FEDERAL UNIVERSITY OF ITAJUBÁ

POSTGRADUATION PROGRAM

IN ELECTRICAL ENGINEERING

MODELLING AND SIMULATION OF INTERDEPENDENCY OF CRITICAL INFRASTRUCTURES IN SMART CITIES

A case study of a non-planned developing city: Itajubá - MG, Brazil

Natália Vilas Boas Pappi Maciel

August 2022

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Dissertation submitted to the Postgraduation Program in Electrical Engineering as partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering.

Concentration Area: Electric Power Systems

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Many people pass through our lives and have no idea of the impact they cause. This section is more than a formality required by the norms; it is a small attempt to acknowledge and retribute these people for all the good they have done and might not know of it.

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DEDICATION

To all people who still have no access to electricity in the world.

ABSTRACT

Along with the development of society, productivity rates increase, causing the needs of the people to change. As a result, new technologies rise to fulfill the stability of the system and maintain the developing trend. This fact leads to the growth in the complexity of cities affecting their vulnerability and sustainability. The study and modeling of the interdependent relationships among cities´ critical infrastructures can provide not only optimal action plans for extreme events scenarios but also provide effective and strategic long-term planning to optimize the system towards the desired goal, which is the case of this research. This work provides a reliable model of the systems in a developing city that aims to represent the interdependent relationships in it, along with its variables, inputs, outputs, and possible modifiers. This plan will hopefully pave the way for the economic and energetic development of the city towards making it a smarter city and also showing that it is possible to make smart the existing, not planned, developing cities.

Keywords – Critical Infrastructures, I2SIM, Interdependency, Smart Cities, Smart Grids, Distributed Generation, PV Deployment, Electric Vehicles**.**

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GLOSSARY

AI	Artificial Intelligence
ANEEL	National Agency of Electrical Energy
CIS	Complex Interdependent Systems Group
DG	Distributed Generation
EV	Electric Vehicles
GCPVS	Grid Connected Photovoltaic System
GDP	Gross Domestic Product
HDI	Human Development Index
HRT	Human Readable Table
I2SIM	Infrastructure Interdependencies Simulation
PTF	Productivity Total Factor
PV	Photovoltaic
SE	Substation
SIN	Interconnected National System
STEM	Science, Technology, Engineering, and Mathematics
SWH	Solar Water Heater
TR	Transformer
UBC	University of British Columbia
UNIFEI	Federal University of Itajubá

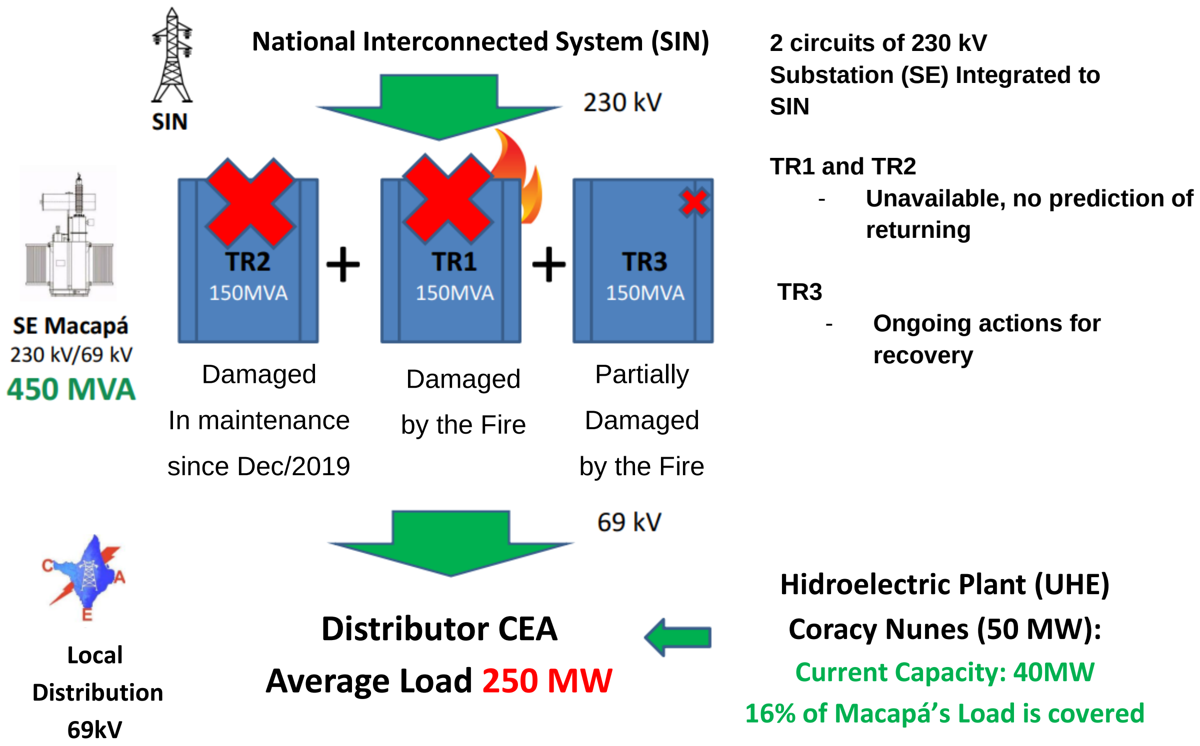
1. INTRODUCTION

1.1. MOTIVATION AND INCITEMENT

Along with the development of society, productivity rates increase, causing the needs of the people to change. As a result, new technologies rise to fulfill the stability of the system and maintain the developing trend. This fact leads to the growth in the complexity of cities affecting their vulnerability and sustainability. It is due to the interdependent relationships among the systems that a city is composed. These systems can be represented by transportation, water, power systems, communication, finance, health systems, etc., which, together and interconnectedly, are responsible for its running. The complexity of the interdependency phenomena becomes evident in extreme scenarios when a certain imbalance is caused in those relationships. These are examples of some extreme events: hurricanes, earthquakes, and floods. In these situations, actions must be taken in a short period to minimize human, environmental and economic losses.

An example of such an extreme scenario that happened in Brazil is the power outage that occurred in Amapá on the 3rd of November 2020, where a fire in the main substation (SE) of the state compromised its three transformers (TR) (one of them was already out of service since 2019), leading to two complete blackouts and 22 days of rotation supply and affecting 90% of the population (around 765 thousand people). The schematic of the substation where this event took place is shown in Figure 1-1. As a result, the water supply system, the food supply, communication, safety, and other systems were also affected, local elections were postponed, and there were acts of vandalism, social upheaval, and protests aggravated by the shortage of police staff due to COVID-19. Through this event, the interconnectedness between systems was made evident, exposing what is called a cascade event in critical infrastructures, which is when the disruption of one single cell leads to an enormous impact on the whole system [1].

Figure 1-1 Amapá's substation failure scheme. Source: Adapted from [2]



The study and modeling of the interdependent relationships can provide not only optimal action plans for extreme events scenarios but also provide effective and strategic long-term planning to optimize the system towards the desired goal. The aspect that defines the difference between such studies is the time scale. In extreme events analysis, on a scale of seconds, decisions and actions must be taken and can make a significant difference in the outcome. In long-term planning, for instance, which is the case of this dissertation, the time scale magnifies to a greater length, so the modeling must be done accordingly. Besides that, both scenarios require an understanding of the existing infrastructure systems, their interdependent relationships, and their different organizational levels.

1.2. PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Electric energy is an indispensable product for society, as it is used, directly or indirectly, in a large part of the activities performed by human beings. In this way, electricity is a crucial factor for technical and economic growth in many different countries. In this context, the population increase and the consequent growth in the need for electric energy end up becoming a worrying factor, considering the scarcity of classic energy sources or the fact that, many times, they are not sustainable and renewable sources. In addition, when the power supply is interrupted, a large part of the activities of urban centers are paralyzed, which causes disturbances and, many times, damage. The costs of this energy supply failure are not just financial; after all, the entire production chain is harmed by it. Based on the relevance of electric energy as an imperative factor for the population's activities, it is important to emphasize that its management requires an adequate structure of production, distribution, and monitoring.

Raising concerns about climate change and also the growing electricity demand have caused the electric grid to change. To efficiently fulfill the actual needs of the planet and also bring development to the population, new pieces of technology have been adopted. In the context of Smart Cities, where one of its purposes is to make the city more sustainable and adequate for its people, the Smart Grids technologies have played this role in the Electric Energy Sector. For example, the search for more sustainable sources of energy has led to the need for energy storage due to the intermittency in renewable generation; the quest to access to information has led to the adoption of smart meters, which helped consumers to be aware of their consumption and reduce usage through richer billing information; the use of remote switches increased system resilience and maintenance efficiency by allowing greater control of the electric system (remarkably important in extreme event scenarios).

According to [3] Smart Grids are designed precisely to promote economy and efficiency through system automation. The Smart Grid intends to highly monitor the use of electric energy, which can improve the supply and reduce losses. For [4], Smart Grids seek to improve the generation, distribution, and consumption of electric energy, making it possible to verify advances in the quality of the energy delivered, in the inspection of the network, in the management of energy, in the system automation and encouraging the use of renewable energy sources. Due to the significant consumption of energy and the evolution of thinking about energy sources and, mainly, the environment, Smart Grid technologies have configured an increasingly close tool, considering the multiple benefits they can offer in the most diverse areas.

Although all the mentioned technologies are already stably set in the energy market worldwide, there are still challenges opposing their implementation in some countries. In photovoltaic (PV) generation, for instance, the economic viability fluctuates according to the country's currency and the dollar exchange rate. A positive variation in the exchange rate of 5% induces an 8% increase in the final system value for a residential consumer in Brazil [5]. Also, the fact that the production of PV panels is concentrated in a few countries makes it not so competitive and allows little variation in the equipment price. Besides that, the countries' legislation towards distributed generation can also be an obstacle when it does not incentive its adoption.

At the same time, great incentives can be malefic for the tariff balance in the electricity economic sector. An example of that is Spain, where a change in the premium tariff and unlimited installed capacity in PV generation caused a vast expansion of grid-connected photovoltaic systems (GCPVS), and not so long after that, due to tariff impacts, the country backed off and reviewed the incentives [6]. In Brazil, the great irradiance rates, high electricity tariff, and the current legislation of distributed generation have been stimulating prosumers to invest in PV generation. However, such incentives are noted to be effective only in low PV penetration levels, which is leading to discussions and change proposals in the legislation. Studies showed that if the current model, net metering, persists, there will be a point when the residential consumers who do not have the means to invest in PV generation and become prosumers will be paying higher distribution tariffs. This increase is estimated to be around 22-47% by 2035 [7].

With that being said, it is possible to say that the analysis of such interdependency is critically differentiated according to where the system is located. And the differentiation goes beyond legal and geographical conditions, but it is also worth mentioning the social and cultural influences that act on this complex, especially in developing and underdeveloped countries where the adoption of new technology contrasts with poverty, hunger, public safety, illiteracy, unemployment, and many other elements. Because of this, bringing development to the population through electricity becomes an increasingly complex task. The point is the many changes on the grid, consequently, the numerous system variables and their relationships need to be better understood to optimize the well-being of the people. Whether it is the legislation, the cultural aspects, or even the technological limitations, these impediments need to be represented altogether in the system as a whole for the comprehension of how electricity and development are connected. The building of a model where these variables are considered will be of great help in pursuing this goal.

Therefore, the global objective of this work is to propose a model to effectively implement Smart Grid techs in a developing city in Brazil. To do so, a model of the sample city is built and from that follows the specific goals below:

- To promote the analysis of the critical infrastructure to optimize resources and mitigate losses;
- To fully comprehend the interconnectedness of the electric grid and the other critical systems in the context of a developing city;
- To promote the adoption of smart grids techs aiming for the optimal development of the city in the long-term run;
- To contribute to long-term economic planning focusing on the optimization of the development of society, considering the information collected from the city and socio-economic indicators.

For this purpose, different smart grid level scenarios will be considered. Therefore, the specific goal of this paper is to find an optimum smart grid level for a developing city in a developing country.

1.3. CONTRIBUTIONS

Energy and economic development are directly connected [8]. Even the definition of the word "energy" agrees with this, which is the capacity for vigorous activities [9] in other words, the capacity to execute some work and work leads to development. As the first contribution, this dissertation provides a reasonable model of the systems in a developing city that aims to represent the interdependent relationships in it, along with its variables, inputs, outputs, and possible modifiers. This model can also be used in future research since it will enable both long- and short-term analysis. Furthermore, starting from the model, the greater contribution of this work is the basis for the strategic adoption of smart grid technologies in the city of study. This plan will hopefully pave the way for the economic and energetic development of the city towards making it a smarter city and also showing that it is possible to make smart existing, not planned, developing cities.

1.4. DISSERTATION ORGANIZATION

Aiming to achieve the proposed goals and support the analysis, this dissertation is presented in seven chapters. In Chapter 1, a brief introduction and contextualization of the problem are given to elucidate a broad view of the dissertation. Also, the goals and contributions of this work are discussed in this section.

In the Second Chapter, the evolving concept and examples of Smart Cities are explored. To better fundament this work, there is a focus on the smart grids' technologies, their specifications, and also the social aspects of smart grids, on how they can improve society´s well-being.

The third chapter has the goal of defining and exploring the concept of distributed generation (DG). Moreover, the current scenario and recent evolution of DG are shown. Also, the impact that it has on the creation of jobs and the variables that affect it are explored.

Chapter 4 discourses the software I2SIM and its ontology used in the model created within it to analyze the interdependency mentioned before. Also, the possibility of integration with different domain simulators is exposed, giving light to a wholesome of possibilities for future research.

In Chapter 5, the research methodology is explained along with the research classification, its context, and the chosen methodology. In addition, the model for the case study proposed in this dissertation is created. Moreover, the collected data, methods of collection, and general assumptions for creating the model are presented, and the simulation/optimization is performed. From that, the strategic plan for energetic development is presented. Here, the simulation is run on a yearly basis, and the desired goals of maximizing well-being, generating jobs, etc., are tentatively optimized.

Chapter 6 has the purpose of exposing the conclusions and considerations about the results obtained from the case study and simulations, along with the research limitations and future research suggestions. References are presented at the end of this dissertation.

2. SMART CITIES

2.1. INTRODUCTION

The phenomenon of urbanization is part of the natural evolution of the so-considered “modern society.” As a result of the increase in population, it has become crucial to optimize the use of resources to better fit and supply the greater amount of people in the cities. To do so, it is necessary to provide the services people need efficiently with minimum impact on the environment. This change in the way cities evolve has led to the emergence of the concept of Smart Cities [10]. This idea not only spread through academic and scientific fields but also in civil society among politicians, city governments, and many different companies. Even though the use of this term has been broadly accepted, it makes it difficult for authors and academic members to get to an accurate and consensual definition of a Smart City [11].

Still, many authors have attempted to define them. Here are some of the definitions they have come up with: [12] mentioned that smart cities have their formation initiated when technological infrastructure is implemented that can integrate all available technologies. For [10], Smart cities can be seen as systems with flows of energy, materials, services, people, and financing. The author of [13] interestingly chose to define it by what it is not: a city where not everyone has access to energy, with hunger, homeless people on the streets, lack of water, and unhygienic places to live, cannot be considered a smart city.

Regardless of the irresolution in the quest for a definition, there is an unanimous agreement that smart cities aim to make cities more efficient for the people living in them and their surroundings. However, it is extremely challenging to keep up with societal development, focus on the well-being of the people and also reduce the environmental impact and carbon footprint [10].

From the definitions presented here, it is possible to infer that cities tend to increase the use of automation, which means that equipment that does not require human intervention will increasingly be used. In this way, inevitably, there will be an increase in energy consumption, which must be carried out consciously and efficiently [14].

For [15], the energy issue represents a crucial aspect of modern cities, considering the significant consumption caused by a large number of electronic devices in use. Consequently, the complexity of the higher demand could make them more vulnerable to disturbances. Therefore, a more effective approach would be to holistically operate the cities, so they can better react to changes. This way, they would not only increase safety and reliability by the better utilization of intelligent, integrated, and optimized networks but also save costs. [10].

2.2. SMART GRIDS

The electricity sector faces a technological improvement that involves the emergence of a modern standard known as Smart Grid, which includes the inclusion of an Information and Communication Technology (ICT) framework in the existing electricity grid [16]. For the United States Department of Energy (DOE), Smart Grid technology does not just mean technology or a device but configures a concept for a widespread system based on an internet environment [17].

According to [18], there are several definitions for Smart Grid. However, all its meanings have in common the association of the electrical network with an information and automation network that provides control, monitoring, communication, and storage technologies, to optimize the use of existing resources.

On [19] it is agreed that, although there is no general agreement on the concept, certain aspects are part of most definitions: great automation and use of dynamic operating procedures, capable of responding promptly to the elements provided by the final consumer. Smart grids would then enable a flow of energy in which the consumer would be able to be a generator of energy for the distributor, when appropriate, by connecting to the grid. It would also be possible to continuously monitor the development of energy use and provide real-time feedback on system changes.

For [20], it is possible to understand smart grids as a collection of technologies capable of making the electrical distribution network more visible, maneuverable, automated, and fast. [21] defines Smart Grid as "an electricity grid that uses digital technology to monitor and manage the transport of electricity from all generation sources, meeting a variety of demands and users. These networks will be able to coordinate the needs and capabilities of all generators, operators, end-users, and electricity market stakeholders, to optimize the use and operation of assets in the process, minimizing costs and environmental impacts while maintaining reliability, resilience, and system stability" [21].

Smart Grid Technology proposes a transformation in the form of energy generation, distribution, and consumption. The so-called intelligent electric energy networks configure an automated system, holder of a bidirectional flow of energy and also of information, which makes possible a follow-up from the plants to the consumers. It is, therefore, a way to promote a range of advantages to both energy concessionaires and consumers since it is possible to provide credibility, optimize energy use, reduce environmental impacts, and contain costs [22].

Among the advantages of Smart Grids, it is possible to highlight the improvement in the quality of electrical energy, the increase in the efficiency of the system, the availability to include renewable energy sources, and the automation of maintenance of operations [19].

Smart grids are intended to benefit energy distributors, consumers, and society. The idea is that more efficient services are provided at a lower cost, in addition to a reduction in consumption caused by the optimization of energy use management. Added to this is the fact that more accurate monitoring of the network could promote a significant reduction in damage to utilities caused by fraud or energy theft [15].

Among the main benefits of implementing smart grids are included [23]:

- Ability to quickly distinguish network problems and solve them;
- Efficient use of the system for postponing or shifting costly investments in energy transmission and distribution;
- Transformation of consumers into active participants in the energy used.

According to [24], smart grids are made up of three subgroups that operate in integration. The first one is "above" the power meter. This means that it includes the generation, transmission, and distribution system, being responsible for the automation and improvement of the system's support and operation actions, in addition to providing information on the system's performance to consumers and the concessionaire.

The second group refers to the energy meter itself. When one talks about smart grids, he or she is talking about smart energy meters, which are largely responsible for the interconnection of the grid with the consumer.

The third group is made up of smart consumers, which are nothing more than companies or homes equipped with smart home appliances and integrated cogeneration systems.

It is important to highlight that the implementation of smart grids suggests a series of challenges, not only financial but also economic and regulatory. There is a need to create specific rules covering issues related to tariffs and demand variations, for example [25]. Furthermore, it is necessary to combine several classic technologies of the energy sector with information and communication technologies, as well as methods that promote the interaction between these technologies to be able to operate together.

It should not be forgotten, also, that just as the parameters of energy supply are different from one country to another, the reasons and incentives for implementing smart grids are not the same either, as well as the installation process and necessary time. There are also cultural aspects characteristic of each country to be considered when talking about the implementation of smart grids [26].

According to [27], the change from the traditional electric grid to the Smart Grid must occur gradually; that is, the technologies must be implemented in parts of the grid, composing "pockets" of sub-grids characterized by the Smart Grid. These subnets will coexist harmoniously with the traditional network. Over time, as the subgrids grow and increase in capacity, the electrical grid as a whole will move towards a smart grid.

For [17], smart grids will be able to completely transform the electrical scenario, changing concepts, actions, planning, and, above all, the relationship with the energy consumer.

2.2.1. **SMART GRIDS IN BRAZIL**

The Brazilian energy generating system predominantly comes from hydroelectric power plants. The generated energy is then purchased through reverse auctions by a centralized buyer in the name of all distributors and sold to final consumers.

This type of energy generation consists of an economically, environmentally, and socially costly system [15].

According to [17], in Brazil, the implementation of smart grids is still in its infancy. The pilot projects started are timid, and the actions of energy concessionaires can be considered incipient, most probably due to uncertainties in regulatory issues and in investment's financial recovery.

Among the attractions of the implementation of the Smart Grid in Brazil, one can highlight the issue of commercial and energy efficiency, as well as increasing the reliability of the system, increasing operational safety, and improving economic and environmental sustainability [28].

According to [29], the implementation of smart grids in municipalities is a key aspect of the design of smart cities, making possible several urban solutions that involve the administration and optimized use of energy, water, waste, mobility, health, governance, and security. Therefore, Smart Grids also have the challenge of linking technical data with the daily lives of people and cities, stimulating the quality of life and the sustainability of energy resources.

2.2.1. **ELECTRIC VEHICLES**

The transportation sector is alone responsible for around 40% of the primary energy consumption in the world [30]. This fact itself not only justifies the shift from fossil fuel to electric-powered vehicles in the climate change scenario but also shows that it is an achievable goal. To do so, the developments towards this change have started to be conquered through the adoption of electric vehicles. However, it is necessary to balance the economic, social, and environmental needs.

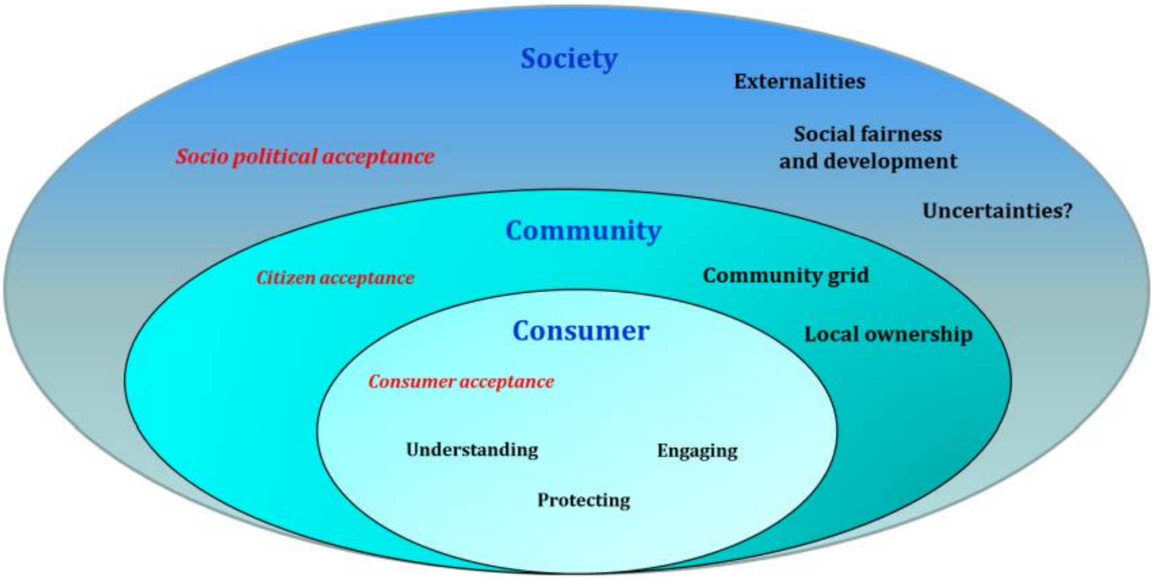
One of the first barriers found while pursuing this shift is the cost of the investment; electric vehicles' cost is around three times higher than that of conventional combustion ones. Also another challenge in this change is battery autonomy. The technology available today still requires constant charges. And one more important consideration: the energy used to power such vehicles should not come from non-renewable sources; otherwise, it would also have an impact on the environment [31]. Brazil has also invested in researching ethanol fuel cells for green hydrogen production for electric mobility (at UNICAMP).

There are more advantages of electric trucks worth mentioning: the decrease in Green House Gas (GHG) emission results in drop-in health costs; electric vehicles do not have tailpipes; they do not emit GHG. The reduced to no noise emission increases the well-being of people and diminishes sound pollution in cities.

2.3. SOCIAL DIMENSION OF SMART GRIDS

Social sustainability and acceptance, and cultural factors and norms play a very important role in smart grids since they shape people's behavior. Still, they are not commonly taken into consideration in Smart Grids projects. The success of its implementation relies on placing the electricity consumers in the focus of the process since the interaction with them is crucial to induce behavioral change (See Figure 2-1 The Social Dimension of Smart Grids: a Framework. Source: [32].). For instance, in the implementation of smart meters, some consumers have presented health and transparency concerns over the effects of wireless emissions generated by the sensors/meters installed. Also, in wind generation, neighbors can present concerns about the noise and safety of vertical axis wind mills. Furthermore, cultural values vary significantly among countries and can lead to different approaches and behaviors. The deployment of smart grids focusing mostly on techno-economic aspects may cost more than originally estimated due to the inability to consider the impact it has on the most affected stakeholders, the electricity consumers [32].

Figure 2-1 The Social Dimension of Smart Grids: a Framework. Source: [32].



Another important aspect is the ability of smart grids and their emerging concepts, systems, and technologies to contribute to achieving universal access to electricity by promoting equitable and inclusive economic and social development without marginalizing the poor. To define this, the term Just Grid was introduced by Welsh et al., 2013 [32]. An example would be the "Lighting for all" program in Brazil, where the goal is to enable the electrification of remote areas, like Amazonia, where there's a very sensitive eco-system and lacks cost-effectiveness due to its distance to big load centers and dispersed consumers with low income and consumption rates [32].

Today some 750 million people lack access to electricity. Projections indicate that by 2030, 660 million people will still lack access to electricity, most of them in Sub-Saharan Africa. In addition, households, enterprises, and public facilities such as clinics, schools, and water supply infrastructure, in some countries lack access to reliable and affordable energy [33]. A possibly viable solution is electrification schemed based on decentralized systems and exploitation of the renewable energy potential [32]. Also, linking renewable energy supply with income-generating activities across sectors can improve productivity, raise incomes, create local jobs, and catalyze rural economies [33].

3. DISTRIBUTED GENERATION

3.1. INTRODUCTION

Distributed Generation (DG) is much more than just a trend in the world. It represents a more efficient way to provide energy to the consumers and even make it possible for them to produce their own, which makes this idea completely compatible with the purpose of making cities smarter. By definition, it means bringing the generation of electricity closer to the load centers, regardless of their power and demand. Data in Figure 3-1 shows that it has been significantly increasing over the last years all over the country. It is also noticeable that in 2022 it has already overcome the number of connections added in 2019. Nevertheless, the biggest increase in the adoption of DG was in the residential consumers in Brazil, as Figure 3-2 shows. This increase is caused by many factors beyond the price and economic interest, such as values (goals desired by the people) and contextual factors (social rules, culture, and access to information) [34].

Figure 3-1 - Number of Annual Connections. Source: [35]

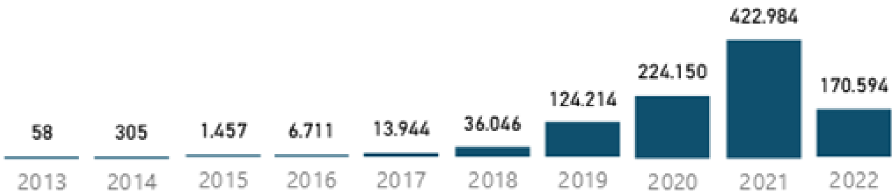
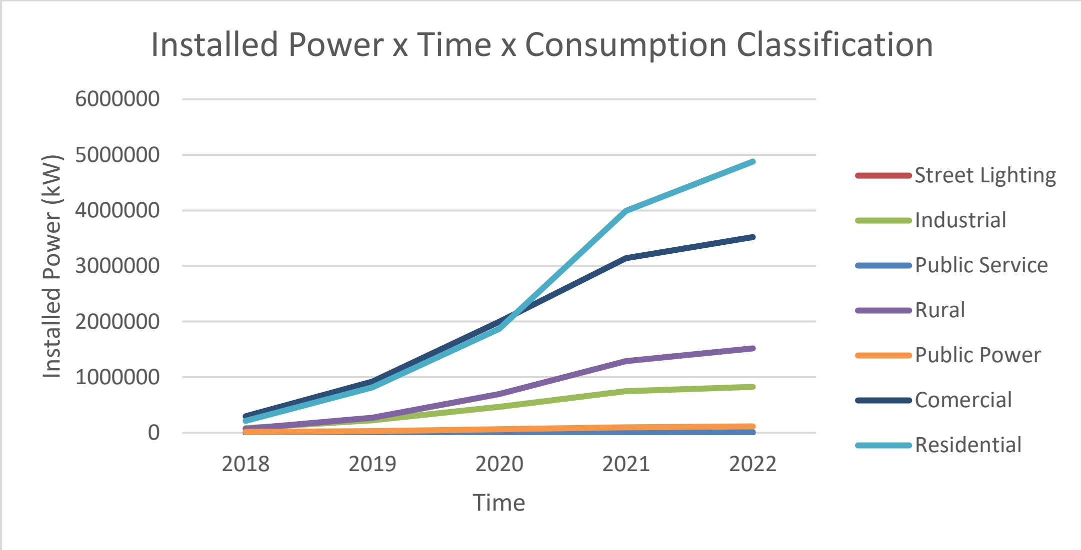


Figure 3-2 – Installed Power by Consumption Classification Over Time.



