for a complex world, 2000.

[25] F. J.W., "Industrial dynamics: a major breakthrough for decision makers," 1958.

[26] F. Riva, "Modelling endogenous complexities in rural electrification: on the local dynamics of growth and the planning of off-grid system," Politecnico di Milano, 2019.

[27] B. Y. Savsel A.K., "Model simplification and validation with indirect structure validity tests," 2006.

[28] E. R. L., "Simplification," and understanding of model. System dynamics review, 1989.

[29] S. K., "Slicing a complex problem for system dynamics modeling. System Dynamics Review," 1992.

[30] G. Marta, "Towards improving sustainable access to electricity in rural area of Tanzania: A System Dynamics approach," Politecnico di Milano, 2020.

[31] B. Z. A. S. H. G. S. J. Zeinab Ravar, "System Dynamics modeling for assessment of water-food-energy resources security and nexus in Gavkhuni basin in Iran," vol. Ecological Indicators , 2020.

[32] C. S. G. B. N. M. R. J. Julius H. Kotir, "A system dynamics simulation model for sustainable water resources managment and agricultural development in the Volta River Basin," vol. Ghana Science of the Total Enviroment, 2016.

[33] E. S. S. Davies, "Global water resources modeling with an integrated model of the social-economic-enviromental system," 2011.

[34] T. S. V. B. A. M. L. Williams, "The Volta river Basin:Water for Food,Economic Growth and Enviroment," 2016.

[35] S. E. A. M. J. A.-K. A. M. B. K. M. Alireza Gohari, "Water transefer as a solution to water shortage : A fix that can Backfire," *Journal od Hydrology,* pp. 23-39, 2013.

[36] K. M. M. Madani, "System dynamics analysis for managing Iran's Zayandeh-Rud river basin," 2009.

[37] H. N. Natalia, "Generalization and accuracy definition of a specific System dynamic model case.Guidelines and best practices definition for future electrification projects in Developing Countries with the use of complementary activities," Politecnico di Milano, 2021.

[38] L. H. a. R. Gable S, "Trajectories for the sustainable development goals: framework and country applications," World Bank Group, Washington D.C., 2015.

[39] R. M. O.-O. Ritchie, "Measuring progress towards the Sustainable Development Goals," 2018. [Online]. Available: https://sdg-tracker.org/. [Accessed 15 June 2022].

[40] E. Commission, Aid delivery methods: Project cycle management guidelines, Brussels: European Commission; EuropeAid Cooperation Office., 2004.

[41] M. O. R. K. C. E. &. D. P. I. Saleh, "A comprehensive analytical approach for policy analysis of system dynamics models," *European Journal of Operational Research,* 2010.

[42] N. O. &. P. L. Ogano, "Analysis of policy options for projects in the electricity sector in Sub Saharan Africa: a system dynamics approach.," *The South African Journal of Industrial Engineering,* 2017.

[43] U. N. S. Division, "UN Data," [Online]. Available: https://unstats.un.org/home/.

[44] W. Bank, "World Development Indicators," [Online]. Available: https://databank.worldbank.org/source/world-development-indicators.

[45] United Nations Development Program, "Human Development Report," Oxford University.

[46] W. Bank, "World Development Indicators.".

[47] IEA, "IEA," [Online]. Available: https://www.iea.org/countries/burundi.

[48] IRENA, "Energy profile Burundi," [Online]. Available: https://www.irena.org/IRENADocuments/Statistical_Profiles/Africa/Burundi_Africa_RE_SP.pdf.

[49] E. B. J. N. C. S. &. M. L. M. Baldwin, "Electrification and rural development:issues of scale in distributed generation," 2015.

[50] T. R. A. o. Engineering, Global Water Security – an engineering perspective, The Royal Academy of Engineering, 2010.

[51] T. E. G. B. T. R. V. J. B. U. a. S. O. Mainieri, "Green building: The influence of enviromental concern on consumer behavior.," 1997.