Moreover, such an increase has presented many advantages to the grid and society. Below is an exploration of them.

Environmental:

Through diversification of the energy matrix with renewable sources such as wind, solar, hydraulic, and biomass, it is possible to diminish the use of fossil fuels in energy generation. Since many countries' energy matrices heavily rely on non-renewable sources, this diversity is of great addition from both environmental and management perspectives.

Technical:

By diminishing the distance that the energy has to travel to reach the consumer, in other words, by bringing the generation closer to the load centers, the total losses may also decrease. It means that the optimal implementation of distributed generation reduces the energy loss in the system. Also, it increases the balance between consumption and demand since the use of storage elements brings certain flexibility to the load demand.

Another advantage presented by DG is the increase in the system reliability with the possibility of islanded systems. This issue has been approached in many studies and optimizations, some of them using I2SIM, aiming to increase the system's resiliency in critical events.

Societal & economical:

And most importantly for this paper, the solar potential presented in the country represents an even bigger potential for the creation of jobs through the creation of new solar plants. Currently, there are 392.494 photovoltaic plants in Southeast Brazil, and the prediction is that it will only escalate [35]. Worldwide, renewable energy created more than 12 million jobs in 2020, and PV is the leader in this matter.

Also, there is the possibility for enterprises to use the money which was saved from energy costs to reinvest and expand, promoting industrial development. By doing this, the balanced imposed by the system will force the society to develop through the creation of other products and services and also create new jobs, which is beneficial for the city from all perspectives.

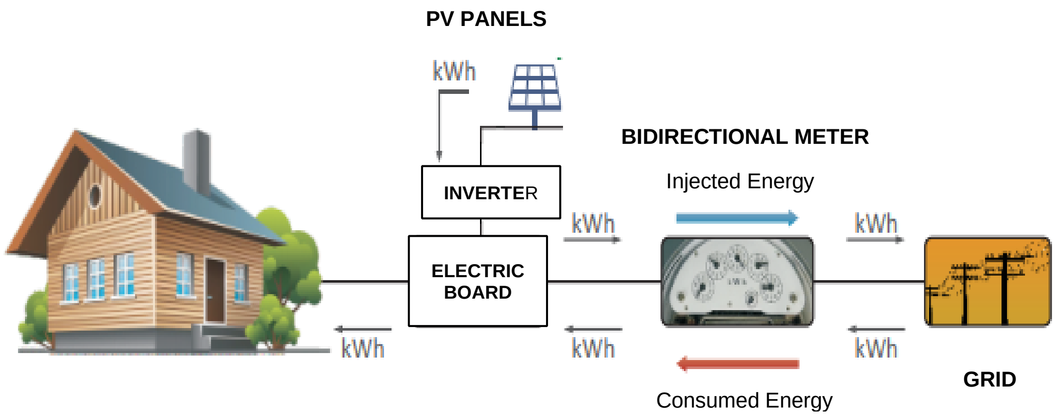
According to [36], the average time for the return of investment in PV generation in universities in Brazil is five years, which can even be shorter due to the increase in energy tariffs; consequently, it leads to lowers risks for investors and contributes to the viability of the project. Considering that universities are critical infrastructures with a great consumption of electricity, the sum of money that would be saved represents the same greatness of investments that would be possible to accomplish in education.

This advantage is valid not only for consumers and prosumers but also for the supply companies. It makes it possible to postpone investments in generation, and it decreases the dependence on transmission lines.

3.2. SOLAR PV

PV Generation is the most popular source of renewable energy, and there are reasons for this: it has a short payback time on investment; it is accessible and broadly accepted both culturally and financially. It converts the energy from the sun into electricity, which means that it uses a source of energy that is available on the whole planet. To do so, the Grid Connected Photovoltaic System (GCPVS) is composed of photovoltaic panels, inverters, and bi-directional energy meters (see Figure 3-3). The panels are often placed on the roof of buildings to optimize the use of space and irradiation collection, especially in big city centers. The inverter is responsible for converting the voltage from DC that was generated in the panels into AC, making it possible for the system to be connected to the grid and also to the house's net.

Figure 3-3 – GCPVS Scheme. Source: Adapted from [37]



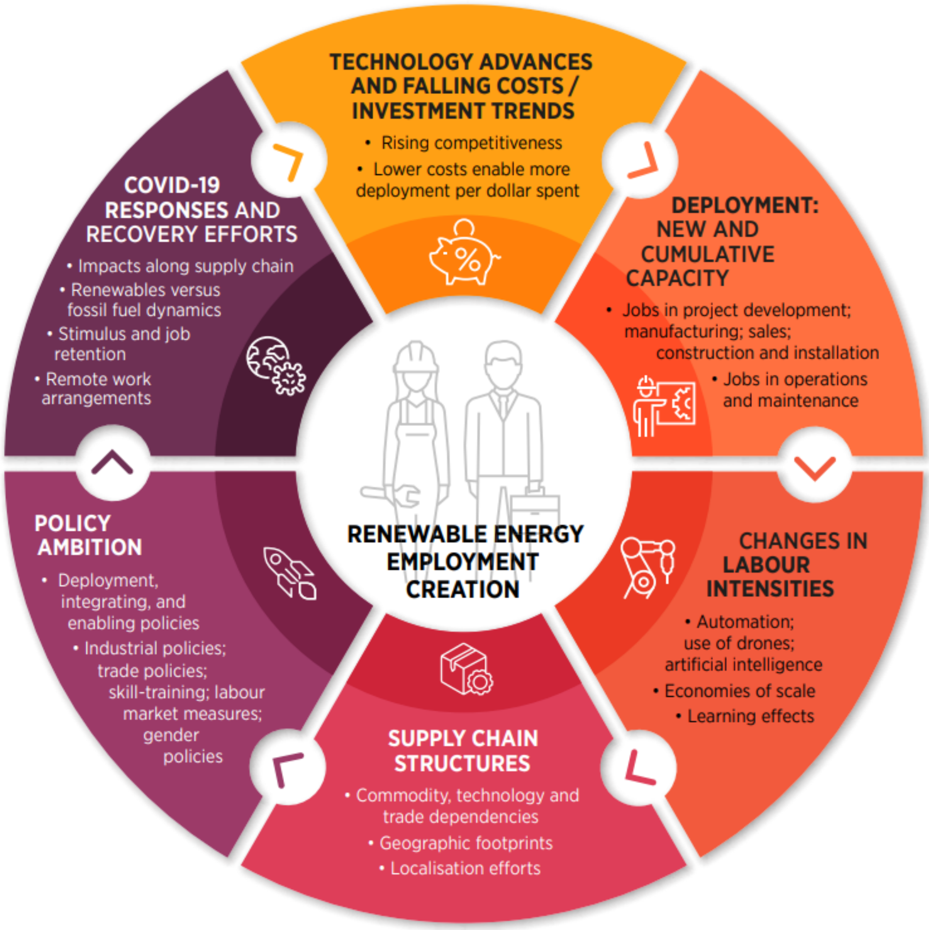
3.3. Socio-Economic Benefits of Renewable Energy Deployment

3.3.1. Employment

As mentioned before, renewable energy is not only beneficial for the environment but for the development of the cities as well. They have the capacity to create jobs, drive economic growth, enhance human health and welfare time [38], and be financially feasible at the same time, and their cost is continuously declining [33]. However, the potential of creating jobs and generating income depends on the extent to which industries along the different segments of the value chain can employ people locally, leverage existing economic activities or create new ones [38].

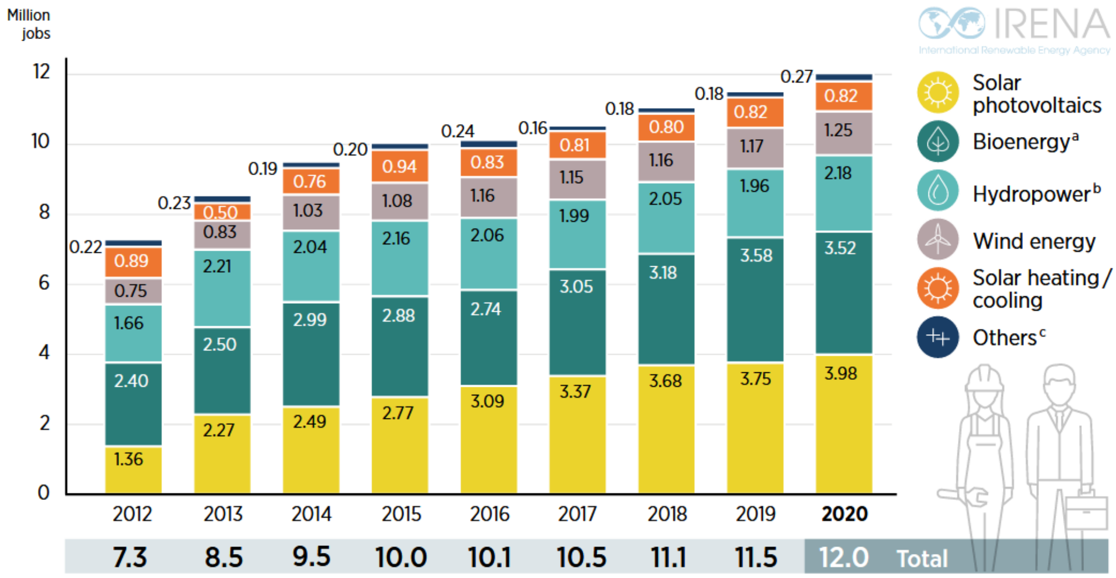
In Figure 3-4, it is possible to see that the factors that influence employment in the renewable sector are extremely broad. On the other hand, they do not differ so much from the employment in other areas, which makes it somehow more predictable. It is important to mention that the energy transition, along with the advances in technology, remains the main driver for job creation in renewable energies.

Figure 3-4 - Factors Influencing Renewable Energy Employment. Source: [33]



In 2020, the renewable energy sector employed 12 million people directly and indirectly. The number has continued to grow worldwide over the past decade, making solar PV one of the largest employers in renewable energy, along with bioenergy, hydropower, and wind power industries (see Figure 3-5) [33].

Figure 3-5 Global Renewable Energy Employment by Technology 2012-2020. Source: [33].



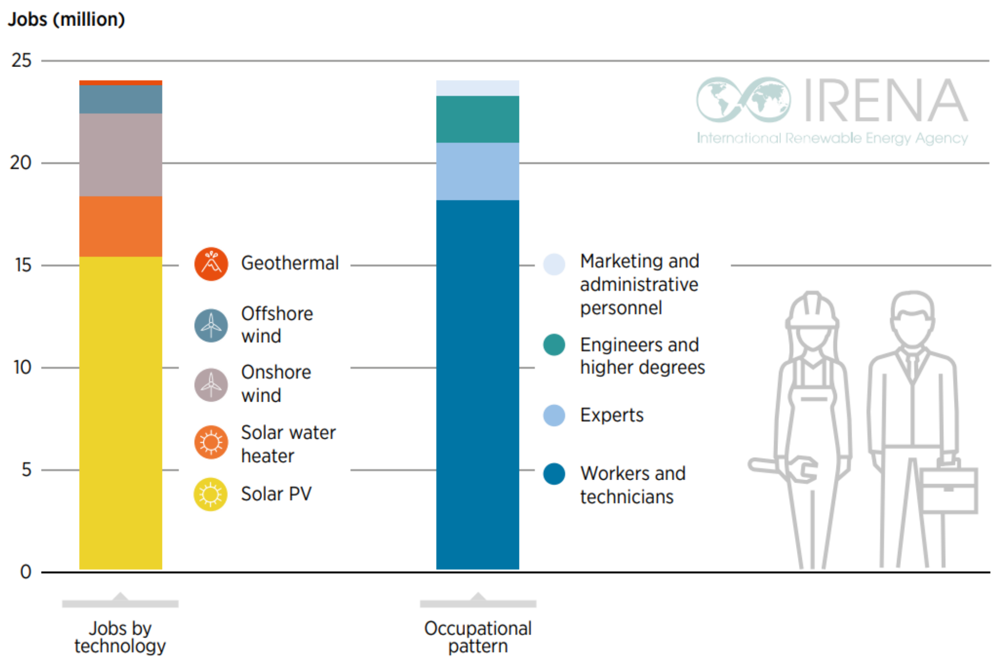
a Includes liquid biofuels, solid biomass and biogas.
b Direct jobs only.
c "Others" includes geothermal energy, concentrated solar power, heat pumps (ground based), municipal and industrial waste, and ocean energy.

Source: IRENA jobs database.

Withal predictions show that the renewable energy sector will globally employ 38 million by 2030 and 43 million people by 2050 under a 1.5 ºC scenario [33]. This scenario was estimated according to the deal signed in Paris in 2015 at the United Nations Convention on Climate change. There, signatories agreed to pursue efforts and try to limit the rise of global temperatures by 2050 to 1.5 ºC above pre-industrial levels.

If policies and pledges remained the same as today, jobs in the energy sector as a whole would grow to 114 million by 2050. On the other hand, under the 1.5 ºC pathway, it would grow to 122 million [33]. In the subset of geothermal, wind, PV, and Solar Water Heater (SWH), it is estimated that it will grow to 23 million. In Figure 3-6, these jobs are analyzed according to the occupational categories. It is evident that most job positions in this area are for workers and technicians, a category that does not necessarily require higher educational degrees.

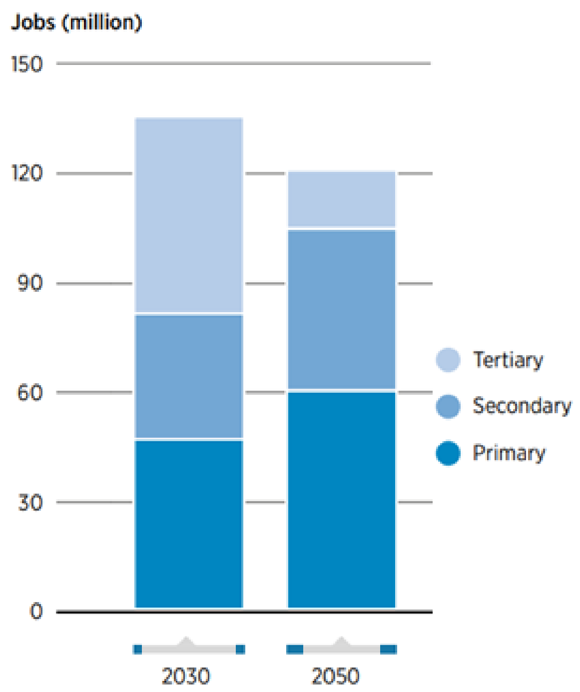
Figure 3-6 - Renewable Energy Jobs in 2050 by selected technologies and occupational categories. Source:[33].



Moreover, the study shows that in the energy sector as a whole, in the 1.5 ºC scenario, half of the jobs created by 2050 will require only a primary or lower secondary education, and 37% will need secondary education. Only 13% of jobs will require a tertiary education at the bachelor's, master's, or doctoral level (See Figure 3-7). It is important to say that the term "lower" does not mean that these jobs do not entail valuable practical skills and problem-solving abilities that cannot be acquired through academic coursework [33].

From this data, it is possible to say that the energy transition to more sustainable sources will be able to create opportunities for people with a range of skills and educational levels since the distribution ratio of educational levels varies according to the distribution of job opportunities.

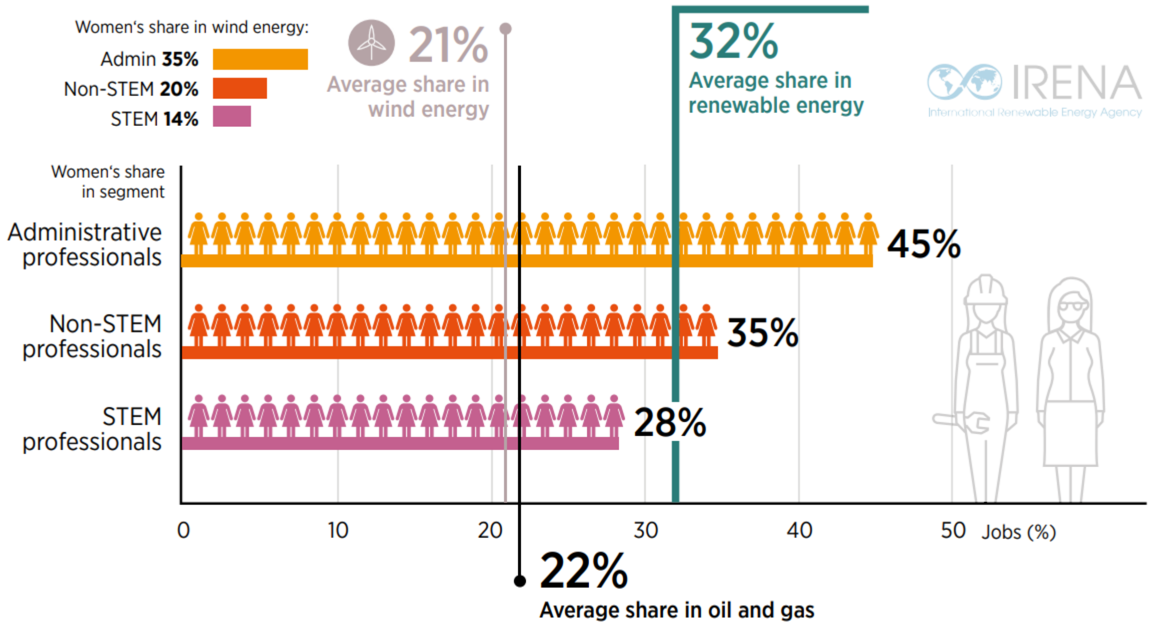
Figure 3-7 - Distribution of Energy Sector Jobs by Educational Level. Source: Adapted from: [33].



It is a challenge for the job market to keep a balance between skills, demand, and supply. In the energy sector specifically, due to the evolving changes in technology and increase in complexity, it has become more difficult to meet such demands and find people with a background in fields such as artificial intelligence (AI), computer science, engineering, etc. To do so, key pathways for delivering such transition skills include on-the-job training (training by employees on the field), vocational training (specialized short courses, for instance), university degrees, and apprenticeships (qualifications delivered in partnership among educational institutions and employers) [33].

Another relevant aspect of job creation is that it is extremely important to ensure that the workforce and the job openings include people from underrepresented and marginalized groups. Those groups can be women, minorities, people with disabilities, low-income people, youth, and older workers. Data from IRENA shows that women account for only 32% of the overall renewable energy workforce, and the challenge is even bigger where energy access is lacking. Also, women are more likely to be employed in lower-paid, non-technical, administrative, and public relations positions than in technical, managerial, or policy-making positions. The causes of this phenomenon, unfortunately, are not exclusive or specific to the energy sector. They could be attitudes, perceptions, and structural obstacles that make it difficult for them to stay and advance in their careers. Figure 3-8 shows that the majority of women employed in the energy industry remain in administrative positions, and a small part in STEM (Science, Technology, Engineering, and Mathematics) professionals [33].

Figure 3-8 - Women's share in the oil and gas, renewables, and wind power workforce. Source: [33].



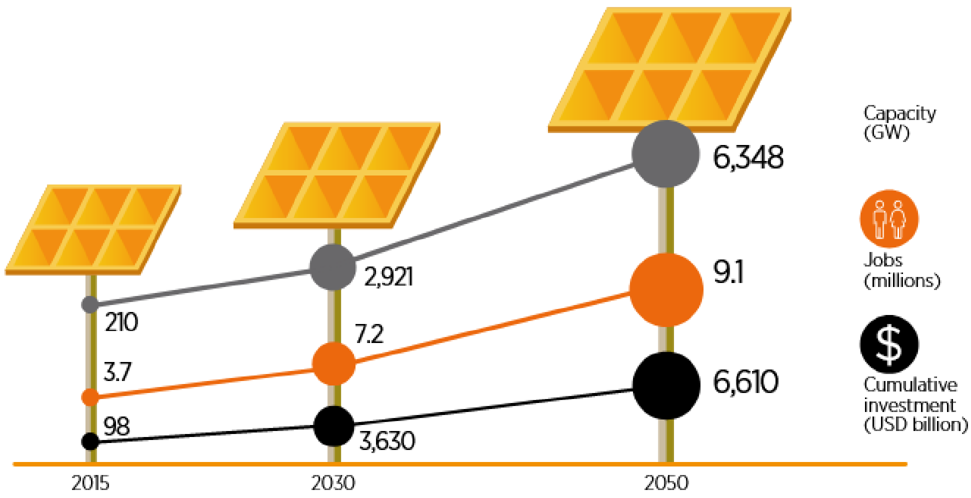
To minimize this gender gap in the energy sector, dedicated measures are needed to ensure equal access to job opportunities. Such measures could be targeted education and training; early exposure to renewable-energy-related topics; scholarships and funded training opportunities; mentorship schemes and targeted apprenticeship programs; equal pay policies; parental leave; part-time work; gender targets, and quotas to ensure a critical mass of female employees at all levels of management, as well as in technical and operational roles. Such efforts are necessary not only in the modern energy sector but also where access to energy is limited [33].

Diversification is not only about the social concept of equity and progress during the transition. It is also about finding a workforce from a wider and deeper pool of talent that is often underestimated. Indicators show that the sector might soon face a shortage of well-trained and experienced individuals, even with the rise in wages. So, the opportunity to diversify the workforce represents a tremendous opportunity for renewable energy [33].

3.3.1.1. Solar PV

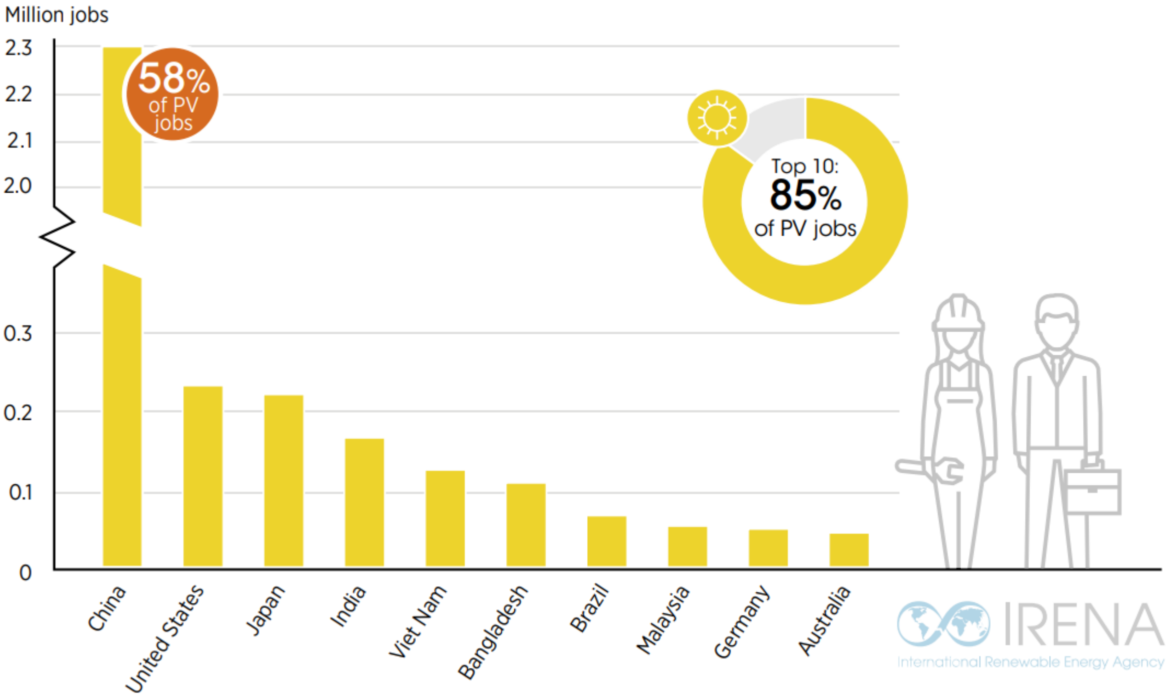
Global employment through PV generation increased by 12% in 2016 to 3.1 million, and the prediction for 2030 and 2050 is 3.6 and 6.6 million, respectively, in all areas: manufacturing, installation, and operation [38]. In 2020, solar PV added 127 GW of capacity, up from 98 GW in 2019. From this, 78 GW (more than 60%) was added in Asian countries [33], as shown in Figure 3-9.

Figure 3-9 - Estimated Cumulative Capacity, Investments, and Employment in Solar PV. Source: [38].



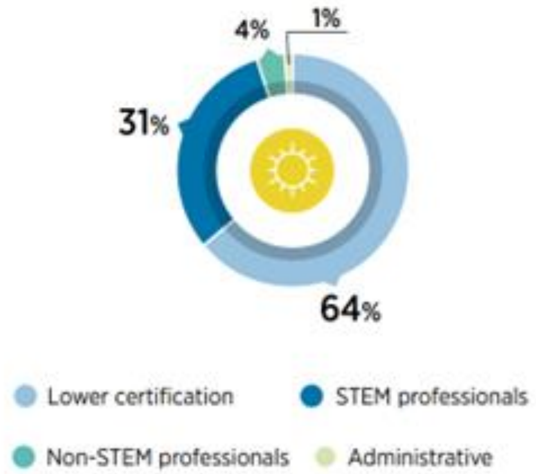
The Asian leadership in PV generation reflects in employment. In Figure 3-10, the Solar PV employment by country is demonstrated. Of the top ten countries, seven are in Asia. Together, the top ten accounted for almost 3.4 million jobs, 85% of the global total, and the Asians accounted for 79.4% of the world's PV jobs. It is due to the fact that they are not only leaders in generation but also in manufacturing and installations. Employment in manufacturing of the main components of PV installations is extremely concentrated in China. In 2019, two-thirds of the world's polysilicon output was produced by Chinese firms [33].

Figure 3-10 - Solar PV Employment: Top 10 Countries. Source: [33].



As expectations are that the sector will continue growing, it is important to better understand the human resources and skills required to produce, install and decommission renewable energy plants. Analyzing the job positions of 35 key occupations in the solar PV sector, results showed that only 16 of them require a university degree, and the others require either skills built through either on-the-job training, vocational training, and/or apprenticeships (see Figure 3-11).

Figure 3-11 - Human Resource Requirements for Workers in Solar PV. Source: [33].



3.3.1.2. Brazilian Scenario

In Brazil, renewable energy deployment employed 12 million people in 2020. Most of them are in biofuels. The general number seems to not have changed from previous years, but the share held by each type of generation has changed. An expressing increase in wind generating capacity in 2020, especially over 2019, led to a cumulative number of 40,200 people working in the area, mostly in construction, secondly in operation and maintenance [33] as shown in Figure 3-12 .

Figure 3-12 - Estimated direct and Indirect Jobs in Renewable Energy Worldwide by Industry (Thousands of Jobs), 2019-20. Source: [33].