[52] K. T., "The psychology of environmentally sustainable behavior: Fitting together pieces of the puzzle," 2002.

[53] T. W. B. R. Observer, "THE DEMAND FOR WATER IN RURAL AREAS: DETERMINANTS AND POLICY IMPLICATIONS," 1993.

[54] *. M. A. H. b. G. E. C. c. H. M. R. d. L. S. e. B. V. K. Regassa E. Namara a, "Agricultural water managment and poverty linkages".

[55] F. M. a. G. P. Nicolas Depretris Chauvin, "Food Production and Consumption Trends in Sub-Saharan Africa: prospects fro the Transformation of the Agricultural Sector," United Nations Development Programm, 2012.

[56] L. D. A. Afreen Siddiqi, "The water-energy nexus in Middle East and North Africa," Harvard University, 2011.

[57] *. N. S. M. a. G. C. A. a. S. M. Reuben M.J. Kadigi a, "Water for irrigation or hydropower generation?—Complex questions regarding water allocation in Tanzania," okoine University of Agriculture, Department of Agricultural Economics and Agribusiness, 2008.

[58] H. C. B. B. E.´. O.´. D. a. R. G. T. A M MacDonald1, "Quantitative maps of groundwater resources in Africa," 2012.

[59] a. L. O. L. U. J. A. &. Y. A. Paul Eze, "Catastrophic health expenditure in sub-Saharan Africa: systematic review and meta-analysis," Bull World Health Organ, 2022.

[60] M. M. M. P. J. P. R. H. Batsirai Majurua, "Health impact of small-community water supply reliability," 2010.

[61] H. R. S. E. E. a. O. S. Ibrahim, "INCOME AND CROP DIVERSIFICATION AMONG FARMING HOUSEHOLDS IN A RURAL AREA OF NORTH CENTRAL NIGERIA," *Journal of Tropical Agriculture, Food, Environment and Extensio,* 2009.

[62] *. M. A. H. b. G. E. C. c. H. M. R. d. L. S. e. B. V. K. Regassa E. Namara a, "Agricultural water management and poverty linkages," 2009.

[63] N. K. a. N. K. Pauline Macharia, "Applying the Water-Energy Nexus for Water Supply—A Diagnostic Review on Energy Use for Water Provision in Africa," 2020.

[64] D. S. J. O. N. A. a. F. A. Aumashvini Gobin, "Assessing the energy and carbon footprints of exploiting and treating brackish groundwater in Cape Town," 2019.

[65] B. Z. A. S. H. G. S. J. Zeinab Ravar, "System dynamics modeling for assessment of water–food–energy resources security and nexus in Gavkhuni basin in Iran," 2010.

[66] J. E. Miller, "Review of Water Resources and Desalination Technologies," 2003.

[67] S. Kalogirou, "Use of parabolic trough solar energy collectors for sea-water desalination".

[68] Z. Z. ,. L. Y. Mohamed A. Eltawil, "A review of renewable energy technologies integrated with desalination systems," 2009.

[69] S. H. M. J. ,. H. E. Mohammad Javad Keyhanpour, " System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach," *Ain Shams Engineering Journal,* 2020.

[70] S. H. M. J. ⇑. H. H. D. Mehdi Rahmani, "SD-DSS model of sustainable groundwater resources management using the water-food-energy security Nexus in Alborz Province," *Ain Shams Engineering Journal,* 2022.

[71] H. I. Mohamed, "EGYPT’S WATER RESOURCES MANAGEMENT UNDER PRESSURE OF DEVELOPMENT".

[72] T. van Gevelt, C. Canales Holzeis, B. Jones and M. Safdar, " Journal Article Insights from an energy poor Rwandan village," 2016.

[73] G. W. Intelligence, Desalination markets 2005–2015: a global assessment and forecast., Global Water Intelligence Publication, 2004..

A Appendix A

Table 11: Fixed parameters

PARAMETER	UM	MIN	MAX	VALUE	SOURCE	MEANING
AlFA-el	-	0	1	1	Cobb-Douglass function	Electrification effect
Average diffusion rate	Week*Appliances /$	0,028	1,11	0,05	Calibration parameter from previous model	The average diffusion rate is the average number of appliances per household per unit of income
Awareness effect HHs	1/week	0,000029	1	0,002871	Calibration parameter from previous model	This parameter reflect the fact that electricity access is perceived or not as an innovation by people.
Awareness effect IGAs	1/week	0,000029	1	0,005	Calibration parameter from previous model	This parameter reflect the fact that electricity access is perceived or not as an innovation by people.
BETA-el	-	0	1	0,497458	Cobb-Douglass function	The increase in the electrification rate of local IGAs and the increase in the total factor productivity of the local market are linearly proportional.

Capacity building requirements for IGA	people/IGA	-	-	12	Calibration parameter from previous model	Number of people necessary per IGA to do the capacity building trainings.
El reliability	-	0	1	0,9583	Calibration parameter from previous model	Power plant reliability which considers the unmet load due to unexpected outages.
Electrical power of appliances	Watt/appliances	2	2000	97	Calibration parameter from previous model	The average units of electricity installed per households.
Energy intensity groundwater extraction	kWh/week	1,1	2,4	1,75	Aumashvini Gobin, "Assessing the energy and carbon footprints of exploiting and treating brackish groundwater " 2019.	Estimates of total direct and indirect energy consumption for various water treatment procedures are given in terms of the amount of energy required (kWh) to generate one unit volume (1 m3)
Energy intensity domestic equipment	kWh/week	-	-	0,006	Batsirai Majurua, "Health impact of small-community water supply reliability," 2010.	Estimates of total direct and indirect energy consumption for various water treatment procedures are given in terms of the amount of energy required (kWh) to generate one unit volume (1 m3)
Energy intensity irrigation	kWh/week	-	-	0,09	Zeinab Ravar, "System dynamics modeling for assessment of water–food–energy resources security and nexus in Gavkhuni basin in Iran," 2010.	Estimates of total direct and indirect energy consumption for various water treatment procedures are given in terms of the amount of energy required (kWh) to generate one unit volume (1 m3)
Energy intensity water desalination	kWh/week	10,5	13	10	J. E. Miller, "Review of Water Resources and Desalination Technologies," 2003.	Estimates of total direct and indirect energy consumption for various water treatment procedures are given in terms of the amount of energy required (kWh) to generate one unit volume (1 m3)

EPSILON farming income	-	0	1	0,000299	Cobb-Douglass function	Changes in the farming income cause a proportional change in the farming productivity.
EPSILON-IGAs income	-	0	1	1	Cobb-Douglass function	Changes in the HHs income cause a proportional change in the market productivity.
Exogenous capacity building	-	0	1	0,080699	Calibration parameter from previous model	Capacity building is intended as building own ability by joining training courses (exogenous intervention)
Food from agriculture	-	0	1	0,8	Nicolas Depretris Chauvin, "Food Production and Consumption Trends in Sub-Saharan Africa: prospects fro the Transformation of the Agricultural Sector," United Nations Development Programm, 2012	The average share of plant-based food is around 80% in rural context of SSA
Fr change in external food expenditure	-	0	1	0,41838	Survey to HHs and IGAs	How much of food sales are purchased by people from external market
Fr change in external market demand	-	0	1	0,472	Calibration parameter from previous model	The external market demand can increase opening the market to external consumers
Fr change in internal IGAs supply	-	0	1	0,108	Calibration parameter from previous model	Some IGAs supply themselves with row materials from other loacl business