	World	China	Brazil	India	United States	European Union (EU27)[o]
Solar PV	3 975[e]	2 300	68	163.5[h]	231.5[i]	194
Liquid biofuels	2 411	51	871[g]	35	271[j]	229
Hydropower[a]	2 182	813.6	175.8	319.5	71[k]	80
Wind power	1 254	550	40	44	116.8	259
Solar heating and cooling	816	670	47.2	21	na	21
Solid biomass[b, c]	765	188		58	44.5[l]	368
Biogas	339	145		85	na	76
Geothermal energy[b, d]	96	3			8[m]	40[d]
CSP	32	11			na	6
Total	**12 018[f]**	**4 732**	**1 202**	**726**	**838.4[n]**	**1 300[f]**

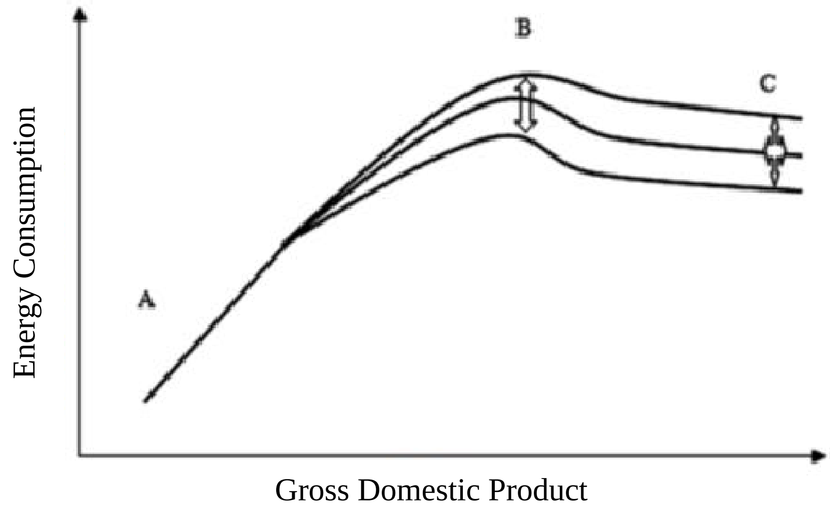
Furthermore, even with the COVID-19 pandemic drops in panel shipments, the number of PV generation installations sharply rose in recent years, making Brazil rank among the top 15 countries worldwide [33]. This sector specifically helped Brazil set a new record of 3 GW added to a total of around 7.7 GW in renewable generation, with 80% of the added capacity being only distributed solar PV. Of the cumulative distributed PV capacity, half of it is concentrated in the states of Minas Gerais, São Paulo, Rio Grande do Sul, and Mato Grosso, being Minas Gerais the far leader in large-scale installations. In sum, Brazil's solar PV employed around 68,000 people in 2020. It is relevant to mention that Brazil was able to achieve such expansion even though panels are still not produced in the country [33].

3.3.2. ENERGY AND DEVELOPMENT

In the light of development, the demand for energy grows accordingly to the economic growth of the country. When comparing the two in a graph, it is possible to see how their behavior follows each other alongside the timeline. According to Tao, such a relationship is a valid correlation. However, as the electricity demand increases, the relationship between industrial production and the Gross Domestic Product (GDP) decreases, hitting a peak point, where the industrial production and the energy demand decrease and get to a constant value or a slight fall. In the long run, energy demand will not continue to increase as the GDP does. This is due to the improvements in industry and technological advances [39].

This relationship can be observed in Figure 3-13, where the behavior is divided into phases. Nowadays, the United States and others developed countries are in phase B or C, and most of the developing countries are in phase A, which is the case of Brazil.

Figure 3-13 - Energy Demand and GDP. Source: [39]



3.3.3. INVESTMENT AND RETURN

Faced with the search for renewable energy, the photovoltaic system is of paramount importance, and the financial analysis of these systems is necessary so that the investment has a positive return. Given this, Brazil, with its vast geographic extension, together with the high incidence of solar radiation, allows the country to invest in this type of system, which takes place through the conversion of solar radiation into electrical energy [40].

There are several studies related to analysis methods to quantify the viability of photovoltaic systems for homes, companies, buildings, and universities, among others, but what everyone seeks is the return on investment, which is nothing more than the quantification of what will be gained by investing in the photovoltaic system, known as ROI (Return on Investment) of the project [41].

Another tool used that serves as a follow-up for investment analysis is the payback time, which analyzes the number of periods required for a business's return on investment. Despite this method, which has some limitations, as it does not consider the appreciation or devaluation of money over time and does not also consider the cash flows that occur after a while, it is widely used because normally, the investor wants to know what his return in time is (years old). But as an alternative, there is the calculation of the discounted (annual) payback, as it considers the effect of money in time discounted to the present at a fair rate (Minimum Rate of Attractiveness).

During the investment analysis of a photovoltaic system, other variables must be analyzed and considered, including the cost of operation and maintenance (cleaning the modules, monitoring services, and possible partial replacement of components when applicable), which according to [42], [36] are one of the factors that most influence the analysis as well as the energy tariff and its annual readjustment that tend to influence the investment of photovoltaic systems because the cash flow revenue is based on the cost avoided by this system, in this way, the higher the kWh price, the more attractive photovoltaic systems become.

4. I2SIM MODELLING AND FRAMEWORK

4.1. INTRODUCTION

Due to the complexity involved in analyzing the combined feasibility of implementing such technologies among interdependent infrastructures, it was necessary to perform this study through virtual simulation. This way, the optimal approach for creating long-term planning can be found more efficiently without the trial-and-error method. For that, the Infrastructure Interdependencies Simulator (I2SIM) is used as a framework to run the cases.

I2Sim is a simulator tool developed by the Complex Interdependent Systems group (CIS) from the Electrical and Computer Engineering Department at UBC – University of British Columbia to investigate critical infrastructures' interdependencies. It was created to improve the assessment, management, and risk mitigation of failure events that are connected to critical infrastructure interdependencies [43]. It was developed based on the idea that every large system is composed of many subsystems and that when these subsystems are systematically coordinated together, the entire system can flourish [44].

So, I2Sim was originally developed in the simulation environment "Simulink" to make it possible for users to analyze the dynamic, linear, and non-linear systems in discrete and continuous sample times. In this environment, the interface interacts with users through block diagrams and tools, making it possible for real-world problems to be modeled and simulated. I2SIM can be used for both planning purposes and real-time disaster response management [44]. A more profound exploration of this environment is described ahead in Ontology. Recently, a Python-based I2SIM modeling has been implemented at UBC.

4.2. INTERDEPENDENCY

By definition, the word interdependency means the condition of two or more things depending on each other [9]. Bringing this concept to the light of city planning, it is possible to observe this phenomenon among the critical infrastructures of cities, where a failure or a change in one of them results in impacts on all the others, causing what is known as the cascade effect. Due to the complexity of city systems, these interdependent relationships may not always be obvious and intuitive like it is believed sometimes. With that being said, to better use the resources of such infrastructures and even propose adequate improvements for them, computational help is required, and that is when I2SIM enters.

To briefly explore this relationship, here are some examples of real ruptures in cities systems where previous planning could have helped to decrease financial and living loss:

In the year 2000, the Sapucaí River overflowed and flooded 80% of the city of Itajubá, causing the death of 5 people and making 10 thousand unsheltered. Because of this, the pavement of roads was damaged and compromising the access to some areas, the phone network stopped working, the water supply system was operating at 40% capacity, and the most drastic consequence was the lack of fresh water and food. Also, as a consequence, it was lacking medicines and vaccines for diseases that are easily spread in this scenario, such as leptospirosis and typhus. Withal, the rainfall index could not be measured since the data is registered in the current Federal University of Itajubá, and its campus was also flooded [45].

Another extreme event scenario that happened in Brazil was the truckers' strike that took place in May 2018. The workers stopped on the 21st, demanding a reduction in the diesel costs, mostly in the taxes on the fuel. Not only they stopped working, but they partially blocked the roads, causing a shortage of fuel, raw materials, and essential products like food. It had a significant impact since road transportation is the most used method to transport goods in the country [46].

Finally, the event that disrupted the whole world on many different levels: the pandemic of COVID-19. Organizationally, companies felt the direct impact of sick and quarantined workers, causing facilities to shut down. Also, they felt the economic repercussions of border closures and interruptions in deliveries of raw materials and components. Projects were delayed and instigated the rethinking of complex international supply chains. In addition, it caused the switch to remote working arrangements, which differ across industries and occupational groups. But generally, it may affect where jobs will be created in the future, which shows the long-term impact of extreme events [33].

4.3. ONTOLOGY

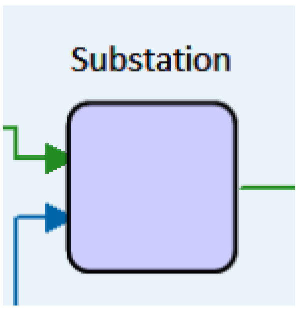
Representing the infrastructures and their interconnectedness requires the model to present different components. These components are defined by their nature and functionality and have distinct functions in the simulation environment. The I2SIM ontology and the description of such components are presented below [47].

4.3.1. CELL

The cell component represents production units. Inside them, the tokens can be created, transformed, and stored. From the input tokens, the output tokens are generated. They can be of the same nature as the inputs or also be the product of combining a set of resources [48]. In other words, the cell functions as the mediator of the relationship between inputs and outputs [49] as illustrated in Figure 4-1. The cells can have many input tokens of different nature but produce only one output token [50].

Depending on how the operational level is determined, they can be classified in two natures: processing and state cells. In processing cells, the operational level is determined by the ratio between the input's availability and output. In state cells, there is not a specific resource to be processed but to produce an output. In summary, in both types of cells, the least available input determines the output level of the Human Readable Table (HRT) and therefore determines the output of the cell [44].

Figure 4-1 I2Sim Production Cell. Source: [44].



4.3.2. TOKEN

The tokens are the inputs and outputs for every component in the model. They represent the flow through the system and serve as exchange units, which are transferred between other units inside the system in the simulation environment [48].

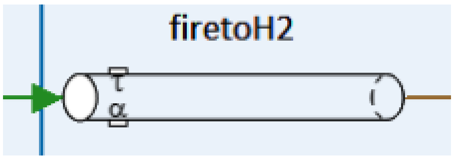
There are two variable types in control systems: controllable and observable. Tokens comprehend both variables, known or observable and unknown or controllable. Also, they can be of any nature, physical or tangible and non-tangible variables, which are called modifiers [44].

4.3.3. CHANNEL

Channels are the units responsible for the transportation of the tokens among the components in the system. In addition, depending on the relationship between the connected units in the study, a delay factor (tau) might be used [48]. Also, they can be characterized by a loss coefficient (alpha) during the transportation process [49] as illustrated in Figure 4-2.

The values for loss and time delay can be determined by other interdependencies in the system and can change throughout the simulation. For example, in a flood scenario, the road blockage will vary as the water continues to flow. These values can also be fed into the simulation environment by external simulators [44].

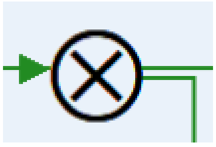
Figure 4-2 - I2Sim Channel. Source: [44].



4.3.4. DISTRIBUTOR

The distributor is the component that allows a unique flow of input to be split into different paths and travel along the system to supply other production units. The distribution ratio determines the values of token outputs, and it is based on percentages applied to the tokens' input port signal [48] (Figure 4-3). The internal optimizer and the external human operator determine this ratio, which allows the variable to be controlled [44]. In resource allocation, the distributor is considered a decision point since it interacts with other layer levels through optimization routines and software [48]. Therefore, it is important to mention that a distributor has only one input and multiple outputs of the same token type. Furthermore, one condition for the allocation is that the total sum of outputs must be equal to the inputs to keep the energy balance in the system. Another condition is that every cell must have a distributor attached to it so that the internal optimizer can redistribute the initial allocation of resources based on maximizing the output of the objective cell [44].

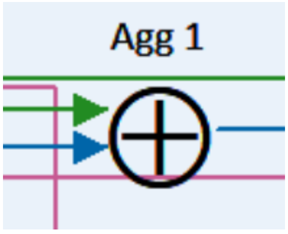
Figure 4-3 - I2Sim Distributor. Source: [44].



4.3.5. AGGREGATOR

Unlike the distributor, the aggregators (Figure 4-4) are the additive elements in I2Sim models [51]. It is a block that receives multiple inputs of type of token and combines them into a unique flow of output or a unique channel [48]. That is to say; an aggregator has many inputs and one output of the same token type [43].

Figure 4-4 - I2Sim Aggregator. Source: [44].

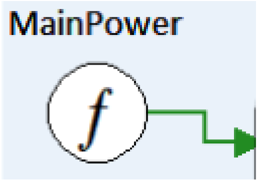


4.3.6. FEEDS (SOURCES)

Sources blocks are used to represent the infrastructure systems that are not included in the I2SIM model, so they connect the external world and I2Sim. They are Thévenin equivalents of the external world in the I2Sim environment. Generally, the values of the feeds change during the entire simulation as the event progresses [44].

For example, an external source of electricity would supply a higher amount of energy as the population grows and demand increases as well, as illustrated in Figure 4-5.

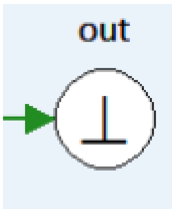
Figure 4-5 - I2Sim Source. Source: [44].



4.3.7. SINKS

The sink blocks (Figure 4-6) have the function of sending internal tokens outside of the I2SIM model. In this way, they function as the outside systems that would absorb tokens produced inside the modeled system. They are also Thévenin equivalents, but this time representing the outside systems that would absorb tokens produced inside the modeled system and, therefore, maintain a physical energy balance within I2Sim [51], [44].

Figure 4-6 - I2Sim Sink. Source: [44].

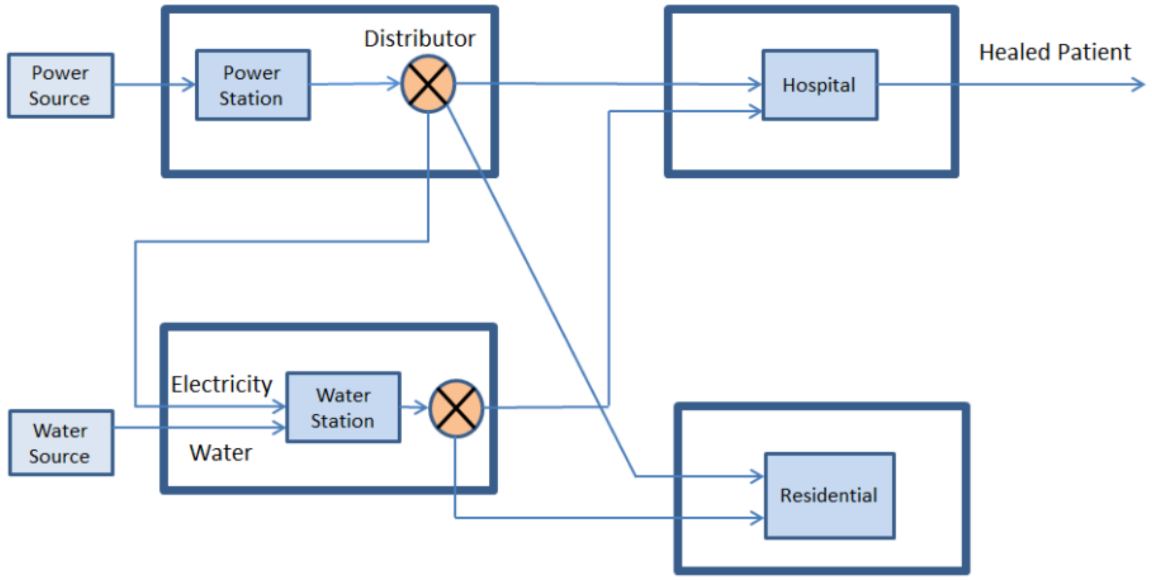


4.4. I2SIM MODELS

To accurately represent the systems of the real world, I2Sim components (See "Ontology") can be used to model multiple dissimilar infrastructure systems. The connections between these units are defined as channels, and the resources and services that flow in them, such as water and power, as defined as tokens. The relationship between the inputs and the output is predefined by a function that describes the operation of the cell (lookup table or Human Readable Table - HRT) [52]. The connection of cells and channels, as well as their inputs and outputs, set up a mathematical formulation of the relationships between the critical infrastructure systems.

Withal, a system of discrete-time equations is created and solved simultaneously for all components at every time step along the timeline to find the operating point of each production cell [43]. Figure 4-7 is a representation of a system composed of a hospital, power and water systems, and residents in a hypothetical city. Electricity is the token that is an input for the hospital, water, and residents' cells. As an output of the hospital cell, there are healed patients [52].

Figure 4-7 - I2Sim Sample Model. Source: [50].



4.4.1. HUMAN READABLE TABLE (HRT)

The Human Readable table is a matrix that connects the inputs to a single output. The output for the first row is a function of all the inputs in that row. Then, the outputs are divided into five discrete levels representing their capacity from 100% to 0%. So, the inputs are also divided into five levels ranging from 100% to 0% available resources to produce the correspondent output and then define the operability of cells [50].

The data used to fill up these tables can come from either historical data or from the infrastructure expert who has first-hand knowledge of the area and the relationships between inputs and outputs. The columns of the HRT are the inputs and outputs represented as vectors. The number of discrete operating levels (rows in the HRT) is determined by the input's spatial resolution. This resolution depends on the data provided and is inherently mapped as a probabilistic function. Therefore, although i2SIM is a deterministic system with a single output, uncertainty is mixed within the system, making it somehow stochastic at the same time [44].

In addition, every input must be independent of another, meaning that they are eigenvectors and not scalar equivalents of each other. The relationship between inputs and output is a mathematical function where the values in each column can be both monotonically increasing or monotonically decreasing where repeated values are allowed [44].

An example of an I2Sim model of an electrical substation is shown in Figure 4-8, along with its HRT in Figure 4-9. The model shows the production cell, one distributor, and three channels. The three sources represent three transmission lines coming into the substation, aggregating into a unique input. On the HRT, it is possible to see the different operability levels of the cell that allows its evaluation of the integrity [53].

Figure 4-8 - Electrical Infrastructure I2Sim Model. Source: [53].

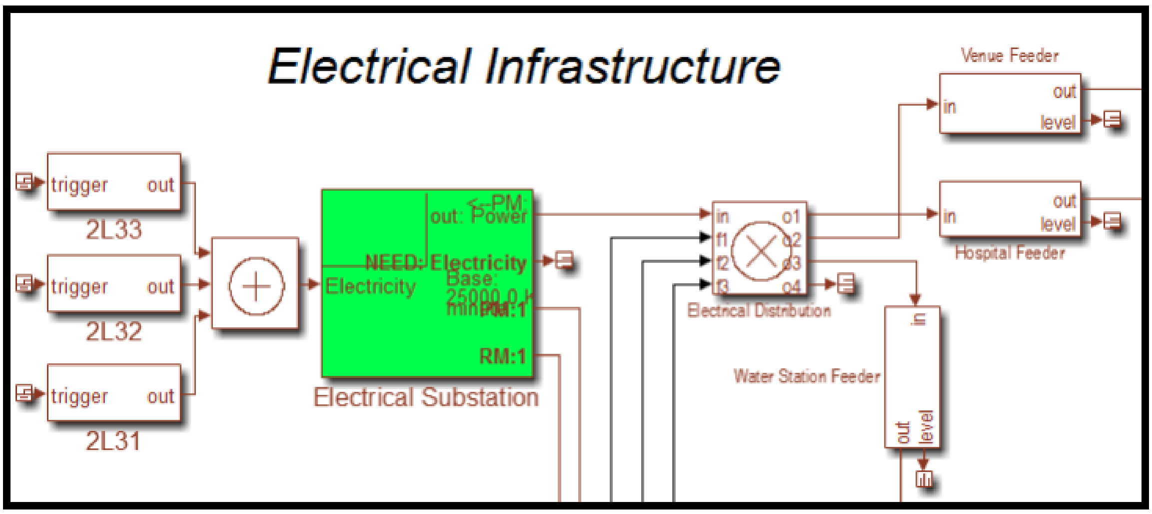


Figure 4.2 Electrical Infrastructure

Figure 4-9 - Electrical Substation HRT. Source: [53].

Output (kW)	**Input** (kW)
25000	25000
18750	18750
12500	12500
6250	6250
0	0

Another and more complex example is shown in Figure 4-10, where the installations of a hospital are modeled. Its inputs are electricity, water, natural gas, and medical gases, and the output is people per hour, meaning the patients that are treated per hour. It means that to treat this number of patients, the described number of resources is needed.

Figure 4-10 - Hospital HRT. Source: [53].

Output (People/h)	**Electricity** (kW)	**Water** (kL/h)	**Natural Gas** (ft^3/h)	**Medical Gas** (%)
10	2000	51	3333	10
7	1500	38	2500	75
5	1000	26	1667	50
2	500	13	833	25
0	0	0	0	0

4.4.1. CELL OPERABILITY LEVEL

As the HRTs as divided into different operability levels, when the simulation is run, the cells are optimized to their optimal integrity level. In the I2Sim-RT version, the operability level in the interface is represented by coloring the cells. The colors and the respective levels are explained in Table 4-1.

Table 4-1 - Colors and Operability Level

	Cell Level
	80 – 100%
	60-80%
	40-60%
	20-40%
	0-20%

5. METHODOLOGY

This chapter presents the search ranking; the justifications for the methodological resources used; the implications and potential limitations of the research; the resources used to better describe the results and obtain the conclusion; the form of data collection, presentation of the report of the analyzes studied and the conclusion of the research.

5.1.1. INTRODUCTION

The research in question is classified as applied in nature due to its practical interest since its results can be applied to solve real problems [54].

Regarding the objectives, it can be said that it is normative research whose concern is to identify the determining or contributing factors for the occurrence of certain phenomena. This type of research seeks to explain the reason for events based on the results offered [55].

Finally, concerning the research method or procedure, it is about modeling and simulation. For [56], the models are powerful and widely used in complex systems analysis. Generally, they can imitate the operations of the real system following its evolution over time; however, they can also be used for an analysis of the system at a particular time. Such models then serve as a basis for simulating the functioning of systems through computational techniques.

5.2. MODELING AND SIMULATION

For [57], a mathematical model refers to a simple drawing of reality or a fraction of a system according to a set of mental or experimental assessments. The general purpose of modeling is to provide conditions for the acquisition of knowledge in a research environment. The analysis of events to create a condition of doubt and problematization is the beginning of the elaboration of a mathematical model.

In this scenario, the modeling and simulation process can be defined as computational experimentation in which a real or idealized system is used for the analysis of authentic problems of a complex nature to measure several operational choices capable of identifying and indicating more efficient ways. Appropriate operations that provide the general optimization of the system [58].

According to [59], modeling and simulation is a tool based on operational research, which uses the constitution of models to understand the environment, identify problems, establish strategies and identify opportunities for improvement.

For [60], performing modeling and simulation experiments allow explaining the behavior of systems; elaborating theories and hypotheses that analyze the evaluated behavior; increasing system performance; launching new systems with the desired performance, in addition to outlining future conduct or the result caused by changes in the set of inputs.

Simulation represents an extremely useful and crucial concept for scientific and technological growth, and, over time, it has gained credibility as an area of study based on the opportunities offered by the development of computing [61].

According to [62], computational modeling and simulation are presented, in this context, as the most viable device, avoiding real changes in the organizational environment, thus providing lower cost, high reliability, and agility in responses.

In the modeling and simulation process, the activities can be summarized as follows: construction of the conceptual model, transformation of the conceptual model into a computational model, and experimental tests in different scenarios, seeking the best alternatives [63].

According to [64], computer simulation models can be divided into static and dynamic. Static models represent a particular moment in time, and dynamic models represent models that change over time. When talking about dynamic simulation, it is possible to classify it as deterministic, which presents a set of inputs and outputs without parameters variability, and stochastic, which presents estimates that oscillate in a random distribution. The stochastic simulation, in turn, is divided into continuous and discrete events. When talking about continuous simulation, the state variables change over the simulation time. When referring to the simulation of discrete events, such variables remain unchanged for a period, being able to be modified after the occurrence of another event.

The use and application of computer modeling and simulation are capable of helping managers in decision-making in problems of significant complexity, in addition to providing a deeper knowledge of an organization's processes [65].

5.3. CASE STUDY

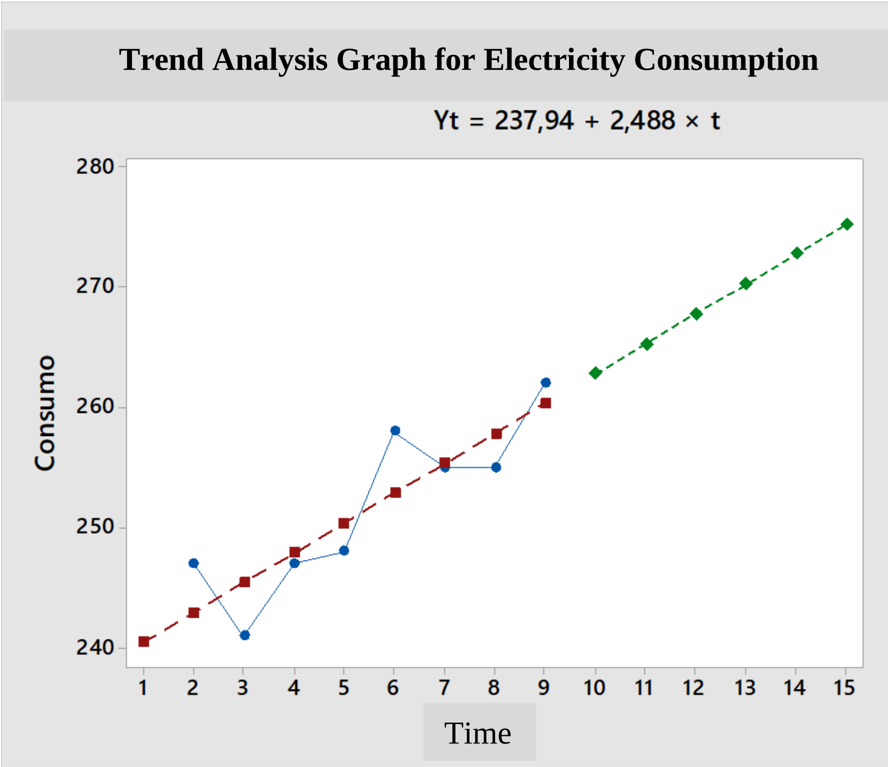
5.3.1. THE CITY

Itajubá is located in the Southeast of Brazil, more precisely in the South of the State of Minas Gerais, with an area of 294,835m². According to the last census from IBGE, 2010, it had 90.658 inhabitants at the time, and the prediction for 2022 is 97.782 inhabitants. Of those, 91,3% reside in the urban area and 8,7% in the rural area [66]. The occupational characteristics of the city are considerably diverse. Nowadays, it has one of the biggest industrial districts in the region. Also, other activities are well developed in the city: commerce, agribusiness, home production, and crafts. The most remarkable activity are the ones related to education and technological development due to the high density of qualified professionals and institutions. Economically, the GDP (Gross Domestic Product) per capita in 2019 was R$32,734.18, and the percentage of occupied people in relation to the total population was 27.5% [66].

The following data about the city was used in the simulation:

In Figure 5-1, the electricity consumption was predicted with a linear tendency analysis for the years of study based on the data available in the Statistical Yearbook of Electricity from EPE [67], [68].

Figure 5-1 - Electricity Consumption Prediction for Itajubá.



The current installed PV Generation in the city, available on the Power BI sheet provided by ANEEL, was used to estimate the avoided costs with electricity [35].

Table 5-1 - Instaled Capacity of PV Generation in Itajubá. Source: Adapted from [35].

Installed PV Generation (kWp)								
Year	2015	2016	2017	2018	2019	2020	2021	2022
Residencial	1,5	58,49	42,96	112,4	367,94	718,59	783,13	637,31
Industrial	0	0	0	0	36	61	20	151
Comercial	0	2	89	69,19	358,16	1493,19	522,68	194,88
Rural	0	0	0	0	80,88	129,21	129,56	139,25
Total per year (kWp)	1,5	91,99	146,96	181,59	842,98	2401,99	1471,37	1122,44
Cumulative (kWp)	1,5	93,49	240,45	422,04	1265,02	3667,01	5138,38	**6260,82**

Using the same reasoning mentioned before, the Education avoided costs were estimated based on current electricity tariffs and installed capacity as described in Table 5-2. To estimate the avoided energy for UNIFEI, it was considered that the panels generate energy 10 hours/day; the year has 365 days; and a 80%

generation rate.

Table 5-2 - Education Installed Capacity and Avoided Energy Costs

Education Avoided Energy		
	Power (kWp)	Energy (kWh/y)
UNIFEI	626	1,827,920
G9	62.1	181,332
Total	688.1	2,009,252

The following indicators in Table 5-3, Table 5-4, Table 5-5, Table 5-6, and Table 5-7 were collected from the Brazilian Institute of Geography and Statistics and were also used as input in the simulations.

Table 5-3 - Basic Education Indicator. Source: [66].

IDEB - Basic Education Indicator					
	2011	2013	2015	2017	2019
Elementary school	5.25	5.5	5.65	5.75	5.75
High School				4	4.3

Table 5-4 - Adult Scholarity. Source: [66].

Adult Population Scholarity		
Year	2000	2010
% of People that Completed High school	49.65	64.53

Table 5-5 - Income per Capita. Source: [66].

Income per capita (R$)				
2000	2010	2018	2019	2022
694.02	948.2	1314	1358	1322

Table 5-6 - Criminality: Nr. of Violent Crimes per Year in Itajubá. Source: [69]

Criminality Indicator						
	2010	2018	2019	2020	2021	2022
No of Violent Crimes/year	23	15.38	13.48	12.7	11.3	14.16

Table 5-7 - Gini Index. Source: [66].