Fr decrease in cost given by EE	-	0	1	0,5	Calibration parameter from previous model	Decreasing factor which considers the effect of electricity use on production costs
Fr decrese in illness water related	1/week	0	infinite	0,57	Batsirai Majurua, "Health impact of small-community water supply reliability," 2010.	How much the illness related to bad quality water decrese thanks to a reliable water system
Fr increase of market expenditures	-	0	infinite	0,634	Calibration parameter from previous model	This value is formulated s as a decrease in the fraction of expenditures for food, in favour of an increase in the percentage of income spent for local goods
Fr of external source of income	-	0	1	0,04	Settled by modeller	In case of HI just a little part of income came from outside the village
Fr of failing IGAs	-	0,24	0,36	0,346144	Calibration parameter from previous model	Fraction of total IGAs that close their activity after few months of starting their activity.
Fr of iGAs that want to start by imitation	-	0,4	0,6	0,5	Calibration parameter from previous model	IGAs over the total amount of IGAs that want to be created , would be created due to imitation
Fr of operating time with electricity	-	0	1	0,6629	Calibration parameter from previous model	The fraction of the working hours during which electricity is used
Fraction of EE-reliant IGAs respect to connected IGAs	-	0	1	0,162	Calibration parameter from previous model	Where the fraction of EE-reliant IGAs variable is the percentage of IGAs that are highly dependent on electricity use.

Fraction of feasible HHs market supply	-	0,6	0,9	0,887545	Calibration parameter from previous model	Percentage of households that can potentially provide goods to business in the market.
GAMMA-el	-	-	-	0,75609	Cobb-Douglass function	Electrification effect
Gamma-rel	-	-	-	0,15	Setted by modeller	Changes in the system's reliability cause a proportional change in the domestic water demand
Hours per day	Hour/week	-	-	24	-	-
Income elasticity	-	0,06	0,15	0,15	Observer, "THE DEMAND FOR WATER IN RURAL AREAS: DETERMINANTS AND POLICY IMPLICATIONS," 1993.	The likelihood that a household would opt to utilize the water system would rise by around 1% for every 10% increase in household income. Simple terms, the higher the elasticity, the greater the amount of water used by households.
Initial available operation time	hour/week	1	84	54,69	survey to HHs	Potentially working hours during daylight
Initial capacity building	-	0	1	0,026228	Calibration parameter from previous model	The number of people already trained over the total population
Initial EE-IGAs coincidence factor	-	0,0176	0,1246	0,1125	Hartvigsson and Ahlgren 2018	Coincidence factor is the fraction of the peak demand of IGAs that is in operation at the time of system peak.

Initial external market demand	goods/(week*HHs)	0	infinite	0,154694	Calibration parameter from previous model	It indicates how much of the products IGAs sell, are purchased by external customers.
Initial external agricultural expenditure	$/(goods*HHs)	0	infinite	0,86	Calibration parameter from previous model	How much of the agricultural products farmers sell, are purchased by external customers.
Initial time to use appliances	hour/week	0	infinite	50	Local survey	Minimum (maximum) value of *initial time to use appliances* among all the appliances calibrated in the original model: tv, phone charger, iron, stereo, decoder, radio
Max capacity building	-	0	1	1	Calibration parameter from previous model	Max number of people already trained over the total population
Max fr of internal IGAs supply	-	0	1	0,6153	Calibration parameter from previous model	An higher or lower constrain of internal IGAs supply, supposing a lack of some specific raw materials, may change the working of the business
Max fr population growth	1/week	-	infinite	0,003430	Calibration parameter from previous model	Calibration parameter and it represent the ractional growth rate , after eletrification, when population is small
Max increase of week expenditure	-	1	infinite	0,0891	Calibration parameter from previous model	Max Households’weekly expenditures in the local market.
Product performace	kg/m^2	1,196	1,45	1,3	Mohammad Javad Keyhanpour, " System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy	Food produced per m^2 of farmed area