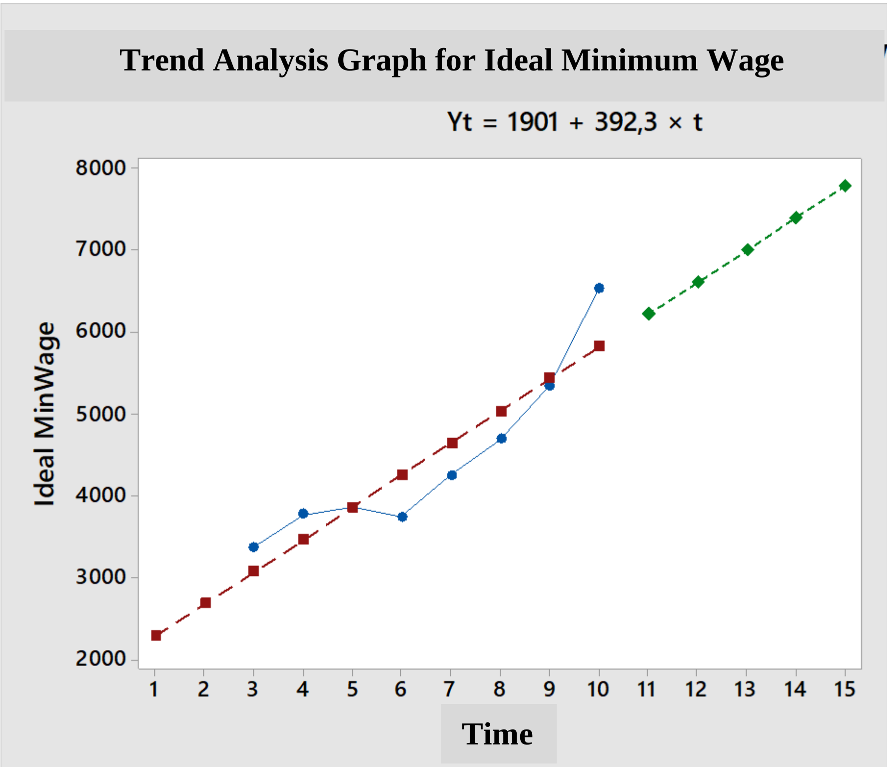
Gini Index	
2003	0.42

Table 5-8 - Ideal Minimum Wage Historical Data

Ideal Minimum Wage			
2015	2016	2017	2018
R$ 3,377.62	R$ 3,777.93	R$ 3,869.92	R$ 3,747.10
2019	2020	2021	2022
R$ 4,259.90	R$ 4,694.57	R$ 5,351.11	R$ 6,535.40

From the ideal minimum wage historical data, a forecast was performed using trend analysis in the software Minitab® as shown in Figure 5-2.

Figure 5-2 - Forecast of Ideal Minimum Wage



5.3.2. CHALLENGES IN COLLECTING INFORMATION

Collecting realistic and reliable information about the city to feed the model is a real challenge. The great extension and variety of areas that the model covers are one of the reasons for this. Also, the circumstances in which this work was developed were a strong aggravating factor. It started to take shape right at the beginning of the pandemic of COVID-19 in 2020. This fact itself emphasized the importance of studying the interdependency of critical infrastructures. Beyond that, it created many outliers in the data collection due to the abnormal behavior of society with social distancing, medical leave, and even the numerous deaths it caused. Furthermore, the Brazilian Institute of Geography and Statistics, which is responsible for performing the census every decade, due to COVID-19 restrictions, could not perform the census that was supposed to be in 2020. So, the information collected about the city had to be projected from the last data available. From a systems engineering perspective, it affects the model numerically but not in quality since the results are based on the order of magnitude of the data. Therefore, it is assumed that it does not take any credit or reliability of the research.

5.4. MODEL DEVELOPMENT

The model was developed based on the idea that an energy system is also a social system, with stakeholders that are institutional agents and citizens [39]. These individual agents and people are interconnected as one depends on the other to exist and be productive in society.

Starting from the Human Development Index, the inputs for the society cell were defined based on the indicators used in its calculation. Then, based on Maslow's Hierarchy of Needs (See Figure 5-3) [70], the other cells were designed along with their inputs and outputs. After that, the model was simplified, focusing on the aspects of society that could suffer an actual impact from the deployment of Smart Grids (See Figure 5-4).

Figure 5-3 - Maslow's Hierarchy of Needs. Source: Adapted from [71]

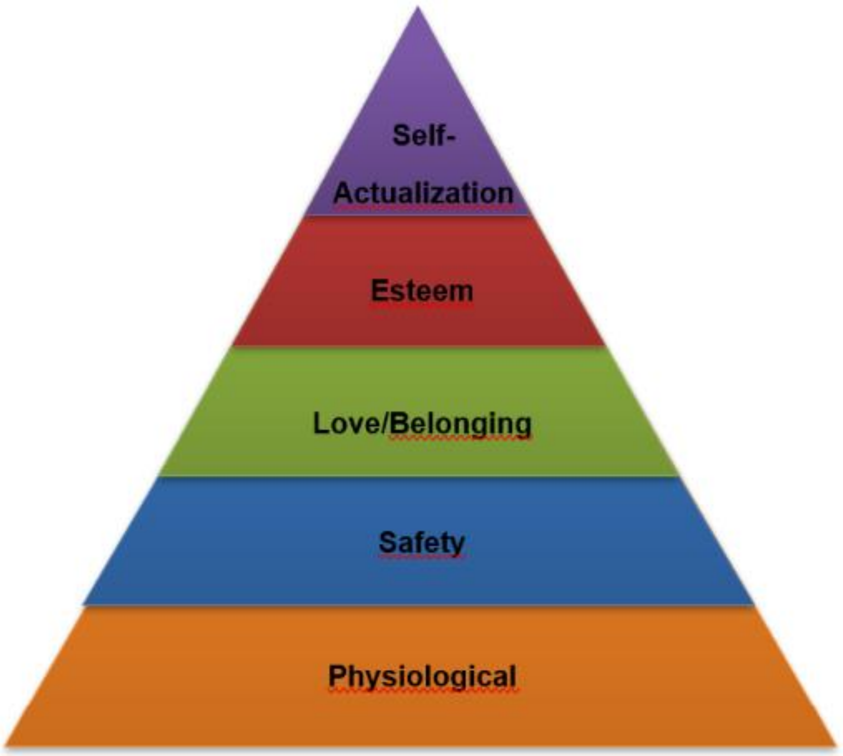
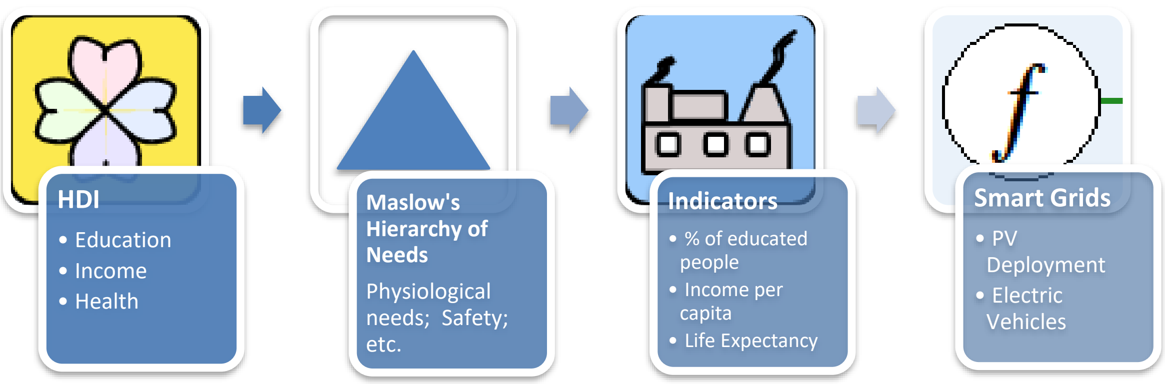


Figure 5-4 - Model Development Schematic



As the simulations were performed and the system's behavior was observed, the need for changes in the model emerged, and therefore three models were created. The first one represents the initial data and assumptions, and the second, where inconsistencies in blocks that were decoupling the model and creating a linear dependency between tokens were adjusted, and the third, where the transportation cell was split into Public and Private Transportation.

5.4.1. GENERAL ASSUMPTIONS

In this section, the assumptions made as the model was developed are explained.

- First, even though transportation, education, and many other cells are composed of other cells in real life, for modeling purposes, it was chosen to simplify each area as a single cell. For example, load transportation, public transportation, and the private commute are a single cell called transportation;
- Also, there are other areas that are not represented in this study, such as the telecommunications system. The choice of what would be included and what was not was based on the possible impact of smart grids on them and on the relevancy of the interdependent relationship to the optimization goal;
- The input data used to feed the HRTs could vary in number according to many different factors related to the indicator. For instance, emissions vary according to the pollutant analyzed, the vehicle category, type of fuel, model, and year of the vehicle [71]. The goal of the inputted data is to have an order of magnitude and importance of the tokens and their relationships;
- Current Net Metering legislation is used to quantify Energy Avoided Costs; That is to say, the ratio for energy generation and energy consumption adopted is 1:1;
- Future changes in legislation can significantly impact the results obtained;
- The costs regarding the investment in distributed generation and the time of return are not considered in the model;
- The authors understand that computational resources are only tools that can help the decision-making process and do not substitute the human capacity for making them.

5.4.2. MODEL 1

5.4.2.1. CELLS

Cell 1 – Society

As a citizen-centric model, this cell (see Figure 5-5) represents the overall goal of the modeling, which is optimizing the HDI of the city. Its HRT is presented in Table 5-9.

Figure 5-5- Society Cell

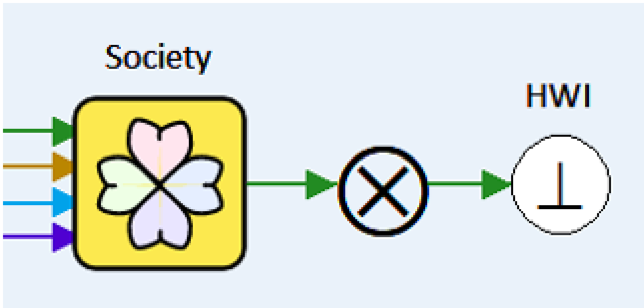


Table 5-9 - Society HRT

1 - SOCIETY					
HRT	y(t)	X1 (t)	X2(t)	X3(t)	X4(t)
Operability	Development	Poverty	Health	Education	Safety
	HDI	Income per capita (R$)	Life Expectancy (Years)	% Adults completed HighSchool	No of avoided violent crimes/year
100	1.000	6535.4	85	100.00	28
75	0.8935	3928.7	81.68	82.27	21
50	0.787	1322	78	64.53	14
25	0.3935	661	39	32.27	7
0	0	0	0	0.00	0

Cell 2 – Transportation

The public transportation system of the city is considerably limited, and it has worsened during the pandemic. However, even with its limitations, it is responsible for a considerable amount of GHG emissions. Culturally, the most common method of transportation in the city is by private combustion vehicles. Consequently, emissions and traffic have become a great issue, especially during peak times. In addition to these evident components of the transportation system, it was added the solid waste collection system. As underestimated as it could be, it is responsible for a great amount of GHG emissions in the cities. Also, it presents interesting flexibility that allows the deployment of PV generation along with electric trucks to be more efficient, as trucks can travel during the night (they do not emit noise) and recharge during the day. This cell is illustrated in Figure 5-6, and its HRT is presented in Table 5-10.

Figure 5-6 - Transportation Cell

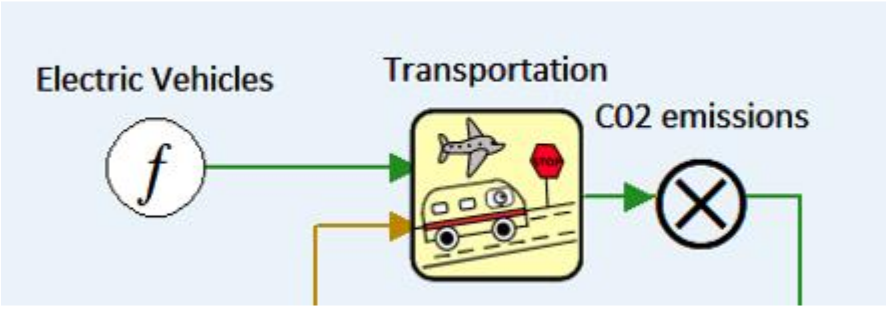


Table 5-10 - Transportation HRT

2 - TRANSPORTATION			
HRT	y(t)	X1 (t)	X2 (t)
Operability	Avoided Emissions	Electric Vehicles	Reliability
	CO_2 kg/y	% of fleet	% of people who use
100	2,288,488	100	50
75	2,288,488	50	35
50	2,288,488	0	20
25	1,144,244	0	10
0	0	0	0

Cell 3 – Health

The health system (see Figure 5-7) is considered a critical infrastructure in any city. This cell represents the process in which the emissions resulting from transportation directly affect the life expectancy of citizens. Additionally, the funds that hypothetically will be saved from investing in distributed generation can help improve the quality of health services in the city. Its HRT is presented in Table 5-11.

Figure 5-7 - Health Cell

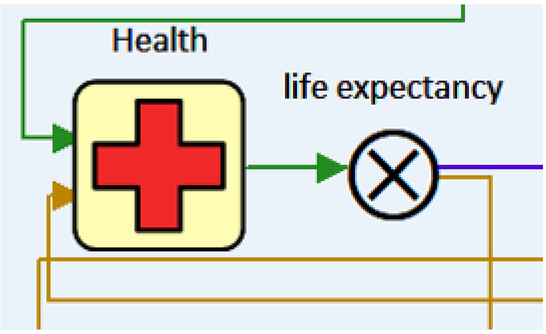


Table 5-11 - Health HRT

3 - HEALTH			
HRT	y(t)	X1 (t)	X2(t)
Operability	Health Indicator	Avoided Energy Funds	Avoided Emissions
	Life Expectancy (Years)	$/year	CO2 kg/y
100	85.29	1,421,255	2,288,488
75	81.68	710,628	2,288,488
50	78	0	2,288,488
25	39.03	0	1,144,244
0	0	0	0

Cell 4 – Education

The studied city, as mentioned earlier, is a reference to superior education. It has five colleges/universities with a wide range of courses. This cell (see Figure 5-8) is responsible for processing the quality of education, measured by the IDEB - Basic Education Development Index, into the percentage of adults that completed high school, assuming that a better quality of education results in higher school retention. Its HRT is presented in Table 5-12.

Figure 5-8 - Education Cell

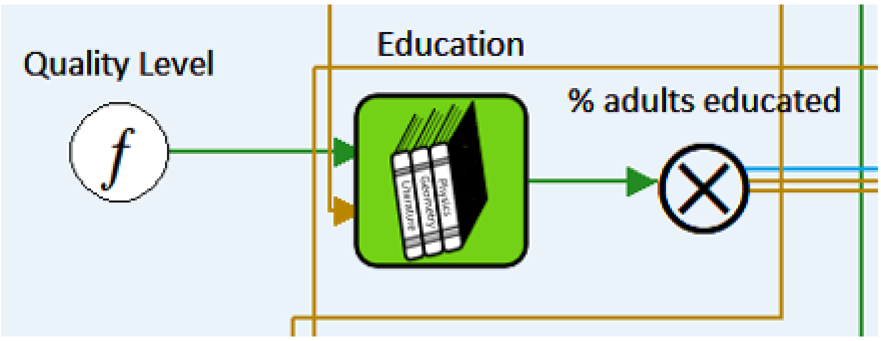


Table 5-12 - Education HRT

4 - EDUCATION			
HRT	y(t)	X1 (t)	X2(t)
Operability	Education Indicator	Avoided Energy Funds	Quality
	% Adults completed HighSchool	$/year	IDEB
100	100.00	2,292,444	10.00
75	82.265	1,785,958	7.513
50	64.53	1,279,472	5.025
25	32.265	639,736	2.513
0	0	0	0

Cell 5 – Economy

The economy cell (see Figure 5-9) accounts for the unemployed people and the jobs created in the city, which subsequently represents the poverty indicator. This indicator is not only used to determine the HDI but also influences the public safety of the city. Its HRT is presented in Table 5-13.

Figure 5-9 - Economy Cell

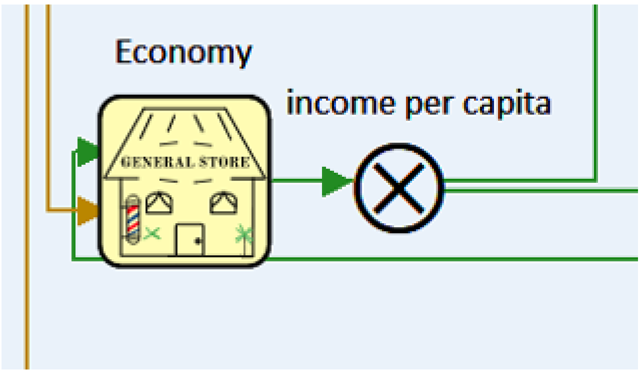


Table 5-13 - Economy HRT

5 - ECONOMY			
HRT	y(t)	X1 (t)	X2(t)
Operability	Poverty	People (Unemployed)	Jobs
	Income per capita (R$)	% economically active people unoccupied	No
100	6,535.4	100.00	32,006
75	3,928.7	96.96	29,633
50	1,322	93.91	27,260
25	661	46.96	20,445
0	0	0.00	13,630

Cell 6 – Safety

Public safety is a matter of great complexity and affects society on many levels. For modeling purposes, the indicators chosen as input to represent their impact on safety were education and unemployment. As an output, the indicator chosen was the number of violent crimes per year. This cell is shown in Figure 5-10, and its HRT is presented in Table 5-14.

Figure 5-10 - Safety Cell

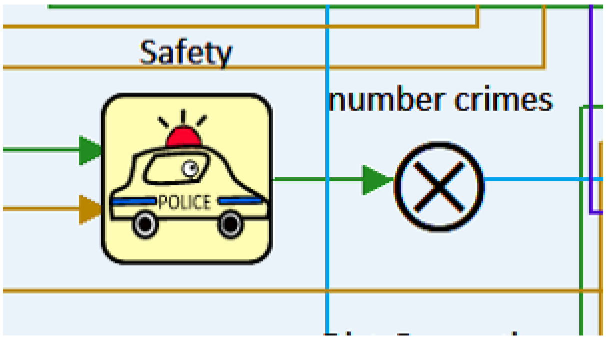


Table 5-14 - Safety HRT

6 - SAFETY			
HRT	y(t)	X1 (t)	X2(t)
Operability	Safety	Education	Poverty
	No of avoided violent crimes/year	% Adults completed HighSchool	Income per capita (R$)
100	28	100.00	6,535.4
75	21	82.27	3,928.7
50	14	64.53	1,322
25	7	32.27	661
0	0	0	0

Cell 7 – Population

The population cell (see Figure 5-11) works as a source for people at productive age. This number is directly impacted by the health system. For instance, during the COVID-19 pandemic, the number of people that were able to work reduced drastically. Its HRT is presented in Table 5-15.

Figure 5-11 - Population Cell

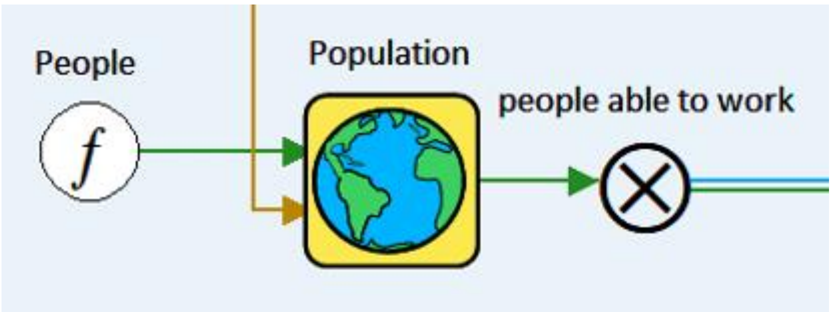


Table 5-15 - Population HRT

7 - POPULATION			
HRT	y(t)	X1 (t)	X2(t)
Operability	People at productive Age	Health	Population (2022)
	No	Life Expectancy (Years)	No
100	67,658	85	97,782
75	67,569	82	97,782
50	67,479	78	97,782
25	67,389	39	97,782
0	0	0	97,782

Cell 8 – Industry and Commerce

The economic flux of the city is represented by this cell (see Figure 5-12). It is responsible for employing the citizens as well as creating jobs and keeping the economy running. Due to its privileged location, between two of the most important highways for evacuating production, the city is the site of big multinational industries. They represent a big part of its Gross Domestic Product – GDP and employment. Its HRT is presented in Table 5-16.

Figure 5-12 - Industry and Commerce Cell

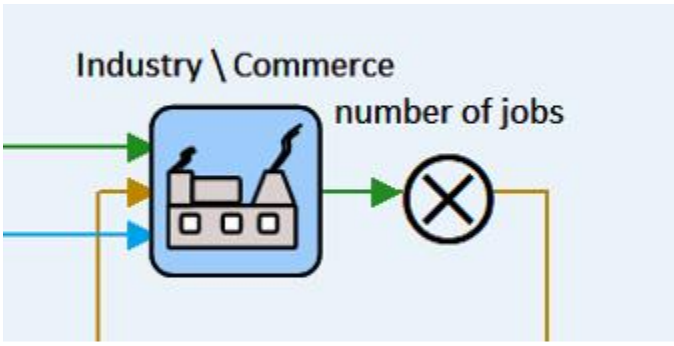


Table 5-16 - Industry and Commerce HRT

8 - INDUSTRY AND COMMERCE				
HRT	y(t)	X1 (t)	X2(t)	X3(t)
Operability	Jobs	People (Employed)	Avoided Energy Funds	Electricity Availability
	No	No	$/year	%
100	43,894	31,336	70,664,996	150
75	35,577	29,298	36,402,774	125
50	27,260	27,260	2,140,553	100
25	20,445	20,445	1,070,276	75
0	13,630	13,630	0	50

Cell 9 – Finance

This cell (see Figure 5-13) represents the finance area specific to electricity consumption. It relocates the avoided funds that would be spent on electricity into the critical infrastructures that adopted them. The reference is the yearly estimated load and current electricity tariff for each consumption group. Its HRT is presented in Table 5-17.

Figure 5-13 - Finance Cell

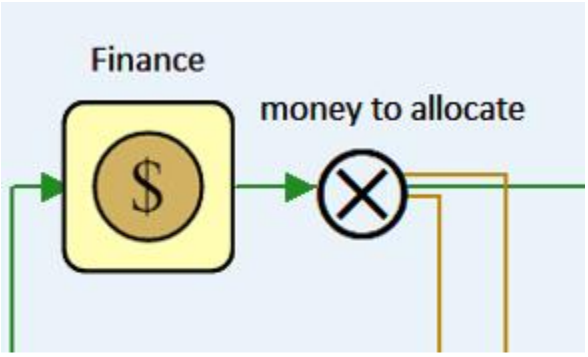


Table 5-17 - Finance HRT

9 - FINANCE		
HRT	y(t)	X1 (t)
Operability	Avoided Energy Funds	PV Generation
	R$/y	% of total load
100	134,461,888	100
75	72,887,526	52.62
50	11,313,165	5.25
25	5,656,582	2.62
0	0	0

Cell 10 – Power Systems

This cell (see Figure 5-14) represents the percentage of PV deployment in relation to the annual average load and how it affects the availability of electricity for further expansion of the industry and commerce sector of the city, assuming that the availability is a critical factor for the installation of new enterprises. Its HRT is presented in Table 5-18.

Figure 5-14 - Power Systems Cell

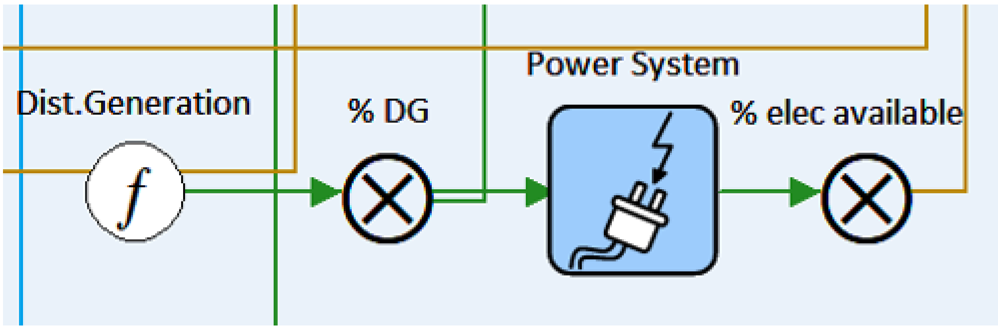


Table 5-18 - Power Systems HRT

10 - POWER SYSTEMS		
HRT	y(t)	X1 (t)
Operability	Electricity Availability	Distributed Generation
	%	% of the yearly load
100	200	100.00
75	150	52.62
50	100	5.25
25	75	2.62
0	50	0

Cell 11 – Unemployment

This production cell (see Figure 5-15) is responsible for inputting the number of unemployed people in the city. This number is affected by how productivity increases and, therefore, how automated the industry is. Also, it is affected by the education level of citizens. Its HRT is presented in Table 5-19.

Figure 5-15 - Unemployment Cell

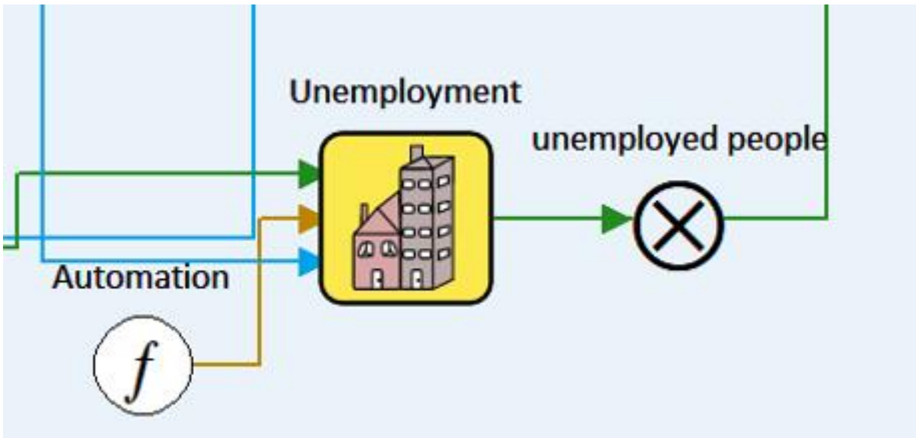


Table 5-19 - Unemployment HRT

11 - UNEMPLOYMENT				
HRT	y(t)	X1 (t)	X2(t)	X3(t)
Operability	Not Unemployed People	People at Productive Age	Education Indicator	Automation
	% economic active people occupied	No	% Adults Completed HighSchool	% Productivity (PTF)
100	100	67,658	100	100
75	96.96	67,569	82	106
50	93.91	67,479	65	113
25	46.96	67,389	32	119
0	0	0	0	125

Cell 12 – Residents

The residents' cell (See Figure 5-16 - Residents I2Sim Cell) represents the use of electricity in residential and rural areas. As an input, there are the avoided electricity funds that are directly connected to the percentage of PV deployment and this sector's load. Its HRT is presented in Table 5-20.

Figure 5-16 - Residents I2Sim Cell

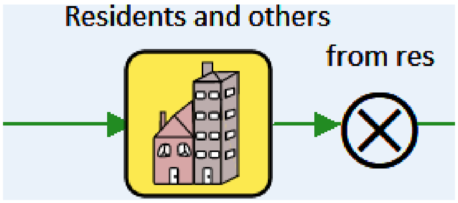


Table 5-20 - Residents HRT

11 - RESIDENTS		
HRT	y(t)	X1 (t)
Operability	No of generating units	Avoided Energy Funds
	No	$/year
100	28,146	43,129,656
75	14,455	22,399,338
50	764	1,669,021
25	382	834,510
0	0	0

5.4.2.2. FEEDS (SOURCES)

The feeders of the modeled system are presented as follows:

Source 1 – Distributed Generation

It feeds the percentage of Distributed Generation in relation to the yearly average load.

Source 2 – Population

It informs the system of the number of citizens in the city for the studied year.

Source 3 – Automation

It feeds the system on the total factor productivity (TFP), an indicator of how the productivity of the industry has evolved since 1981 (reference year).

Source 4 – Electric Vehicles

It feeds the information on how much of the city's fleet is substituted by electric vehicles in percentage.

Source 5 – Reliability

It provides information about how reliable public transportation is by using as an indicator the percentage of people who use it.

Source 6 – Quality of Education

It inputs the Education cell the information about the quality of education, measured by the IDEB.

5.4.2.3. DISTRIBUTORS

The distributors are described in Table 5-21 as how they were inputted in the initial state. Due to how the software is developed and, therefore, for mathematical reasons, some of the distributors are merely system's requirements to keep its consistency in energy balance.