					approach," *Ain Shams Engineering Journal,* 2020.	
Production cost without EE	$/goods	0	infinite	0,8829	Calibration parameter from previous model	The production cost without electricity use
Reference land productivity	-	0	infinite	0,668949	Settled by modeller	Calibration parameter representing a proxy of the intial farming productivity
Reference factor productivity	goods/(IGA*hour)	0	infinite	0,372	Calibration parameter from previous model	Productivity of IGAs, how many goods they produce in an hour.
Reliability 0	-	0	0,9995	0,58	Batsirai Majurua, "Health impact of small-community water supply reliability," 2010.	Power plant reliability which considers the unmet load due to unexpected outages.
Reliability max	-	0,9583	0,9995	0,98	Calibration parameter from previous model	Power plant reliability which considers the unmet load due to unexpected outages.
Saturation limit	appliances/HHs	0	infinite	30	Calibration parameter from previous model	Saturation limit parameter which represents the realistic ownership of appliances per household
Social contagion HHs	1/week	0,0029	0,0365	0,014855	Van Den Bulte, 2002	Drivers of the diffusion of electrical connections

social contagion IGAs	1/week	0,0029	0,0365	0,003901	Van Den Bulte ,2002	Drivers of the diffusion of electrical connections
Spillover of Capacity Building	people/IGA	0	1	0,143	Calibration parameter from previous model	The change in capacity building due to electrification effect depends proportionally on the connection rate of IGAs
THETA-capacity building elacticity	-	0	1	0,440177	Cobb-Douglass function	The increase in the informal education activities and the increase in the market and farming productivities are linearly proportional.
Tima to adapt water use	week	1	infinite	52	Setted by modeller	After water access how much time it takes to appriciate that they have more water
Time to adapt productivity	week	1	infinite	317,653	Calibration parameter from previous model	After electrification, how much time it takes for IGAs to appreciate that they have more time for labours.
Time to adapt desalination capacity	week	1	infinite	104	Setted by modeller	Average time to build up or extend a desalinator
Time to adapt electricity use	week	0	infinite	5,7	Calibration parameter from previous model	Since the electriciy fee is paid once per month, I set that people change their electricity use based on the value of the bill
Time to adapt farming producticity	week	1	infinite	9,40315E+12	Calibration parameter from previous model	After electrification, how much time it takes for HHS and IGAs to appreciate that they have more time for farming labours.

Time to adapt reliability	week	1	infinite	260	Setted by modeller	Time to increse the reliability of the system
Time to adapt yield	week	1	infinite	500	Setted by modeller	After agriculture water access how much time it takes to appriciate that they have more water
Time to dismiss activity	week	0	infinite	1	Calibration parameter from previous model	Delay time for dismission of the activity
Time to get the loan	week	0	infinite	1	Calibration parameter from previous model	How much time it takes for the HHs or IGAs to receive the loan from the bank after they confirm the request.
Time to increase groundwater capacity	week	1	infinite	52	Setted by modeller	Average time to build up or extend groundwater withdraw
Time to perceive market dynamics	week	1	infinite	10	Calibration parameter from previous model	The time needed to form expectations about potential changes in market dynamic
Time to perceive more time for farming	week	1	infinite	26,4	Calibration parameter from previous model	After electrification how much time it takes to appriciate that they have more time
Time to perceive more time for working	week	0	infinite	21000	Calibration parameter from previous model	After electrification, how much time it takes for HHS and IGAs to appreciate that they have more time for farming labours.

Water pumping efficiency	-	-	-	0,7	Afreen Siddiqi, "The water-energy nexus in Middle East and North Africa," Harvard University, 2019	-
Water requirement for land	m^3/(week*m^2)	-	-	0,096	Mehdi Rahmani, "SD-DSS model of sustainable groundwater resources management using the water-food-energy security Nexus in Alborz Province," *Ain Shams Engineering Journal,* 2022.	The weekly water requirement for a unit of land extensio
Watt to kWAtt	Kwatt/watt	-	-	0,001	Engineering conversion	-
week	week	-	-	-	-	-
weeks in a month	week	-	-	4,25	-	-
weeks in a year	week	-	-	52,143	-	-
Willngness to pay HHs	-	0,048	0,192	0,088	Insights from an energy poor Rwandan village,2016,Gevelt	Money HHs would be able to spend for being connected to the grid.