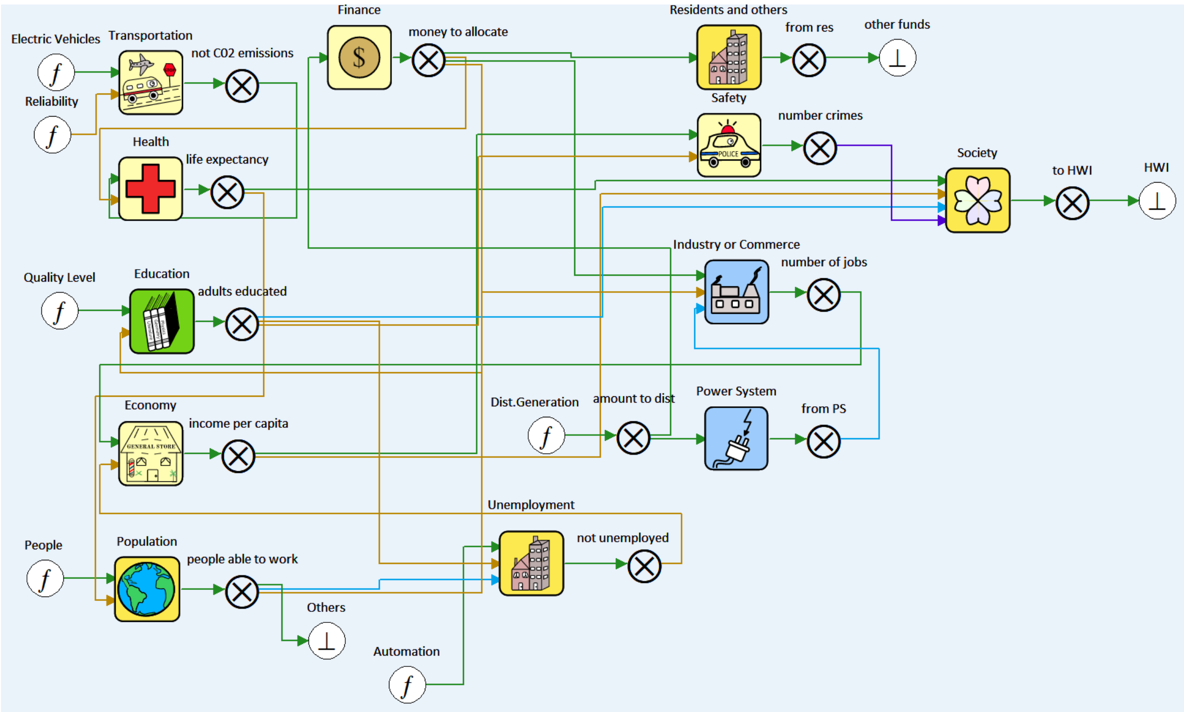
Table 5-21 – I2Sim Distributors

Distributor	***Function***	***Ratio %***				
		Input	**Output1**	**Output2**	**Output3**	**Output4**
1	System's requirement	-	-	-	-	-
2	System's requirement	-	-	-	-	-
3	Broadcaster	-	-	-	-	-
4	Broadcaster	-	-	-	-	-
5	Broadcaster	-	-	-	-	-
6	System's requirement	-	-	-	-	-
7	Unemployment rate	People at productive age 100%	Employed 40%	Unemployed 6.09%	Sink 53.91%	-
8	System's requirement		-	-	-	
9	Allocation of Funds	Avoided Energy Costs 100%	Industry 49.8%	Health 0%	Education 29.8%	Residents 20.4%
10	System's requirement	-	-	-	-	-
11	Broadcaster	-	-	-	-	-
12	System's requirement	-	-	-	-	-

5.4.2.4. THE MODEL

Finally, after considering all the aspects mentioned and weighing their relevance to the study, the model was built, as shown in Figure 5-17.

Figure 5-17 - I2Sim Model Schematic



5.4.3. MODEL 2

Model 2 was created to better adjust the system's relationships according to the mathematical functioning of the software. First, the distributors that worked as broadcasters were changed into regular distributors. It was done because broadcasters in this model were actually decoupling the system and creating inherent linear dependency within the model. This way, some inputs of the society cell had to be removed. However, it does not affect the overall dependency of the factors that are used to calculate the HDI because they are still connected to this cell, but this time not directly connected.

5.4.3.1. CELLS

The cells and their HRTs used in the second model, according to the changes previously mentioned, are presented in the following tables.

Table 5-22 - Society HRT - Model 2

1 - SOCIETY		
HRT	y(t)	X1(t)

Operability	Development	Safety
	HDI	No of avoided violent crimes/year
100	1.0	28
75	0.8935	21
50	0.787	14
25	0.3935	7
0	0	0

Table 5-23 - Transportation HRT - Model 2

2 - TRANSPORTATION			
HRT	y(t)	X1 (t)	X2 (t)
Operability	Avoided Emissions	Electric Vehicles	Reliability
	CO_2 kg/y	% of fleet	% of people who use
100	2,288,488	100	50
75	1,144,244	50	35
50	0	0	20
25	0	0	10
0	0	0	0

Table 5-24 - Health HRT - Model 2

3 - HEALTH			
HRT	y(t)	X1 (t)	X2(t)
Operability	Health Indicator	Avoided Energy Funds	Avoided Emissions
	Life Expectancy	$/year	CO_2 kg/y
100	85.29	1,421,255	2,288,488
75	81.68	710,628	1,144,244
50	78	0	0
25	39.03	0	0
0	0	0	0

Table 5-25 - Capacitation HRT - Model 2

4 - CAPACITATION		
HRT	y(t)	X2(t)
Operability	Education Indicator	Quality
	% Adults completed HighSchool	IDEB
100	100.00	10.00
75	82.265	7.513
50	64.53	5.025
25	32.265	2.513
0	0	0

Table 5-26 - Education HRT - Model 2

5 - EDUCATION		
HRT	y (t)	X1 (t)
Operability	Quality	Avoided Energy Funds
	IDEB	$/year
100	10.00	2,292,444
75	7.513	1,785,958
50	5.025	1,279,472
25	2.513	639,736
0	0	0

Table 5-27 - Safety HRT - Model 2

6 - SAFETY				
HRT	y(t)	X1 (t)	X2 (t)	X3(t)
Operability	Safety	Education	Not Unemployed People	Equality
	Avoided violent crimes per year	% Adults completed HighSchool	% Economic Active people occupied	Not Gini Index
100	28	33.33	100	1
75	21	27.42	96.96	0.79
50	14	21.51	93.91	0.58
25	7	10.76	46.96	0.29
0	0	0.00	0	0

Table 5-28 - Population HRT - Model 2

7 - POPULATION			
HRT	y(t)	X1 (t)	X2(t)
Operability	People at productive age	Health	Population (2022)
	No	Life Expectancy	No
100	67,502	85	97,782
75	67,491	82	97,782
50	67,479	78	97,782
25	67,389	39	97,782
0	0	0	97,782

Table 5-29 - Industry and Commerce HRT - Model 2

8 - INDUSTRY AND COMMERCE				
HRT	y(t)	X1 (t)	X2(t)	X3(t)
Operability	Jobs	People (Employed)	Avoided Energy Funds	Electricity Availability
	No	No	$/year	%
100	43,894	31,336	70,664,996	200
75	35,577	29,298	36,402,774	125

50	27,260	27,260	2,140,553	100
25	20,445	20,445	1,070,276	75
0	13,630	13,630	0	50

Table 5-30 - Finance HRT - Model 2

9 - FINANCE		
HRT	y(t)	X1 (t)
Operability	Avoided Energy Costs	PV Generation
	R$/y	% of total load
100	134,461,888	100
75	72,887,526	52.62
50	11,313,165	5.25
25	5,656,582	2.62
0	0	0

Table 5-31 - Power Systems HRT - Model 2

10 - POWER SYSTEMS		
HRT	y(t)	X1 (t)
Operability	Electricity Availability	Distributed Generation
	%	%
100	200	100.00
75	150	52.62
50	100	5.25
25	75	2.62
0	50	0

Table 5-32 - Unemployment HRT - Model 2

11 - UNEMPLOYMENT					
HRT	y(t)	X1 (t)	X2(t)	X3(t)	X4(t)
Operability	Not Unemployed People	People at Productive Age	Education Indicator	Automation	Jobs
	% ec. Active people occupied	No	% Adults completed HighSchool	TFP	No
100	100	67,502	67	100	32,006
75	96.96	67,491	55	106	29,633
50	93.91	67,479	43	113	27,260
25	46.96	67,389	22	119	20,445
0	0	0	0	125	13,630

Table 5-33 - Residents HRT - Model 2

12 - RESIDENTS		
HRT	y(t)	X1 (t)

Operability	nº of generating units	Avoided Energy Funds
		$/year
100	28,146	43,129,656
75	14,455	22,399,338
50	764	1,669,021
25	382	834,510
0	0	0

5.4.3.2. FEEDS (SOURCES)

Here are presented the main changes in the sources made in Model 2:

Firstly, the source that inputs the quality of education to the Education Cell was changed into a cell that is fed by the avoided electricity costs. This way, the possible investments in education with the avoided costs could be represented in the system.

Then, another source was added to the safety cell to represent poverty, which is the Gini index, an indicator that measures the overall distribution of income.

5.4.3.3. DISTRIBUTORS

The main change made in the distributors was the elimination of broadcasters. It had to be done because they were actually decoupling the system and creating inherent linear dependency. Therefore, for Model 2, the distributors were designed as shown in Table 5-34.

Table 5-34 - Distributors Model 2

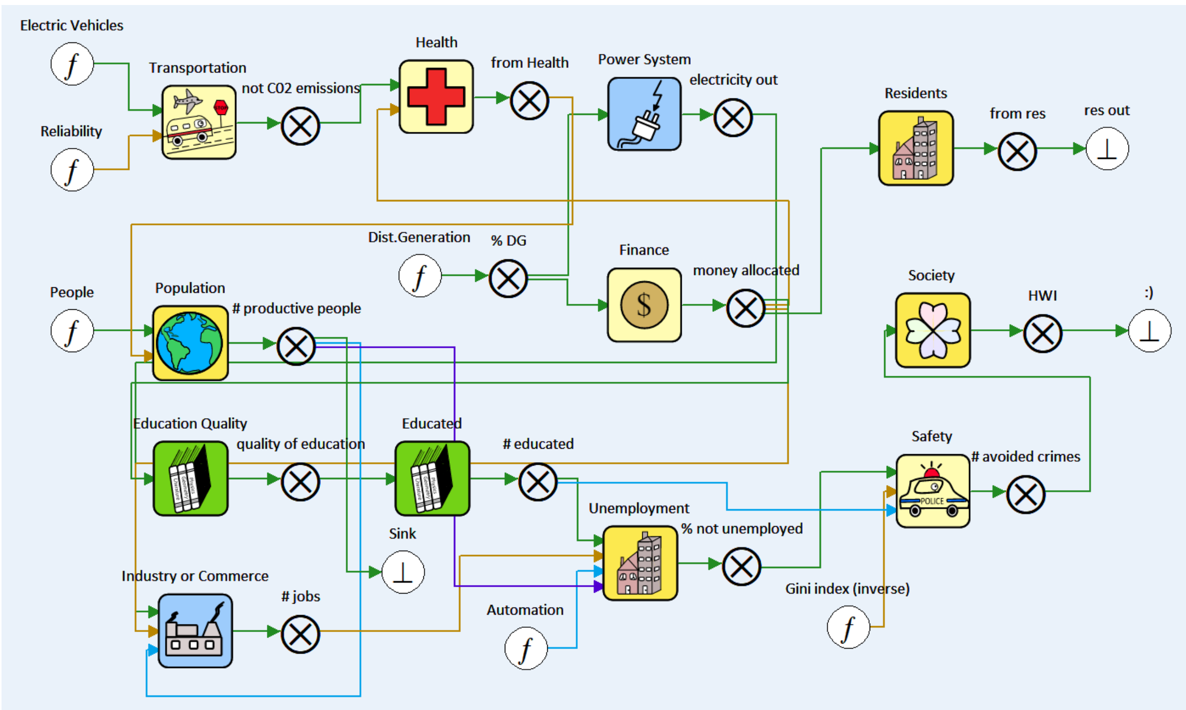
Distributor	***Function***	***Ratio %***				
		Input	**Output1**	**Output2**	**Output3**	**Output4**
1	System's requirement	-	-	-	-	-
2	System's requirement	-	-	-	-	-
3	System's requirement	-	-	-	-	-
4		% of Educated Adults 100%	Safety 33%	Unem-ployment 66%	-	-
5	System's requirement	-	-	-	-	-
6	System's	-	-	-	-	-

	requirement					
7	Unem-ployment rate	People at productive age 100%	Employed 40%	Unemployed 6.09%	Sink 53.91%	-
8	System's requirement		-	-	-	
9	Allocation of Funds	Avoided Energy Costs 100%	Industry 49.8%	Health 0%	Educa-tion 29.8%	Residents 20.4%
10	System's requirement	-	-	-	-	-
11	System's requirement	-	-	-	-	-
12	System's requirement	-	-	-	-	-

5.4.3.4. THE MODEL

After all the adjustments and changes were made, Model 2 was created, as presented in Figure 5-18.

Figure 5-18 - I2Sim Schematic - Model 2



5.4.4. MODEL 3

Model 3 was created to consolidate all the changes mentioned before with the separation of the public transportation and private commute into two different cells. This way, the reliability of public transportation and the percentage of EVs do not limite each other. Also, the initial operability level for both cells was established as 0%. Table 5-35 and Table 5-36 show the HRTs for the new cells included in the model. Another important change made was the initial operability level of these cells and the Health cell, that was changed to 0% due to mathematical purposes, to avoid repeated values in the HRTs (See Table 5-37)

Table 5-35 - Private Transportation - Model 3

2 - PRIVATE TRANSPORTATION		
HRT	y(t)	X1 (t)
Operability	Avoided Emissions	Reliabiity
	CO2 kg/y	% of people who use
100	1,144,244	50
75	858,183	40
50	572,122	30
25	286,061	20
0	0	10

Table 5-36 - Public Transportation - Model 3

13 - PUBLIC TRANSPORTATION		
HRT	y(t)	X1 (t)
Operability	Avoided Emissions	Electric Vehicles
	CO2 kg/y	% of fleet
100	1,144,244	100
75	858,183	75
50	572,122	50
25	286,061	25
0	0	0

Table 5-37 - Health HRT - Model 3

3 - HEALTH			
HRT	y(t)	X1 (t)	X2(t)
Operability	Health Indicator	Avoided Energy Costs	Avoided Emissions
	Life Expectancy	R$/year	CO2 kg/y
100	85,29	1,421,255	1,144,244
75	83,48	947,504	858,183
50	82	710,628	572,122
25	79,8675	473,752	286,061
0	78,06	0	0

5.5. SIMULATION

The overall goal of this optimization is to find the optimal PV percentage of penetration and EV for the city by maximizing the HDI as it relates to its critical infrastructures through their indicators. As a citizen-centric model, the objective cell is the society's cell. By maximizing the city's development up to its limitations, employment is also maximized, avoided costs of electricity can be relocated and help improve other socioeconomic aspects of the city as well. According to IRENA, 2017, PV deployment can assess different segments of the value chain and improve local value creation. This means that it is possible to leverage existing critical infrastructures by maximizing domestic value creation [38].

To find this optimal value, different scenarios were simulated for both models. Table 5-38 and Table 5-39 refer to Model 1, and then, to find the optimal allocation of distributed generation for this very same model, different scenarios were created, as shown in Table 5-40. For Model 2, the scenarios used are described in

Table 5-4141.

Table 5-38 – Model 1 - Scenarios for I2Sim Simulation 1

Scenario Number	Source	Source values	Cell Operability Level (%)	
1.0 – Base Case: **Current in 2022**	Dist. Generation	5.25	Transportation	0
	Electric Vehicles	0	Health	0
	Reliability	20	Population	0
	Quality of Education	5.025	Unemployment	0
	Population	97,782.0	Economy	0
	Automation	112.8	Safety	25
			Power System	50
			Finance	25
			Residents	50
			Industry	0
			Education	50
			Society (HWB)	0
1.1 – Increase % of DG to 60%	Dist. Generation	60	Transportation	0
	Electric Vehicles	0	Health	0
	Reliability	20	Population	0
	Quality of Education	5.025	Unemployment	0
	Population	97,782.0	Economy	0
	Automation	112.8	Safety	25
			Power System	100
			Finance	75
			Residents	75
			Industry	0

			Education	50
			Society (HWB)	0
1.2 – Increase the % of DG to 60% and DG to 50%.	Dist. Generation	60	Transportation	25
	Electric Vehicles	50	Health	0
	Reliability	20	Population	0
	Quality of Education	5.025	Unemployment	50
	Population	97,782.0	Economy	0
	Automation	112.8	Safety	25
			Power System	100
			Finance	75
			Residents	75
			Industry	0
			Education	50
			Society (HWB)	0

Table 5-39 – Model 1 - Allocation of Avoided Energy Costs and PV Generation

Allocation of Funds			
Sector	**Scenarios 1.1 and 2**	**Scenarios 1.3 and 1.4 and 1.6**	**Scenario 1.5**
Education	0.2978	0.2978	0.308
Health	0	0.3	0.5
Residents	0.4982	0.2040	0.1
Industry	0.2040	0.1928	0.092

Table 5-40 - Model 1 Scenarios for I2Sim Simulation 2

Scenario Number	% Distributed Generation	% of Electric Vehicles	Reliability	Sector	Ratios
2.0	50	75	50	Education Health Residents Industry	0.298 0 0.498 0.204
2.1	50	75	50	Education Health Residents Industry	0.298 0.1 0.398 0.204
2.2	50	90	50	Education Health Residents Industry	0.298 0.1 0.398 0.204
2.3	50	100	50	Education Health Residents Industry	0.298 0.1 0.398 0.204

Table 5-41 - Model 2 - Scenarios for I2Sim Simulation

Scenario Number	**Source**	**Source Values**	**Distributor Ratios**	**Cell Operability Level (%)**	
0 – Base Case:	Dist. Generation	5.25	Money allocated:	Transportation	0

Current in 2022	Electric Vehicles EV Reliability Population Automation Gini index (in-verse)	0 20 97782.0 112.8 0.58	Health = 0 Industry = 0.498 Education = 0.298 Residents = 0.204 <u>Productive people:</u> Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 <u>Educated:</u> Unemployed: 0.666 Safety = 0.333	Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	0 0 0 0 25 25 50 0 100 75 0
1 – Increase % of DG to 60%	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (in-verse)	60 0 20 97782.0 112.8 0.58	<u>Money allocated:</u> Health = 0 Industry = 0.498 Education = 0.298 Residents = 0.204 <u>Productive people:</u> Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 <u>Educated:</u> Unemployed: 0.666 Safety = 0.333	Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	0 0 0 0 0 75 75 50 0 100 100 0
2 – Increase the % of DG to 60% and EV to 50%.	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (in-verse)	60 50 20 97782.0 112.8 0.58	<u>Money allocated:</u> Health = 0 Industry = 0.498 Education = 0.298 Residents = 0.204 <u>Productive people:</u> Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 <u>Educated:</u> Unemployed: 0.666 Safety = 0.333	Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	50 0 0 0 0 75 75 50 0 100 100 0
3 - Increase the % of DG to 60% and EV to 50% and Reliability to 50%	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (in-verse)	60 50 50 97782.0 112.8 0.58	<u>Money allocated:</u> Health = 0 Industry = 0.498 Education = 0.298 Residents = 0.204 <u>Productive people:</u> Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 <u>Educated:</u> Unemployed: 0.666 Safety = 0.333	Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	75 0 0 0 0 75 75 50 0 100 100 0

4. Change money allocated – take from Industry and move to Health. Keep source values same as Scenario 3	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (inverse)	60 50 50 97782.0 112.8 0.58	<u>Money allocated:</u> Health = 0.3 Industry = 0.1928 Education = 0.298 Residents = 0.2040 <u>Productive people:</u> Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 <u>Educated:</u> Unemployed: 0.666 Safety = 0.333	Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	75 25 0 0 0 75 75 50 50 100 100 0
5. Same as scenario 4, but increase EV to 75%	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (inverse)	60 75 50 97782.0 112.8 0.58	<u>Money allocated:</u> Health = 0.3 Industry = 0.1928 Education = 0.298 Residents = 0.2040 <u>Productive people:</u> Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 <u>Educated:</u> Unemployed: 0.666 Safety = 0.333	Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	75 25 0 0 0 75 75 50 50 100 100 0
6. Same as scenario 5, but increase EV to 90%	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (inverse)	60 90 50 97782.0 112.8 0.58	<u>Money allocated:</u> Health = 0.3 Industry = 0.1928 Education = 0.298 Residents = 0.2040 <u>Productive people:</u> Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 <u>Educated:</u> Unemployed: 0.666 Safety = 0.333	Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	75 25 0 0 0 75 75 50 50 100 100 0
7. Same as Scenario 6, EV to 100% and reliability to 100%; change distribution ratio for employment to more to the "unemployment" cell, which is actually not	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (inverse)	60 90 50 97782.0 112.8 0.58	<u>Money allocated:</u> Health = 0.3 Industry = 0.1928 Education = 0.298 Residents = 0.2040 <u>Productive people:</u> **Industry = 0.2** **Unemployed = 0.6** **Sink = 0.2** <u>Educated:</u>	Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	75 25 0 0 0 75 75 50 50 100 100 0

unemployed or employed.	Unemployed: 0.666 Safety = 0.333

Table 5-42 - Model 3 - Scenarios for I2Sim Simulation

Scenario Number	Source	Source values	Distributor Ratios	Cell Operability Level (%)	
0 – Base Case: Current in 2022	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (inverse)	5.25 % 0 20 97782.0 112.8 0.58	Money allocated: Health = 0 Industry = 0.498 Education = 0.298 Residents = 0.204 Productive people: Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 Educated: Unemployed: 0.666 Safety = 0.333	Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	0 0 0 0 0 25 25 50 0 10 0 75 0
Case 1	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (inverse)	**60 %** **75 %** **50 %** 97782.0 112.8 0.58	Money allocated: **Health = 0.02** **Industry = 0.478** Education = 0.298 Residents = 0.204 Productive people: Industry = 0.4 Unemployed = 0.0609 Sink = 0.5391 Educated: Unemployed: 0.666 Safety = 0.333	Public Transportation Private Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	10 0 75 10 0 10 0 25 0 75 75 75 50 10 0 10 0 25
Case 2 -	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (inverse)	**60 %** **75 %** **50 %** 97782.0 112.8 0.58	Money allocated: **Health = 0.02** **Industry = 0.478** Education = 0.298 Residents = 0.204 Productive people: Industry = 0.3 Unemployed = 0.2 Sink = 0.5 Educated: Unemployed: 0.666 Safety = 0.333	Public Transportation Private Transportation Health Population Unemployment Safety Power System Finance Residents Industry Education Quality Educated **Society (HWB)**	10 0 75 10 0 10 0 25 0 75 75 75 50 10 0 10 0 25

Case 3 –	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (in-verse)	**60 %** **75 %** **50 %** 97782.0 112.8 0.58	<u>Money allocated:</u> **Health = 0.02** **Industry = 0.478** Education = 0.298 Residents = 0.204 <u>Productive people:</u> **Industry = 0.4** **Unemployed = 0.2** **Sink = 0.4** <u>Educated:</u> Unemployed: 0.666 Safety = 0.333	Society at 50%!
Case 4 – Best case with least amount of EV and still have Society at 50%	Dist. Generation Electric Vehicles EV Reliability Population Automation Gini index (in-verse)	**60 %** **50 %** **50 %** 97782.0 112.8 0.58	**<u>Money allocated:</u>** **Health = 0.02** **Industry = 0.478** **Education = 0.298** **Residents = 0.204** **<u>Productive people:</u>** **Industry = 0.4** **Unemployed = 0.2** **Sink = 0.4** **<u>Educated:</u>** Unemployed: 0.666 Safety = 0.333	**Society at 50%**

5.6. MODEL 1 - RESULTS & ANALYSIS

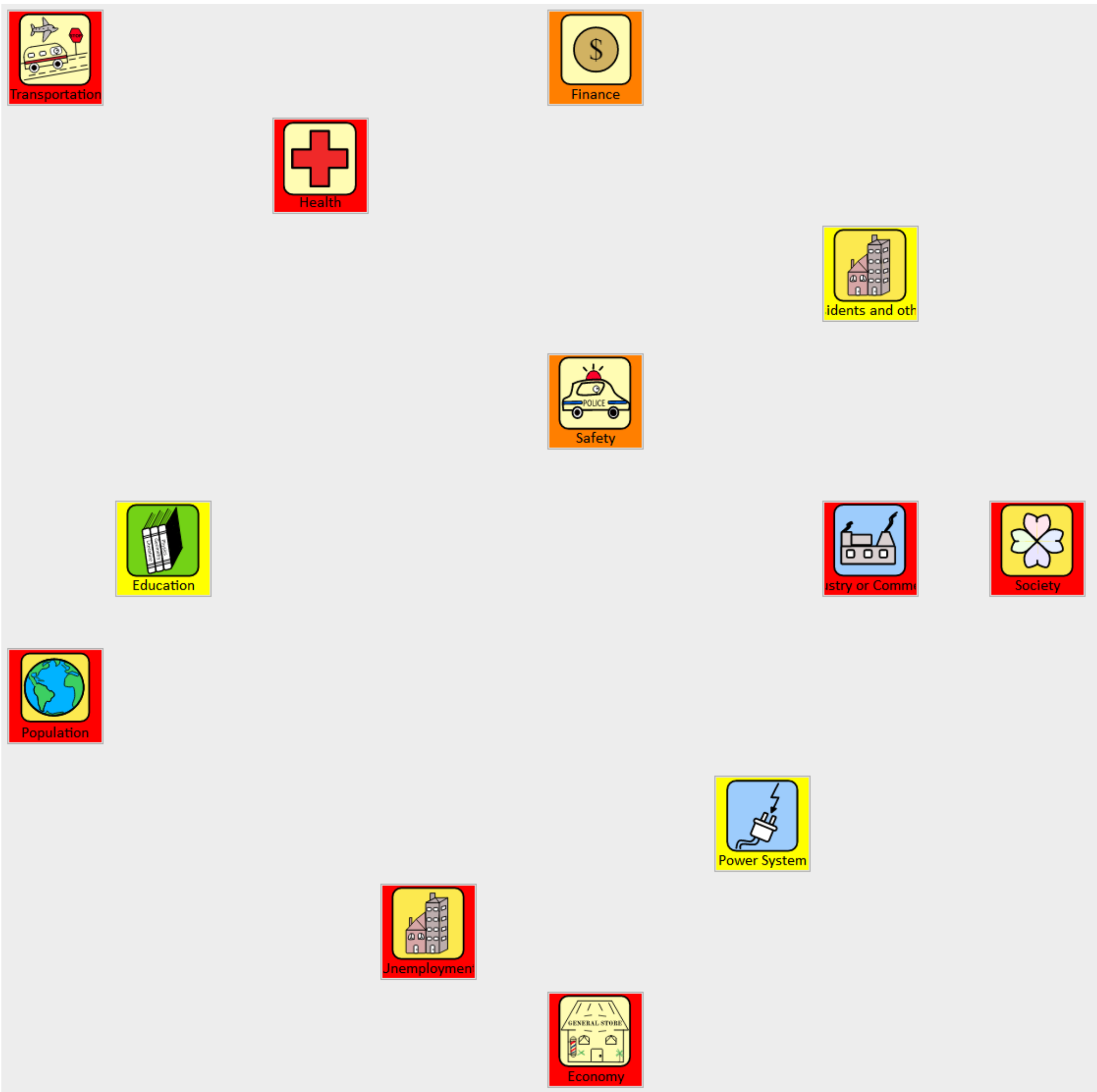
According to the scenarios exposed earlier for Model 1, the simulation was run, and the following results were obtained.

5.6.1. SCENARIO 1.0 - BASE SCENARIO - 2022

This is the base scenario for all simulations. The inputs used here are the ones described under the topic "Cells." It uses current data on the modeled city on the 50% percent operability level. For 100% operability, the numbers used were references of the maximum possible number for each indicator. For instance, the HDI varies from zero to one; 100% operability is one, and 50% is the current HDI value. In addition, for the non-indicator tokens, such as avoided energy costs, the numbers used were the maximum value possible for that year. Consequently, the 50% operability level is the current avoided electricity costs, based on that year's tariff and percentage of DG penetration. For 100% operability, the value was based on a hypothetical 100%

penetration with that year's tariff and load. Thus, this was one of the reasons why the simulation needed to be performed on a yearly basis. The following figures show the results obtained from this first simulation. They serve as a reference for the further ones and also give an idea of the relationships between cells and decision points. Figure 5-19 - I2Sim Schematic for Base Scenario shows the interface of I2Sim once this scenario was simulated.