Willngness to pay IGA	-	-	-	0,013598	Calibration parameter from previous model	Money IGAs would be able to spend for being connected to the grid.
Working days in a week	day/week	6	7	6,67826	-	-

Table 12: context dependent parameters

PARAMETER	UM	MIN	MAX	VALUE	SOURCE	MEANING
Annual population growth rate	-	-	-	0,03	World Bank Data, 2018	Annual population growth rate for year t is the exponential rate of growth of midyear t-1 to t, expressed as a percentage
Food consumption per capita	Kg/(capita*week)	-	-	10,36	Zeinab Ravar, "System Dynamics modeling for assessment of water-food-energy resources security " 2020	Average food demand per capita in rurual context
Fr if initial HHs to be connected	-	0	1	1,00	Local observation	It is referred to the number of HI HHs that would be connected at the beginning of the electrification project.
Fr income for education expenditure	-	0	1	0,10	A comparison of real Households consumption expenditures and price levels in Africa,Africa Development Bank, 2012	Before electrification, fraction of the income that households allocate to education for their children.
Households size	people/ households	-	-	4,80	United Nations , Database on Households size and composition 2019	Average number of peolpe per households
Initial Income	$/HH*week(or month)	-	-	4,60	World Bank Data	Average income oh households

Initial domestic water demand	m^3/(week*capita)	0	infinite	0,33	Mehdi Rahmani, *Ain Shams Engineering Journal,* 2022.	Average water demand per capita
Initial fr income for food expenditure	-	0	1	0,43	A comparison of real Households consumption expenditures and price levels in Africa,Africa Development Bank, 2014	Before electrification, fraction of the income that HI households spent in purchasing food from the local market.
Initial fr income for medical expenditure	-	0	1	0,25	sdg-tracker.org	If the IGA has the total amount of money it spent on creating the IGA, use this value. If not, compute the total amount of investing summing the possible expenses: local, furniture, machinery... Finally, compute the average of total money invested for setting up the IGA
Initial fr of HHs close to the grid	-	0	1	0,06	Local observation	HHs that physically are close to the grid.
Initial population	people	-	-	3.000,00	field study/setted by modeller	Starting population
Internal migration effect	-	0	infinite	1,18	calibration parameter from previous model	Electrification had a null (=1) and positive (>1) effect on the internal migration
Investment for a new IGA	$/IGA	0	Infinite	1.500,00	The Global Competitiveness Report, World Economic Forum 2019	Money an IGA has to invest for its creation.

Local currency to USD	$/currency	-	-	0,00	currency exchange, Jan 2022	
Max cropland available	m^2	-	-	200.000,00	Local observation	Context specific parameter which limit the cropland expansion
Max fraction income for health expenditure	-	0	1	0,40	sdg-tracker.org	Max possibile fraction of income spent for health expenditure
Max Groundwater extraction	m^3/week	-	-	500,00	Local observation	Context specific parameter which limit the goal seeking function for the groundwater usage
Power EE-IGA	Watt/IGA	0	infinite	15.940,00	Local observation	Power capacitiy installed for EE-reliant IGAs.
Power notEE-IGA	Watt/IGA	0	infinite	60,00	Local observation	Power capacitiy installed for notEE-reliant IGAs.
Price to cost factor	-	1	4	3,00	settled by modeller	This parameter affects the local market revenues which change the price of goods and service
Surface water	m^3/week	-	-	10.000,00	Local observation	Surface water available in the context (basin, lake, river etc.)

Time for setting-up the IGA	weeks	-	-	0,57	The Global Competitiveness Report, World Economic Forum 2019	Time it takes for an IGA to set up its business.

Table 13: free parameters

PARAMETER	UM	MIN	MAX	VALUE	SOURCE	MEANING
Annual fee rate RESIDENTIAL/ PRODUCTIVE	-	-	-	0,005	Setted by modeller	Fixed annual rate
Annual increase	-	-	-	0,05	Setted by modeller	Tariff have been implemented in the model and it is represented as an exponential growth behaviour, starting from an initial low and subsidized fee which progressively increases with a fixed annual rate
Electricity-Fee elasticity for EE-reliant IGAs	-	-1	0	0	Setted by modeller	The quantity demanded of the energy does not vary as the price changes. It is constant. Whatever the price, the IGAs always buys the same quantity.
Electricity-Fee elasticity for not EE-reliant IGAs	-	-1	0	-1	Setted by modeller	The quantity demanded of the energy vary as the price changes.
Electricity-Income elasticity HHs	-	-1	0	-0,93	Setted by modeller	Elasticity possibile value. It is a calibration parameter representing households' load sensitivity to changes in the electricity cost respect their income
Fee at start	$/IGA	-	-	40	Setted by modeller	Initial fee that households pay for being connected to the grid
Fr decrese in cost given by EE	-	0	1	0,5	Setted by modeller	Decreasing factor which considers the effect of electricity use on production costs.

fraction of feasible HHs market supply	-	0,6	0,9	0,8875	Interview to manager director/setteled by modeller	Percetage of households that can potentially provide goods to business in the market
Franction of sharing meter	-	0,48	0,72	0,719	Interview to manager director/setteled by modeller	Fraction of meter shared between users
Initial available operation time	hour/week	1	84	55	Setted by modeller/ observation	Time spent for working
Initial fixed electricity fee in local currency	local currency/HH*week (or month)	-	-	15	Setted by modeller	Initial fee that households pay for being connected to the grid.
Initial fr of Internal IGAs supply	-	0	1	0,0424	Setted by modeller	Some IGAs supply themselves with rae materials from other local business
Initial variable electricity fee in $ PRODUCTIVE	$/HH*week(or month)	-	-	0,11	Setted by modeller	Initial fee that IGAs pay for being connected to the grid.
Initial variable electricity fee in $ RESIDENTIAL	$/HH*week(or month)	-	-	0,06	Setted by modeller	Initial fee that households pay for being connected to the grid.
Irrigation efficiency	-	34%	42%	0,4	Alireza Gohari, "Water transefer as a solution to water shortage : A fix that can Backfire," *Journal od Hydrology,* pp. 23-39, 2013.	The amount of water removed from the water source that is used by the crop. This value is determined by irrigation system management, water distribution characteristics, crop water use rates, weather and soil conditions.

Multiple year increase	-	-	-	0,6	Setted by modeller	Concerning the *fixed electricity tariff*, it gradually increases through multiple years with an annual growth rate
Reference factor productivity	goods/(IGA*hour)	0	infinite	0,372	Calibration parameter from previous model	This is reference productivity in case of maximum 8 hours per day per 6 days at work, initial level of primary school, no secondary school, no electricity access, initial income of HI income.

Table 14: scenario settings parameters

PARAMETER	UM	MIN	MAX	VALUE	SOURCE	MEANING
Agri water DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Capacity building DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Desalination DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Domestic water DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Electricity availability DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Electricity availability DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Fr of people using microcredits	-	0	1	0,38		Franction of total people that has obtain a microcredit

Groundwater DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Initial desalination capacity	m^3/week	-	-	0	-	This parameter is suppposted to be the initial value of desalinator capacity due to the increse in the demand along time window
Initial groundwater capacity	m^3/week	-	-	0	-	This parameter is suppposted to be the initial value of groundwater capacity starting with the hypotesis that the exploitment of the resource will increase with population and income growth
Microcredit DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Monthly fraction of interest	-	0	1	0,03		Interest applied to the loans granted by the local bank.
Payback	week	4	106	52		Time to payback money for investment
Savings DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Share of diesel generator utilization	-	0	1	0,3	-	Share of total energy supplied by diesel generator

Share of surface water utilization	-	0	1	0,9	-	Share of total surface water utilization for hydropower production
Surface DUMMY	-	-	-	1	-	Parameter in charge of active or deactivate the use of any of complementary activities
Total access to electricity	-	-	-	1	-	Parameter to measure the total fraction of people with the aim of being connected to the grid.
Years	years	0	infinite	20	-	Time window of the simulation

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