Figure 5-19 - I2Sim Schematic for Base Scenario 1.0



5.6.1.1. *ANALYSIS*

From the previous plots, some points about the model could be made as described here:

With 0% of electric vehicles, CO_2 emissions increase, and the avoided CO_2 emissions (“not emissions”) decrease, as expected. Therefore, the transportation cell is working at 0% operability. This means that the health cell is working at 0% operability (life expectancy is limited by CO_2 emissions). As the Health cell is operating at the 0% level, it also limits the number of economically active people that works at 0% too. As productive people feed the unemployment cell and the industry cell, the unemployment cell is limited by it. Then, there is a low level of people employed in the economy cell.

The Economy cell feeds the Safety cell (poverty index), which shows that there is a high number of crimes (or low level of “avoided crimes/not crimes”). The Economy cell is also limited by the Industry Cell (lack of jobs) due to both 0 EV and low penetration of Distributed Generation. Additionally, the safety index feeds the Society cell at a level of 0%.

With only 5.25% distributed generation, the Finance cell is limited by %DG. This means that there is only $2.20M to allocate to the other cells. This money is distributed to Health, Education, Industry, and Residents/Others ($0 to Health, $4M to Education, $6.725M to Industry, and $2.75M to Residents/Others).

The industry still operates at 0% because the amount of funds allocated to Industry is not enough to operate at a higher operating level. However, the amount allocated to Education is enough for it to operate at a higher operating level (25%). This means that the education indicator level increases to 32%.

Both the low level of employed people and the percentage of distributed generation affect the Industry cell, which produces jobs. Although the population cell is operating at approximately 0%, it still produces people able to work (approximately 1,950 people). These people are fed to the Unemployment cell; however, the unemployment cell is limited by the percentage of adults educated; in other words, by the quality of education.

By identifying the limiting agents of the system, it was possible to move forward with the different scenarios described ahead.

5.6.2. SCENARIO 1.1

In this scenario, PV penetration was increased to 60%. The following plots refer to the results obtained.

Figure 5-20 - I2Sim Schematic for Scenario 1.1

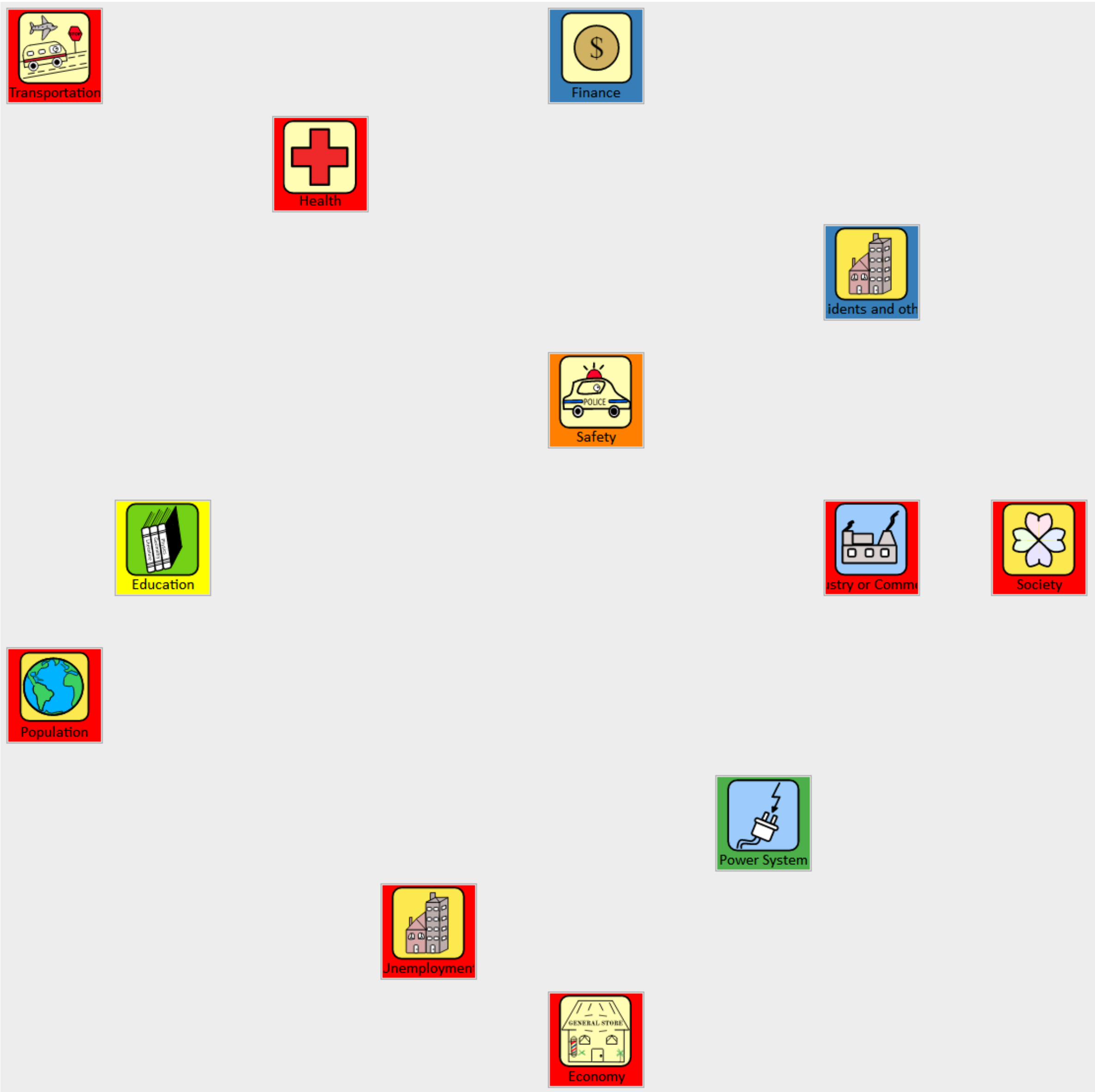


Figure 5-21 - Scenario 1.1 - Finance Cell

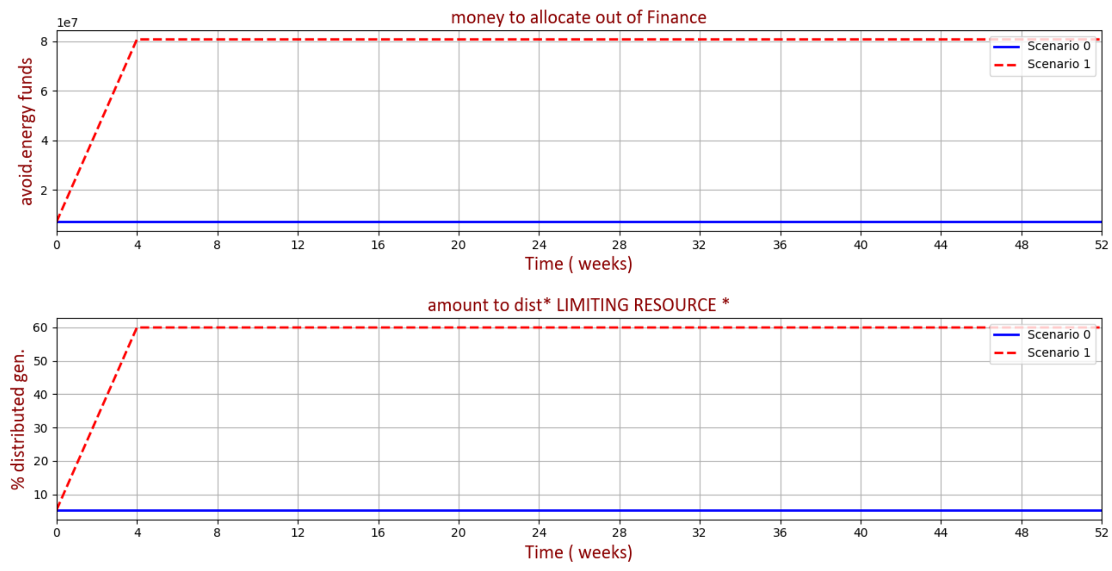
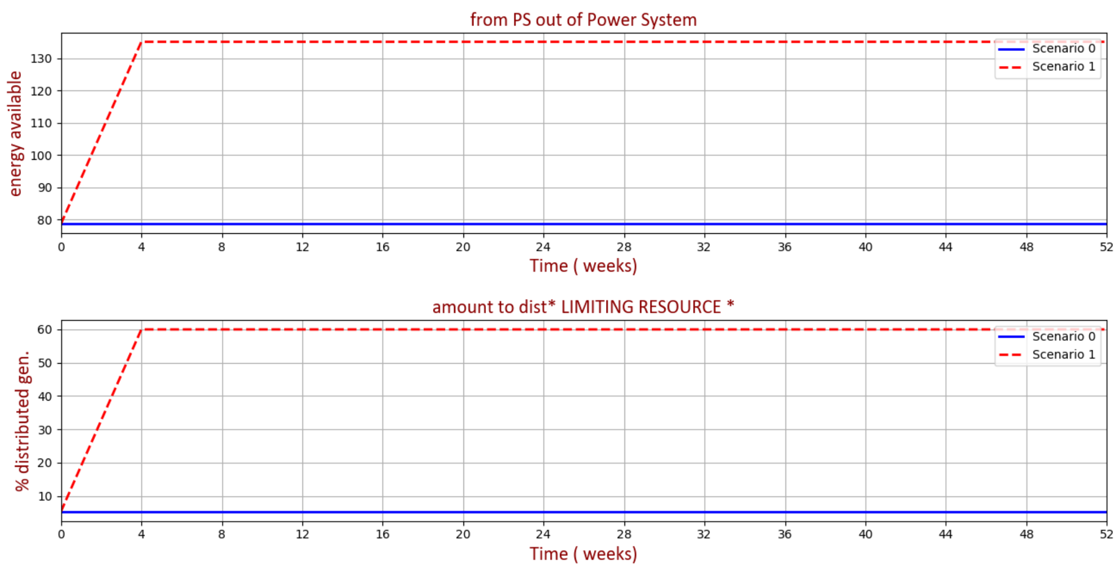


Figure 5-22 - Scenario 1.1 - Power Systems Cell



5.6.2.1. *ANALYSIS*

In this scenario, by increasing DG to 60% injected, the percentage of electricity available will increase reasonably. This causes the Power System cell to be operating at 100% operability (134% electricity available).

This increase in the percentage of DG penetration also increases the Finance Cell to operate at 75% capacity now (or at $81M). This money is distributed to Health, Education, Industry, and Residents/Others.

Despite the increase in money allocated to these sectors, the number of adults educated still remains at 64%, and the quality level of education is still at level 5, so the number of adults educated remains the same out of the Education Cell. It means that, even though there is more money to allocate to the critical infrastructures, this investment is not able to increase the number of educated adults, and that becomes a limiting agent to development.

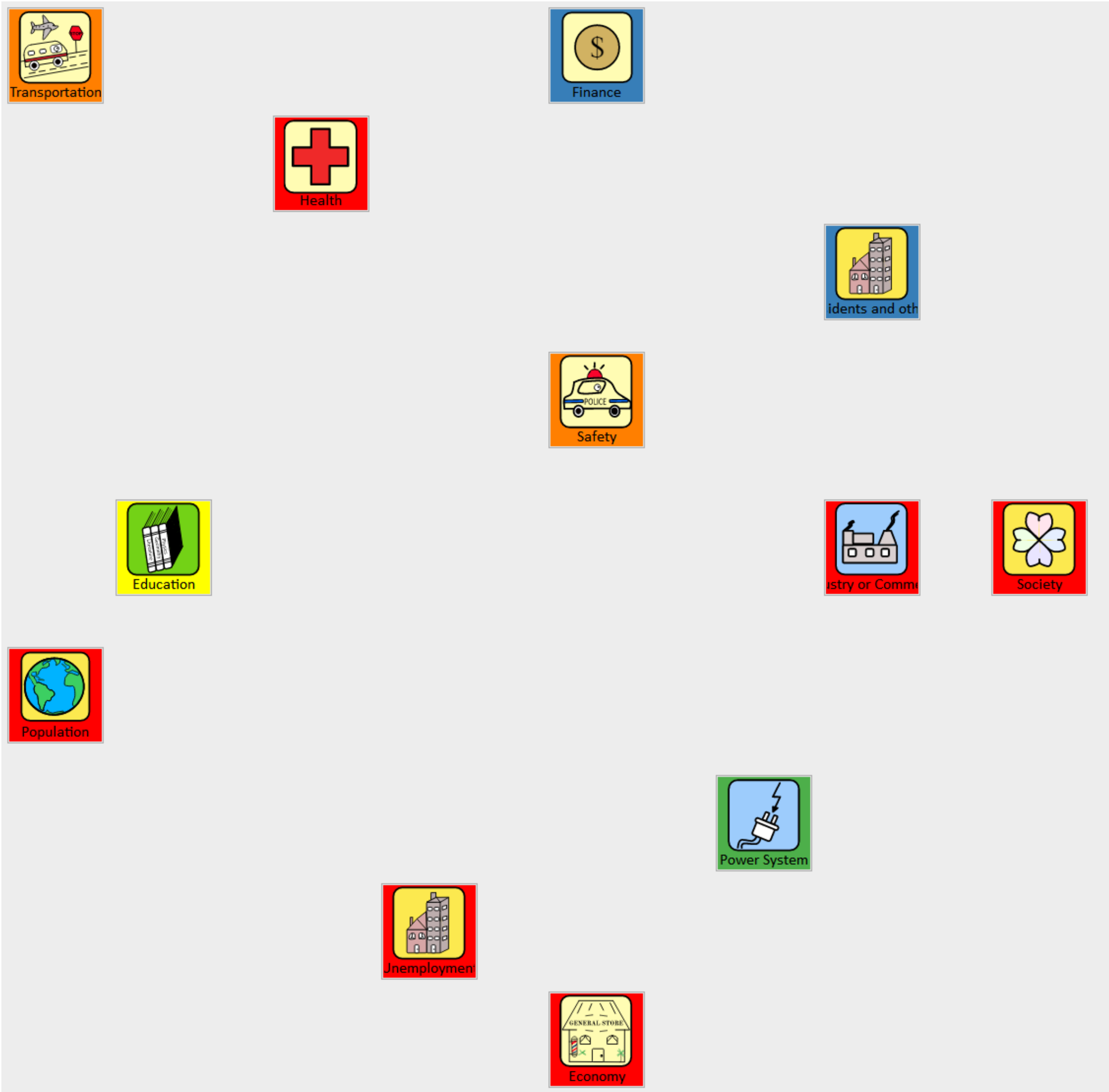
Although the education cell has increased, the health factor of 100% carbon emissions (0% avoided carbon emissions / not emissions) limits the unemployment cell, which cascades and limits the number of employed people, which limits the safety cell, and therefore, society cells are still limited and operate at 0%.

Electricity feeds the Industry Cell; however, despite the increase in Industry, the people able to work are still limiting the number of jobs, and so the Society cell does not change operability. This limiting could only be overcome as the population grows and more people are able to work for the deployment of Distributed Generation.

5.6.3. SCENARIO 1.2

In this scenario, distributed Generation was increased by 60%, and the percentage of the fleet covered by Electric Vehicles by 50%. The plots of the results are presented in the following figures:

Figure 5-23 - I2Sim Interface for Scenario 1.2



5.6.3.1. ANALYSIS

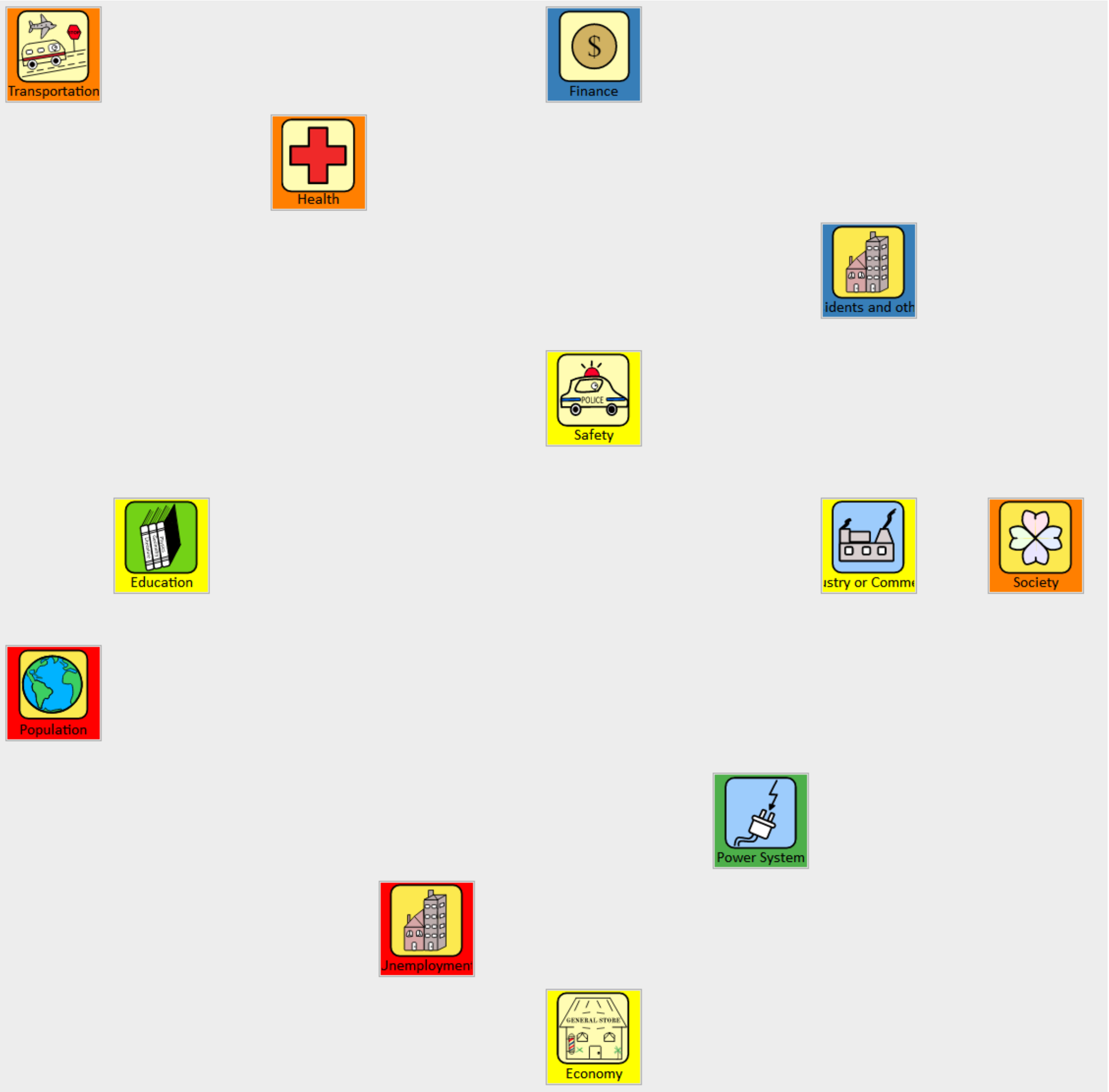
With the increase of DG to 60% and the increase of EV to 50%, the Transportation Cell increases to operating at 25% because emissions were avoided. However, the Health sector is still limited by the lack of extra money allocated to it that the cells depending on health (such as society and population) will still be operating at their low operating level.

The only way to increase health at this point is to allocate finances to the Health sector. This will increase the Society and Unemployment Cells. It means that more important than deploying Distributed Generation is deploying it at many different critical infrastructures. The interdependency existing between these systems ends up limiting the overall goal, which is improving the Human Development Index.

5.6.4. **SCENARIO 1.3**

In this scenario, due to the limiting resources indicated in the previous one, the distributed generation, together with its allocation of funds, was changed to 30% to Health. Additionally, Distributed Generation was changed to 60%, Electric Vehicles to 50%, and the reliability of the Public Transportation System remained the same.

Figure 5-24 - I2Sim Interface - Scenario 1.3



5.6.4.1. ANALYSIS

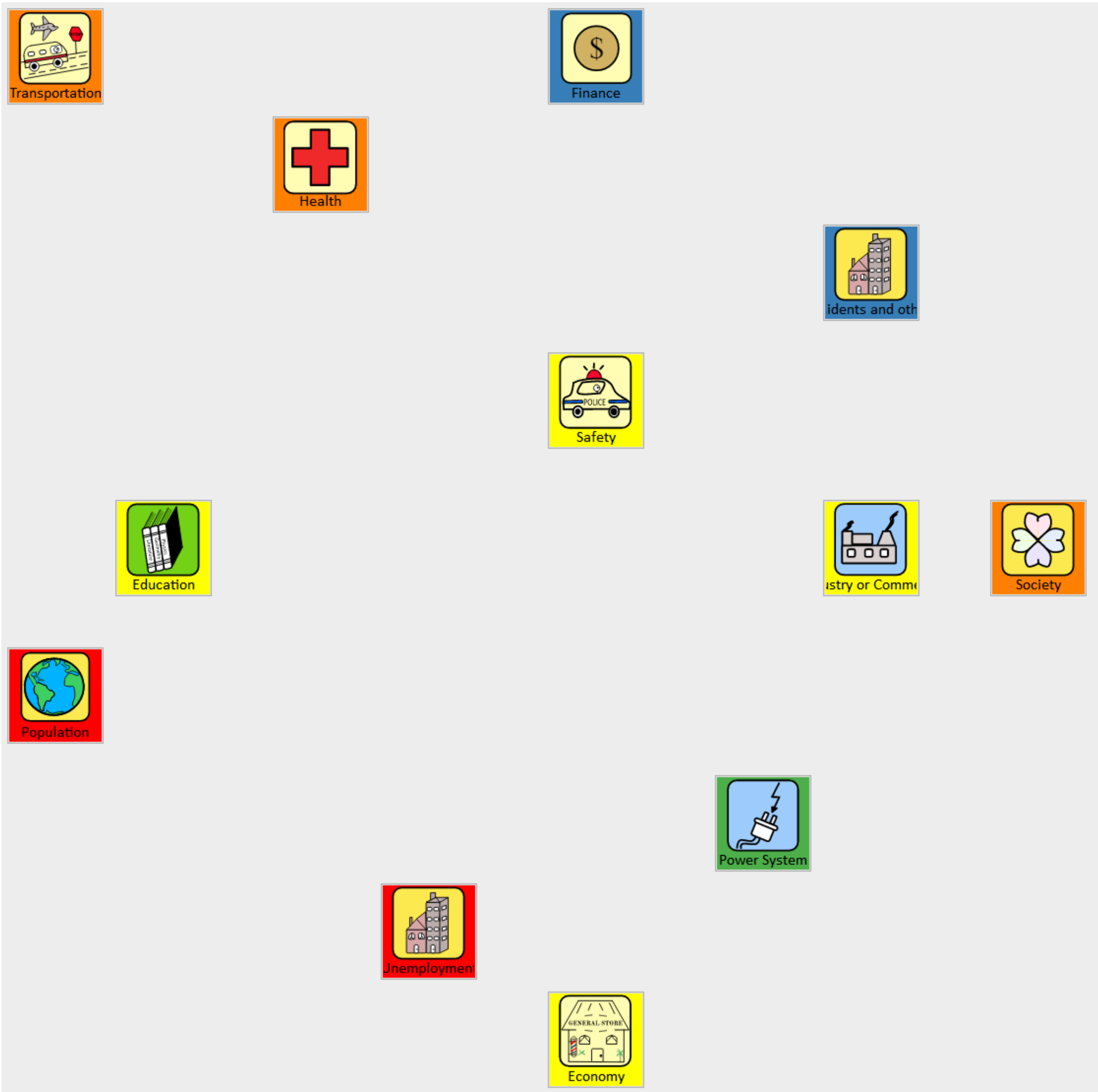
With different distribution ratios for PV deployment, a great change in most of the cells was observed. This reinforces what was concluded from the last scenario that the deployment of Distributed Generation should be encouraged in the different critical infrastructures of the system. Otherwise, their interdependency will create limiting factors for the development of society.

However, Health (Life Expectancy), Poverty (Income per capita), and Population (Number of people available to work) are still limiting resources. This is due to the unaltered change in reliability in the Public Transportation system that ends up limiting Health and, consequently, all the others.

5.6.5. SCENARIO 1.4

In this scenario, the ratio for distributed generation among the Critical Infrastructures was maintained the same as in the previous one. Nevertheless, the reliability of the Public Transportation System was increased to 50%.

Figure 5-25 - Scenario 1.4 - I2SIM Interface



5.6.5.1. *ANALYSIS*

The results of this simulation are not presented here because they were the same as the previous one. However, the Transportation Cell is now limited by the percentage of Electric Vehicles and not reliability.

5.6.6. SCENARIO 1.5

In this scenario, the distributed generation, together with its allocation of funds, was changed to 31% for Education, 50% for Health, 10% for residents/others, and 9% for Industry. Additionally, PV Generation was set up to 60%, reliability to 50%, and Electric Vehicles to 50%. In summarizing, the inputs were the same as Scenario 1.4 but with different distribution ratios.

Even with these changes, the resources did not change enough for the cells to operate at a higher operating level. Hence, the results were the same as Scenario 1.4 and are not repeated here.

5.6.6.1. *ANALYSIS*

By getting the same results as before, it was possible to conclude that the new distribution rations with the same percentage of PV penetration were not enough to improve Society's Development.

5.6.7. SCENARIO 1.6

For this scenario, the distribution rates for Scenario 1.3 were used along with an increased PV penetration of 100%. The plots of the results are presented in Figure 5-26 to Figure 5-34.

Figure 5-26 - Scenario 1.6 - I2SIM Interface

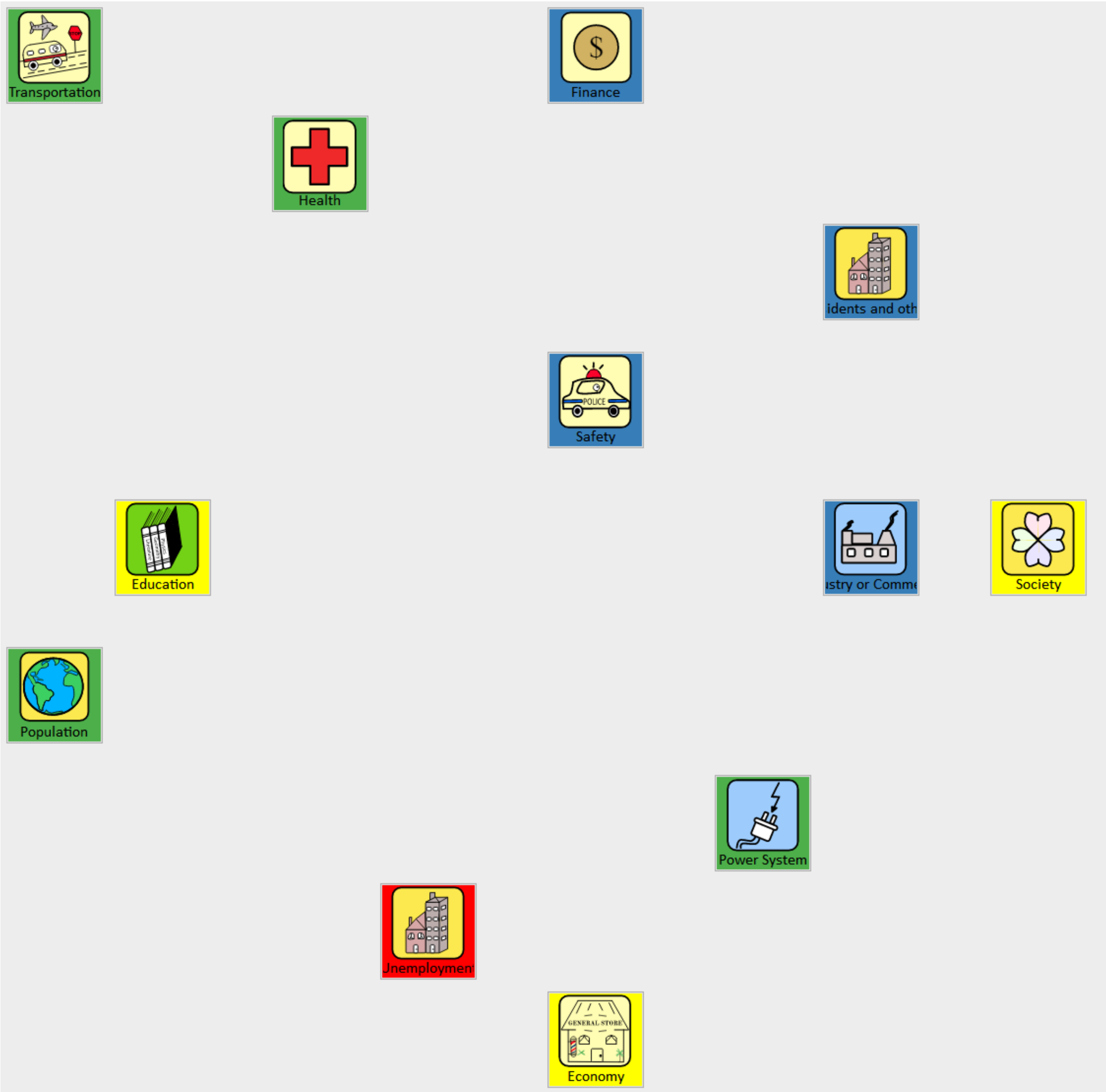


Figure 5-27 - Scenario 1.6 - Economy Cell

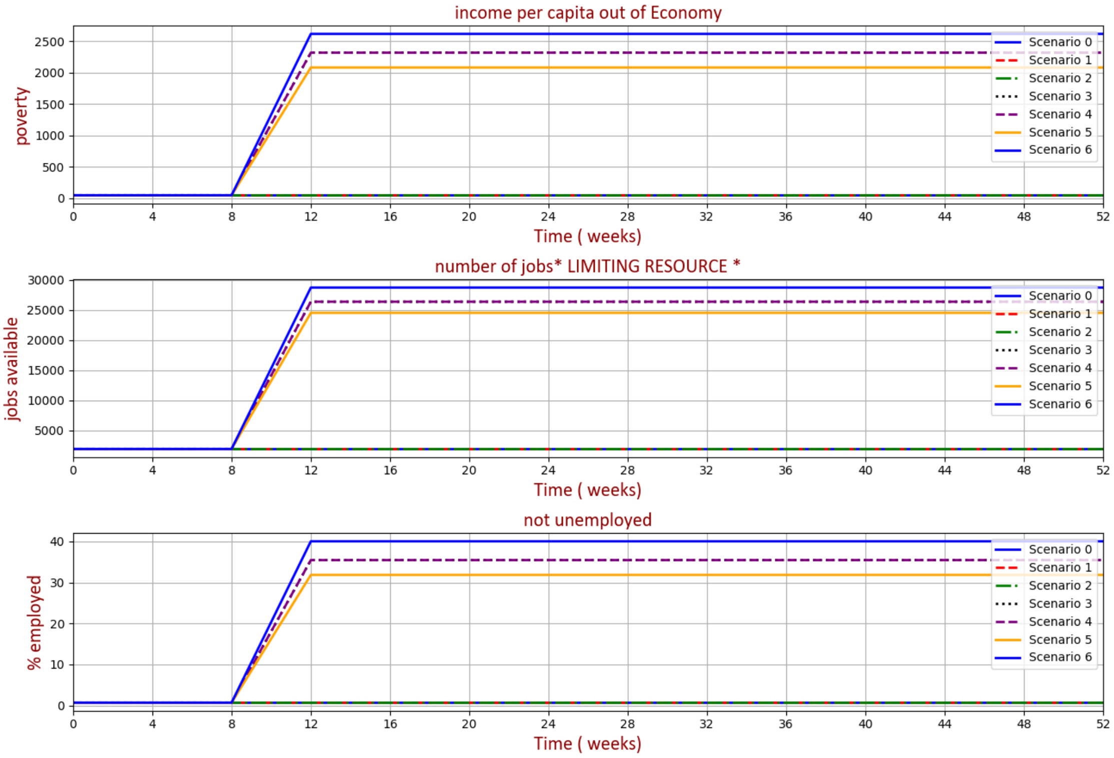


Figure 5-28 - Scenario 1.6 - Health Cell

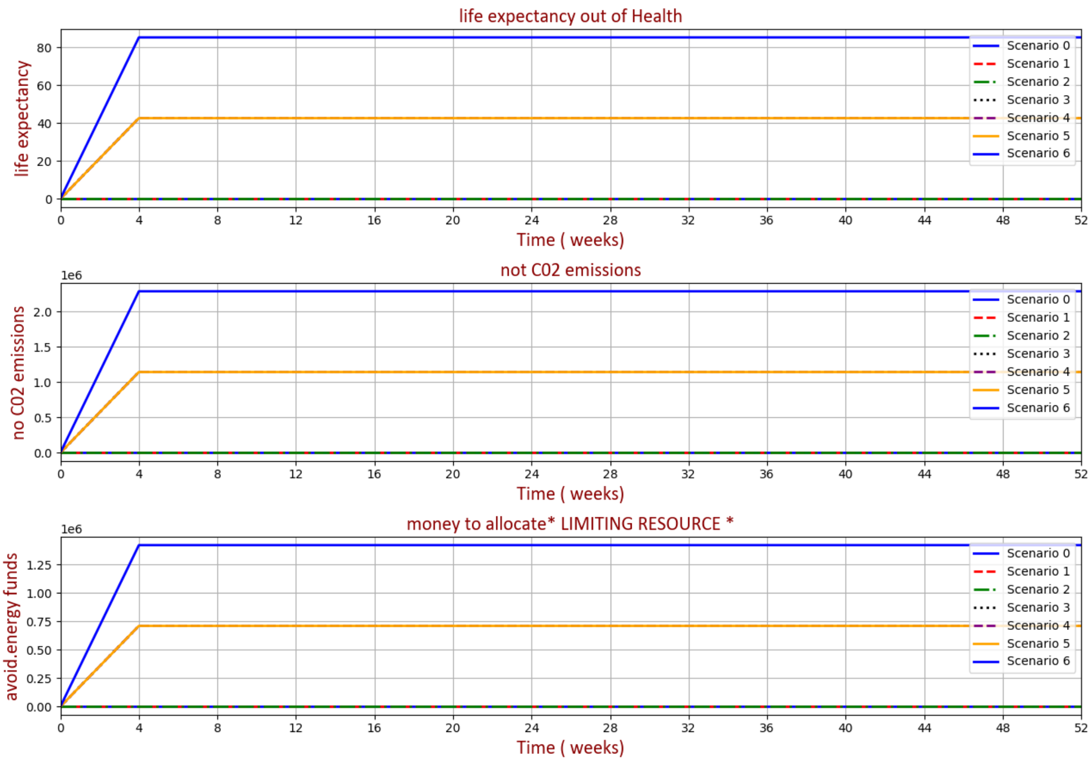


Figure 5-29 - Scenario 1.6 - Industry Cell

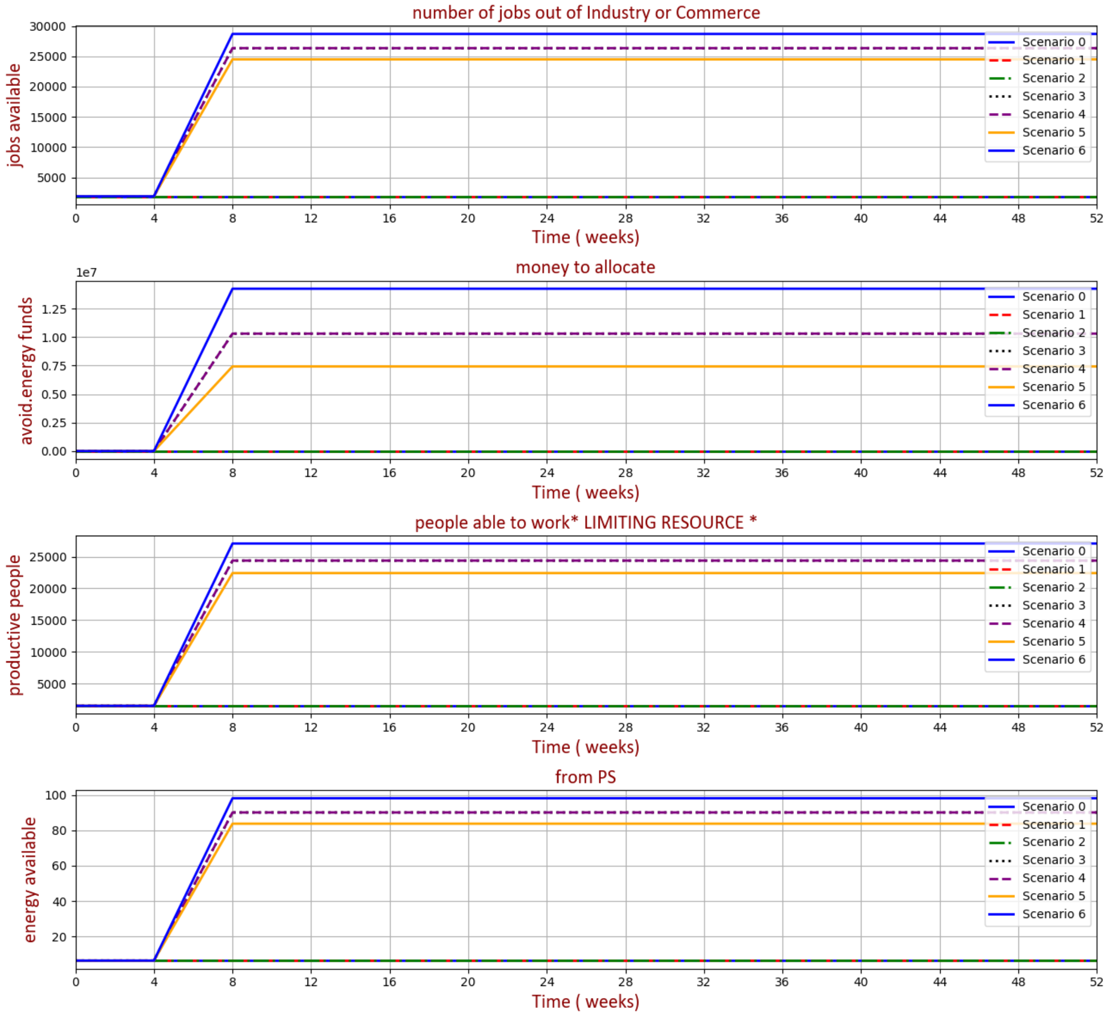


Figure 5-30 - Scenario 1.6 - Population Cell

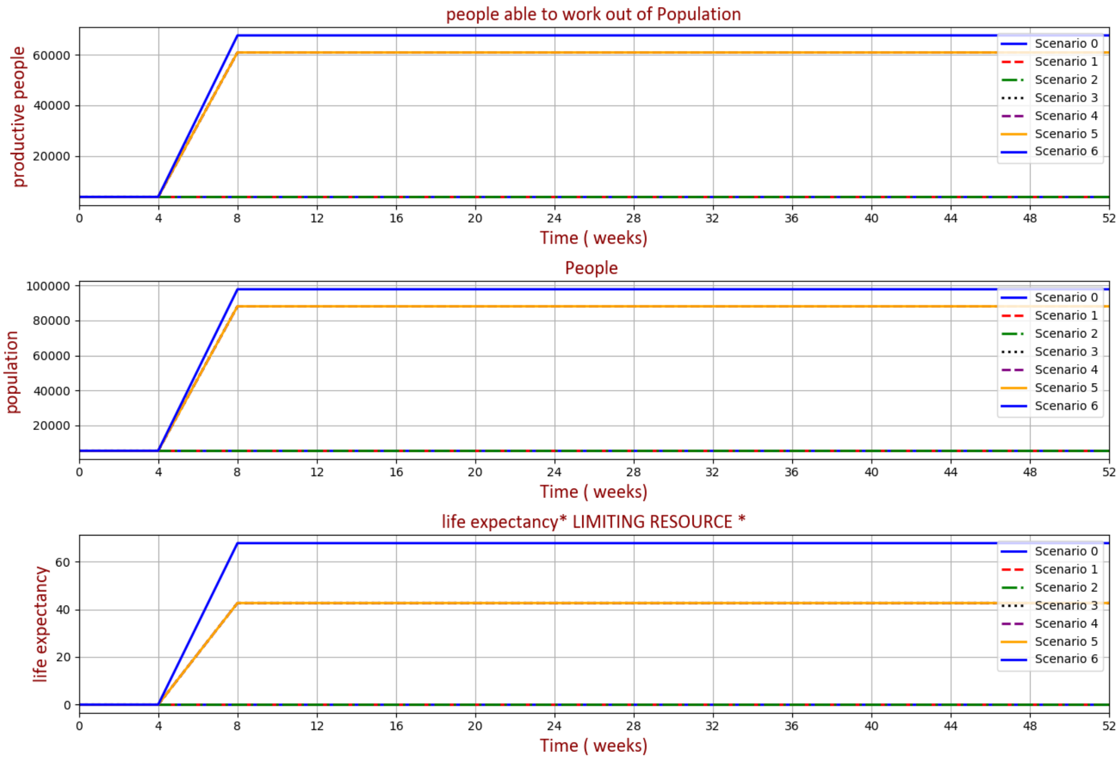


Figure 5-31 - Scenario 1.6 - Safety Cell

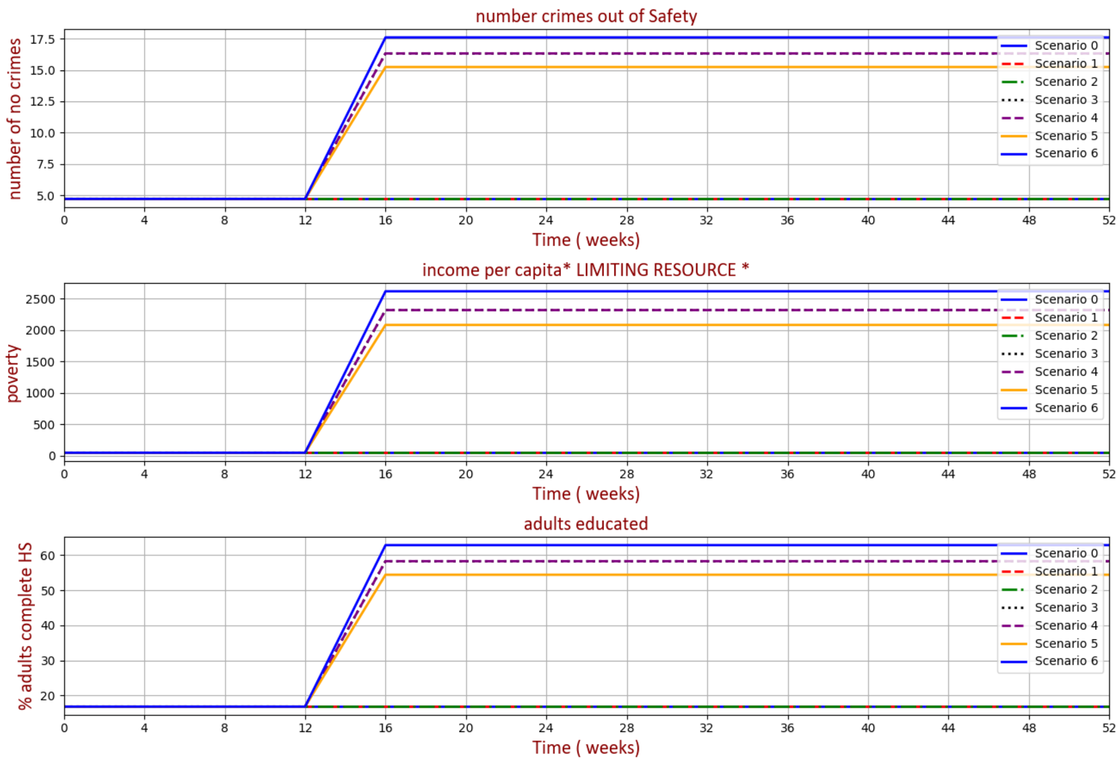


Figure 5-32 - Scenario 1.6 - Transportation Cell

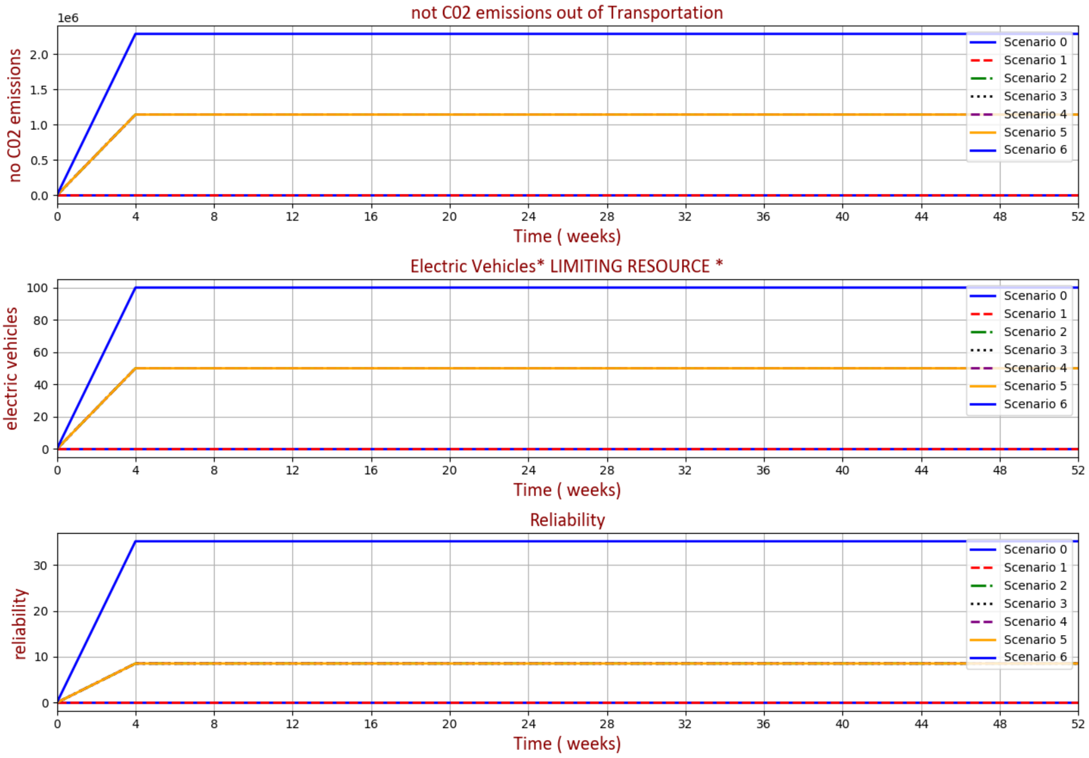


Figure 5-33 - Scenario 1.6 - Unemployment

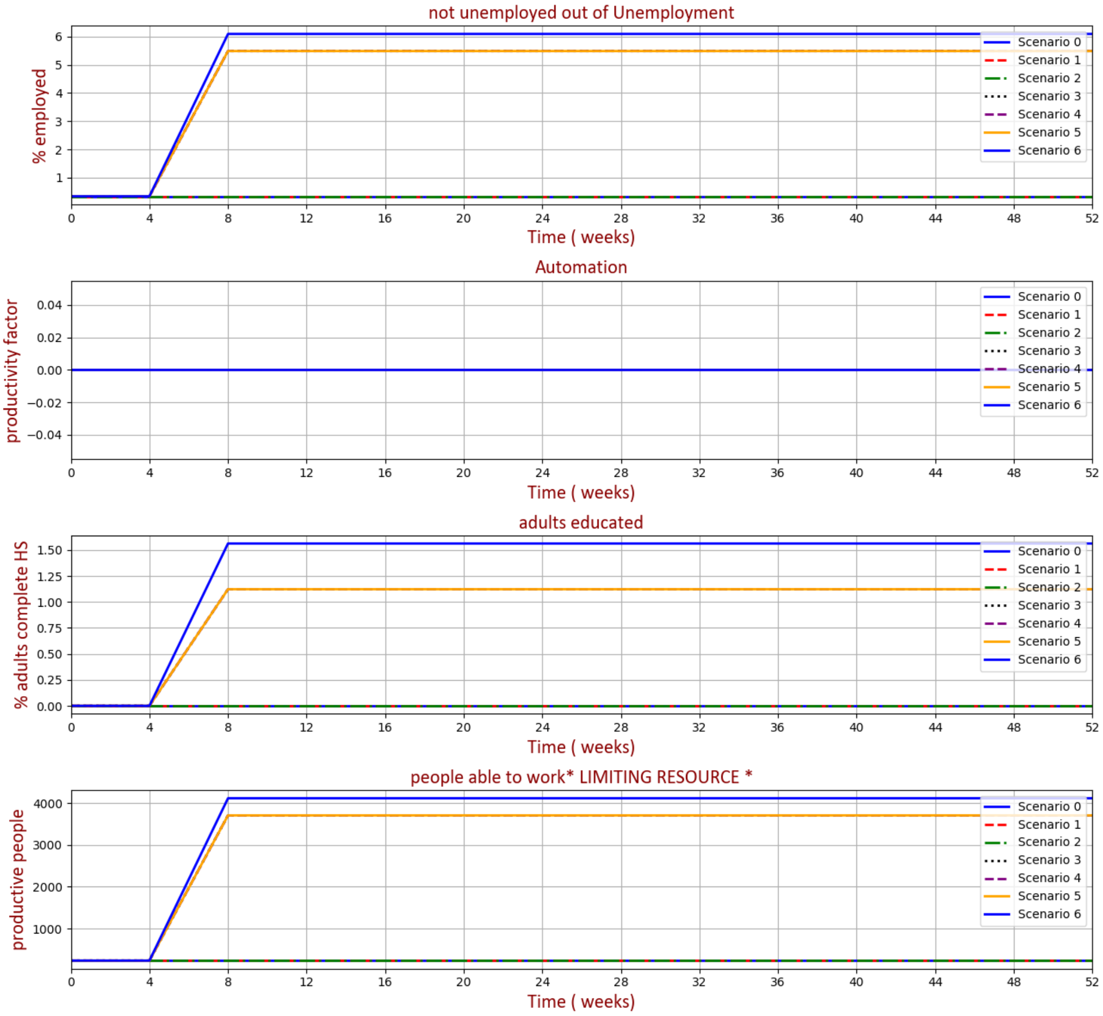
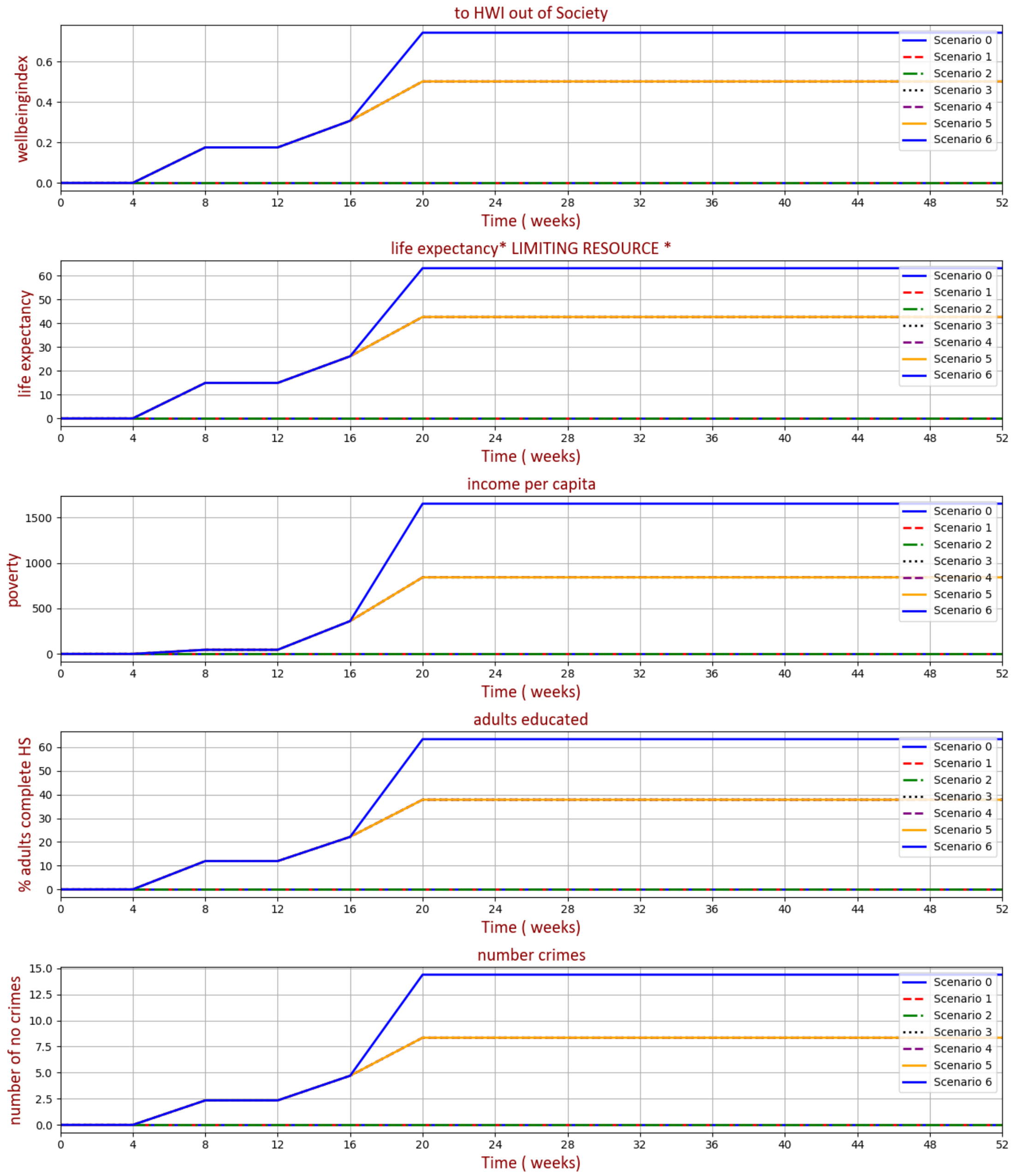


Figure 5-34 - Scenario 1.6 - Society Cell



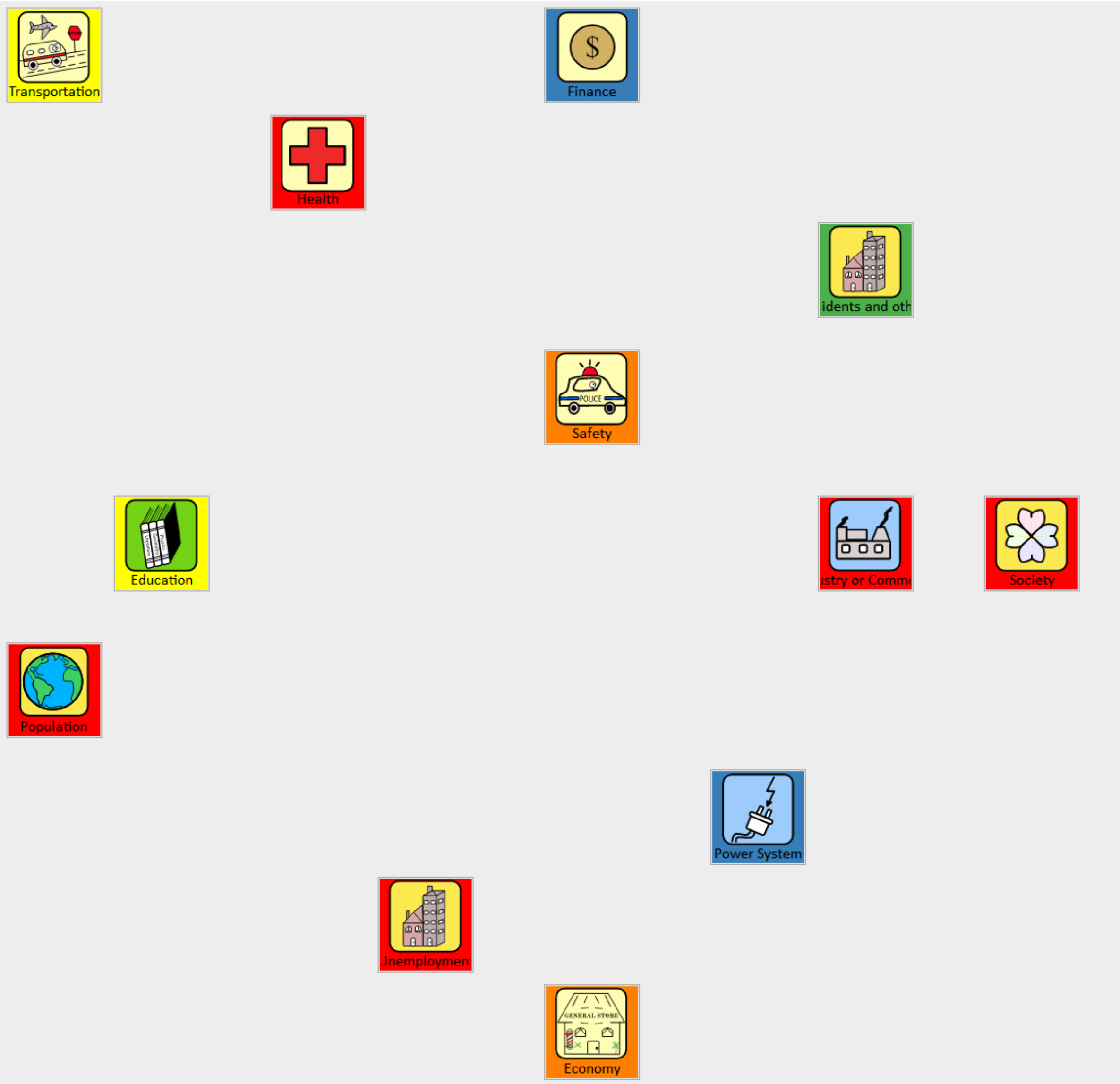
5.6.7.1. ANALYSIS

Even using the improved distribution ratios for DG deployment and scaling Electric Vehicles up to 100%, the simulation still presented limiting resources. These are quality of education, income per capita, and mostly the people available to work. This fact reinforces what was observed earlier regardless of the feasibility of 100% Electric Vehicles.

5.6.1. SCENARIO 2.0 – BASE SCENARIO

This Scenario is the base scenario for the second round of simulations, where the goal was to find an optimal allocation of distributed generation / avoided electricity costs.

Figure 5-35 - I2SIM Interface - Scenario 2.0



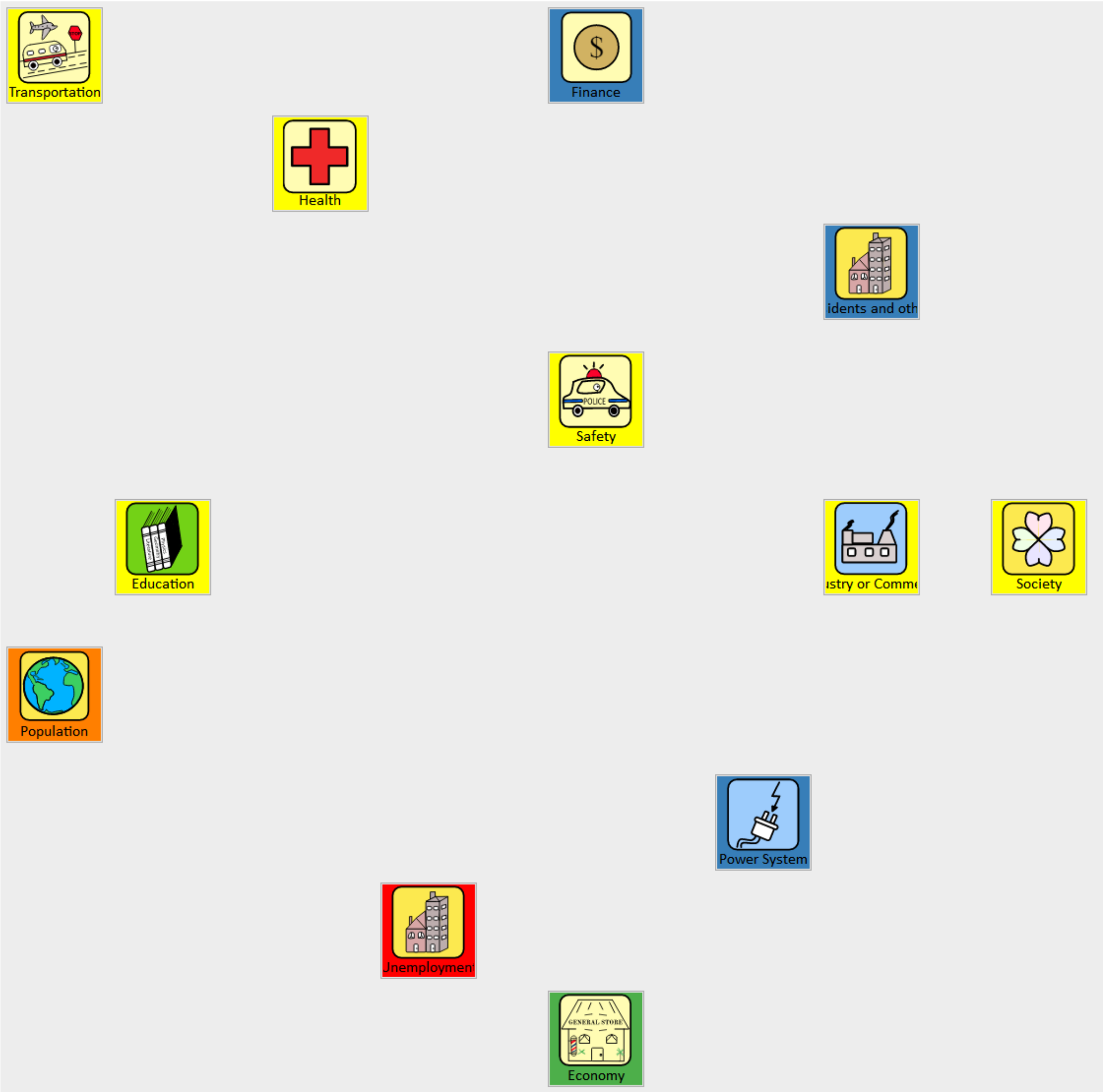
5.6.1.1. ANALYSIS

In this base scenario, the Society cell level remained at five, limited by the Health input, that, consequently, limits the people available to work, which is also limited due to the current population of the city. In brief, it is not a favorable scenario for society.

5.6.2. SCENARIO 2.1

In this scenario, the share of the total penetration of PV directed to Health was increased to 10%. The results from this simulation are exposed in Figure 5-36 to **Erro! Fonte de referência não encontrada.**.

Figure 5-36 - Scenario 2.1 - I2Sim Interface



5.6.2.1. ANALYSIS

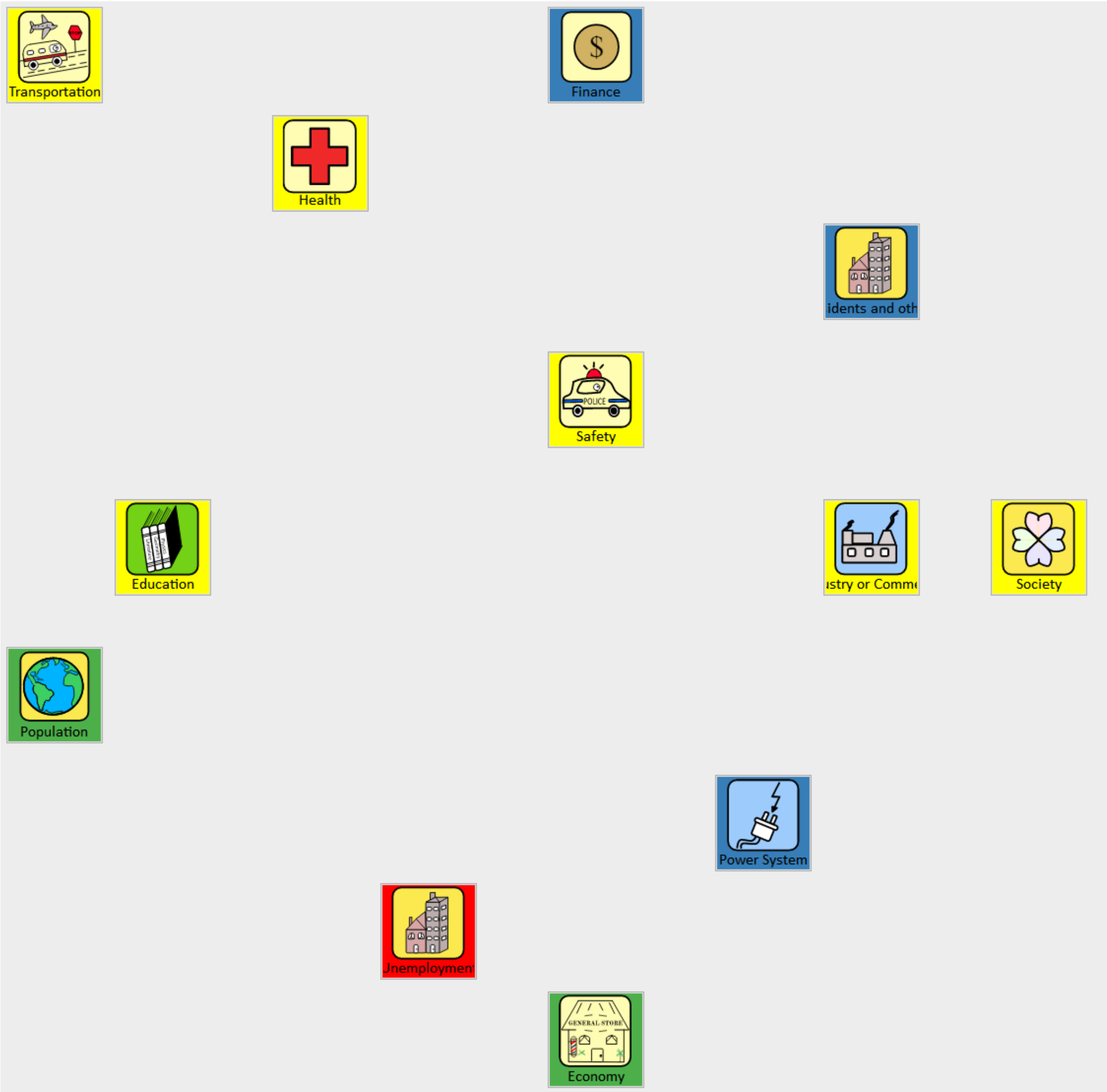
By increasing the percentage of the total PV deployment to 30% for Health,

Health was still a limiting resource, but this time it was limited by the number of Electric Vehicles.

5.6.3. SCENARIO 2.2

For this scenario, previous distribution rates were maintained, and the percentage of Electric Vehicles was risen up to 90% (regardless of its feasibility, only for the system's behavior observation purposes).

Figure 5-37 - I2SIM Interface - Scenario 2.2



5.6.3.1. ANALYSIS

Again, even with the absurd and unreal amount of Electric Vehicles penetration, the society cell stayed at level 3, still limited by health. Which, in consequence, limited the number of people able to work.

5.6.4. SCENARIO 2.3

In this scenario, based on the previous results, the even more unrealistic percentage of 100% Electric Vehicles was tried. The distribution rates of DG were maintained. In Figure 5-38 to Figure 5-45 are the plots of the results obtained.

Figure 5-38 - I2Sim Interface - Scenario 2.3

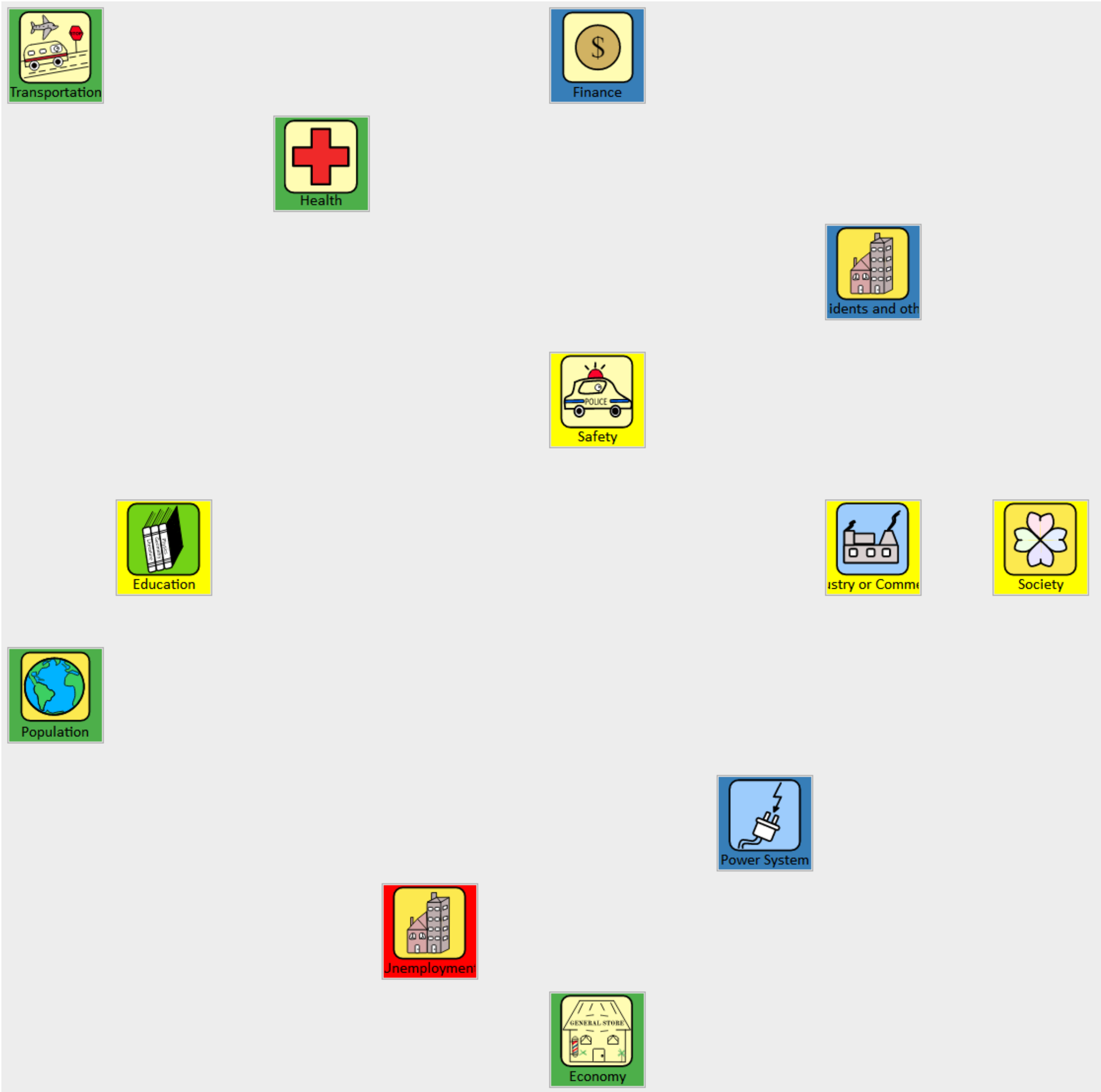


Figure 5-39 - Scenario 2.3 - Health Cell

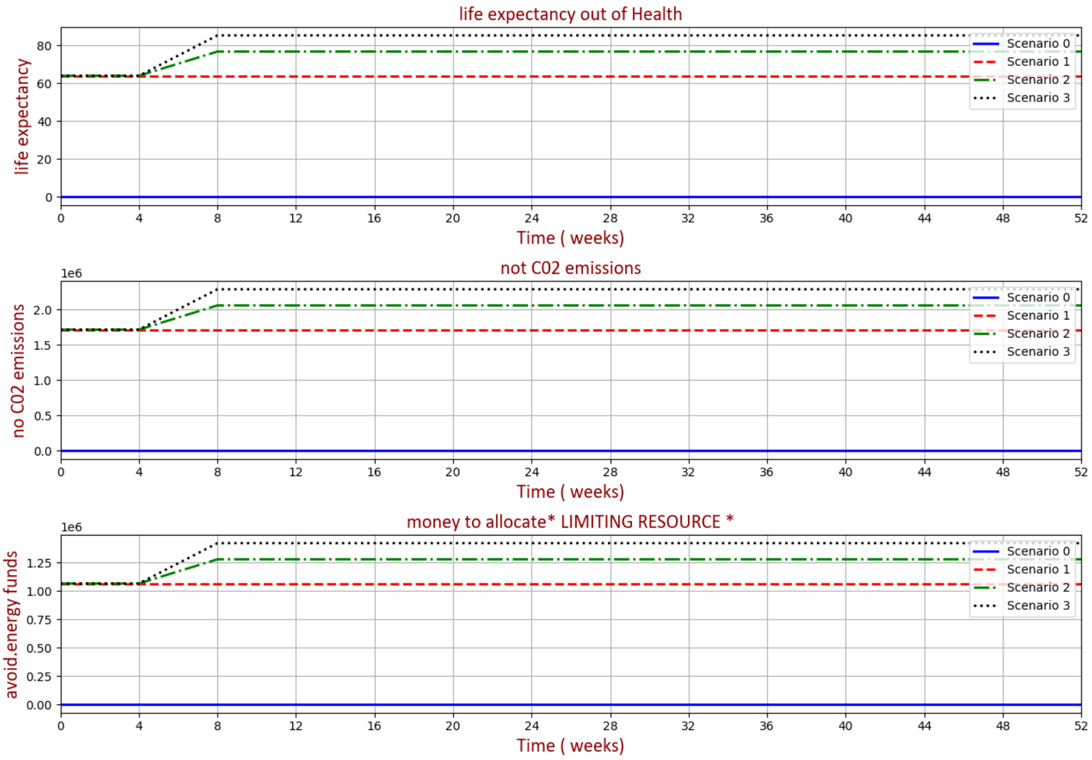


Figure 5-40 - Scenario 2.3 - Industry Cell

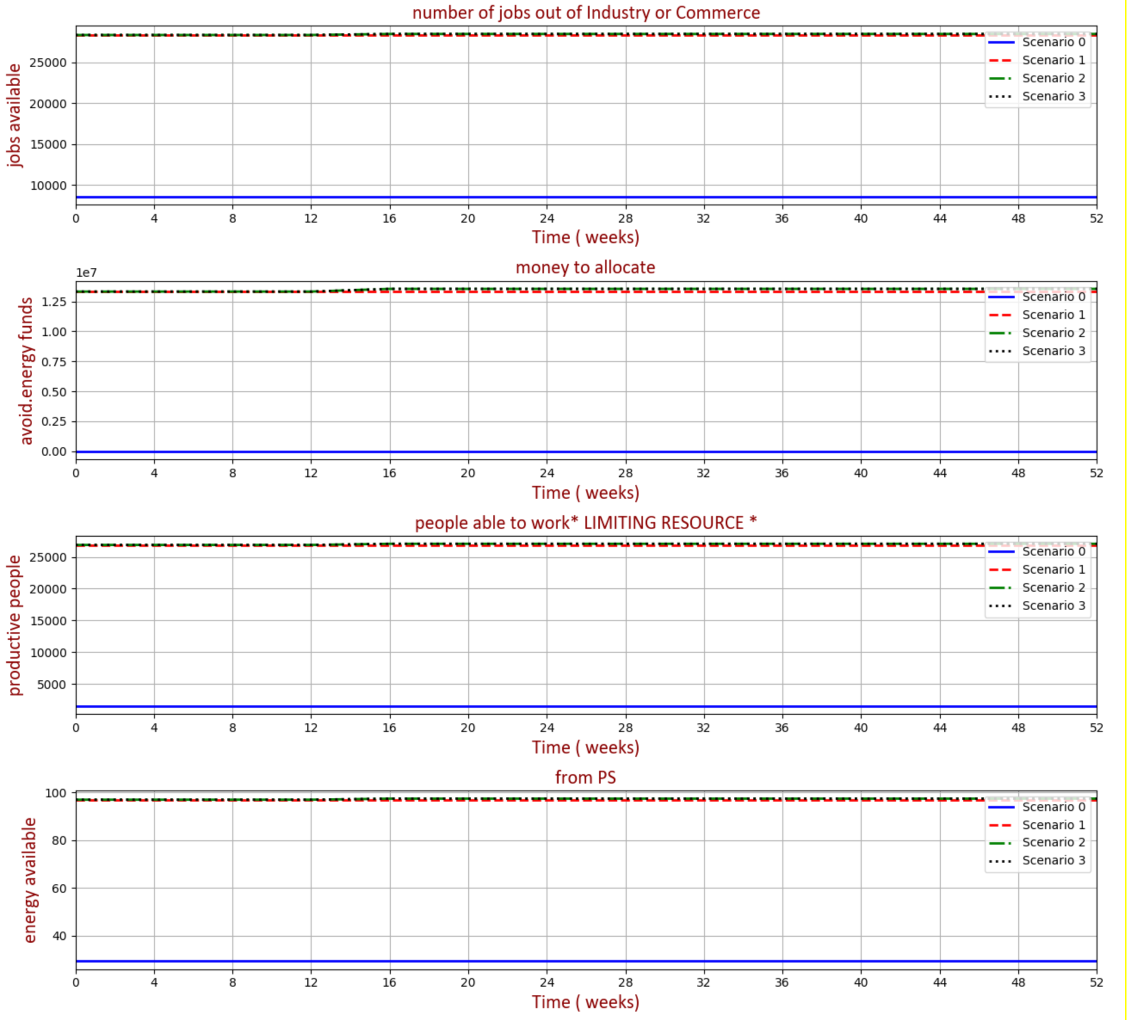


Figure 5-41 - Scenario 2.3 - Population Cell

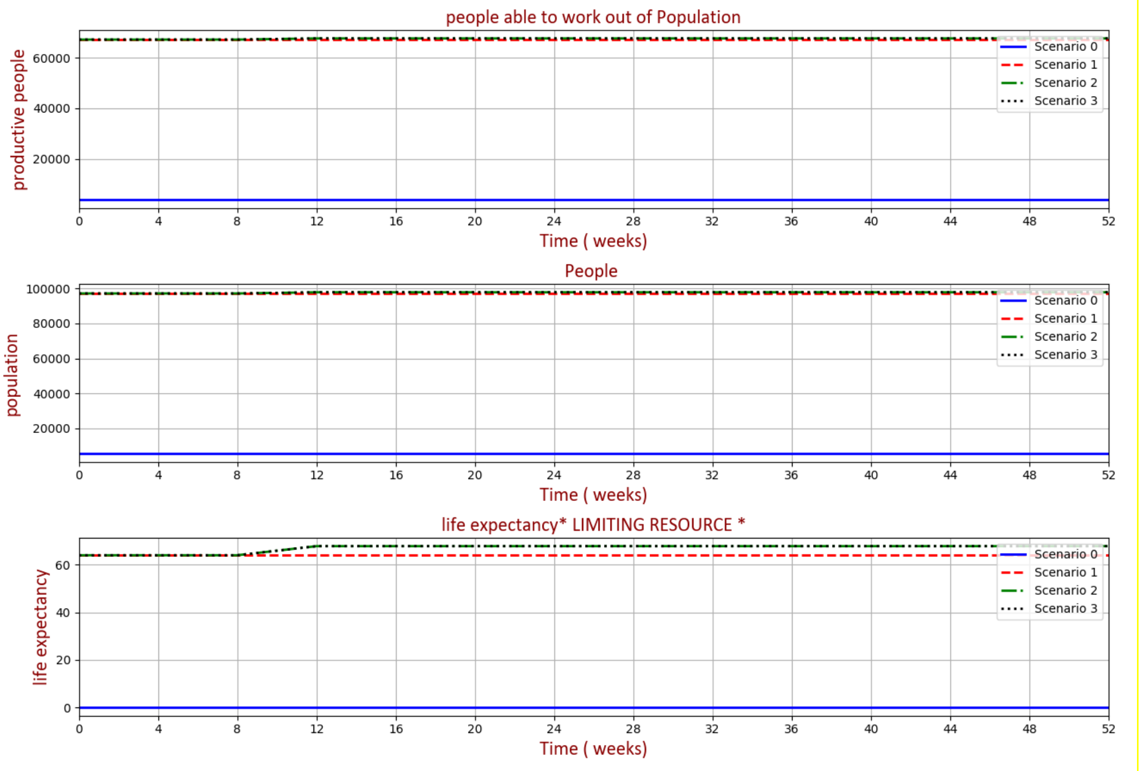


Figure 5-42 - Scenario 2.3 - Safety Cell

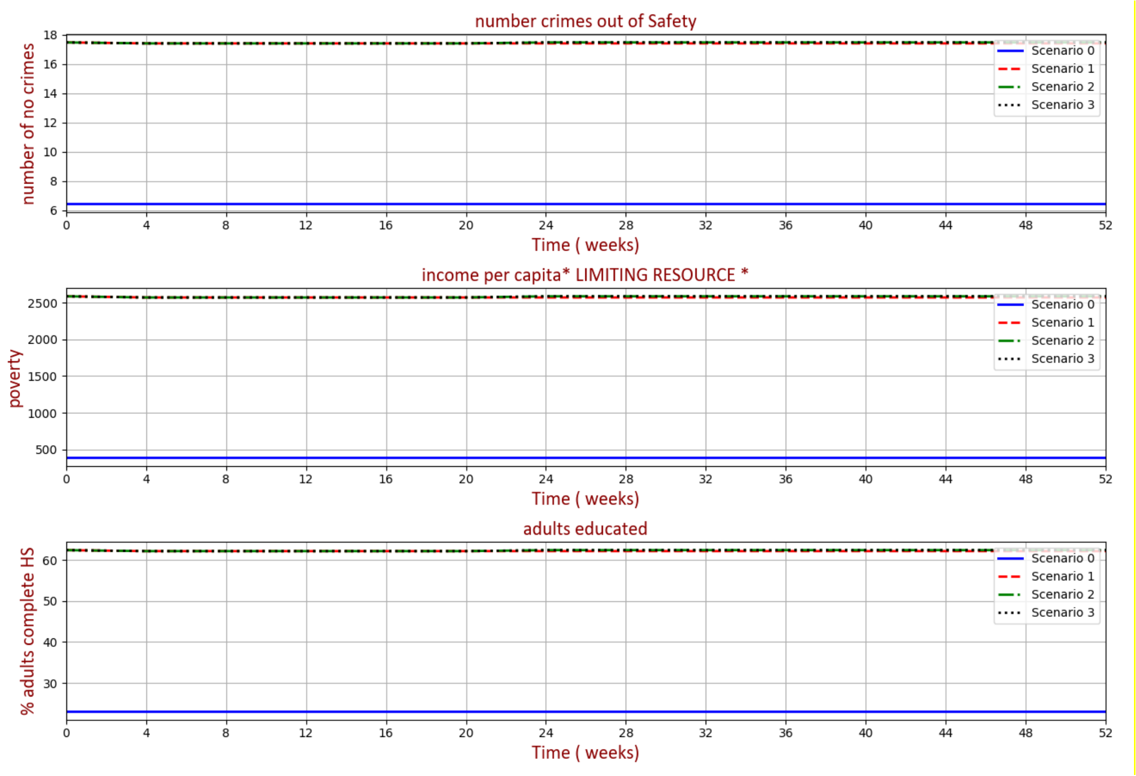


Figure 5-43 - Scenario 2.3 - Transportation Cell

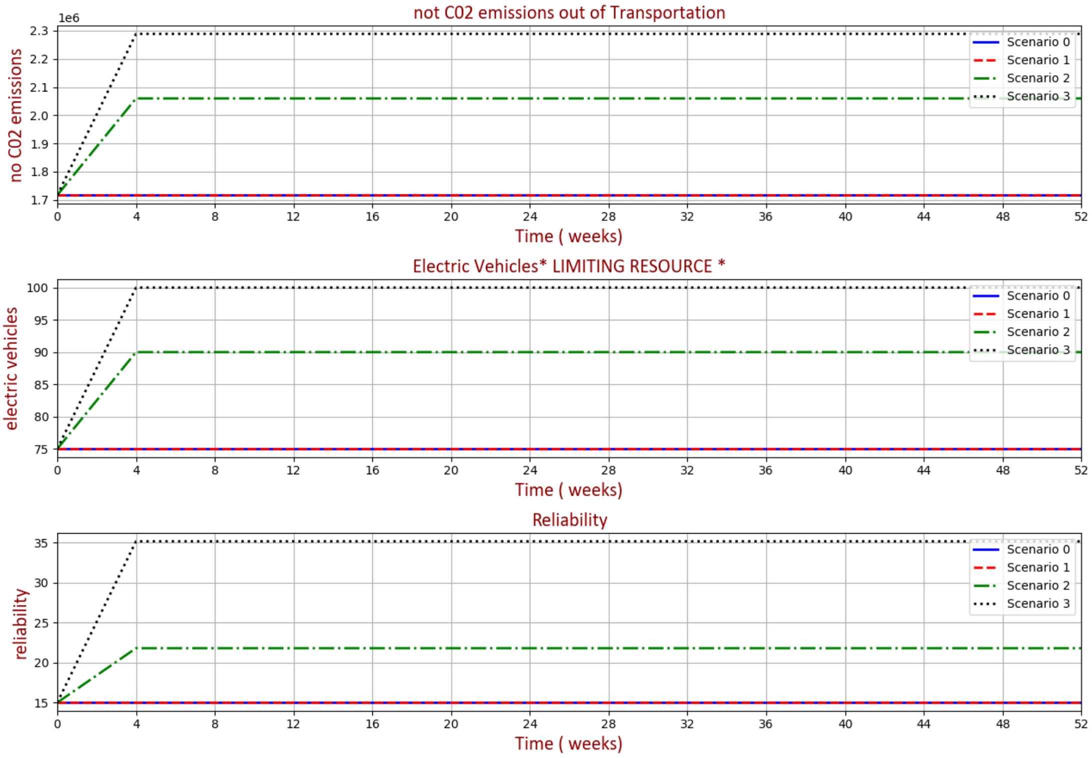


Figure 5-44 - Scenario 2.3 - Unemployment Cell

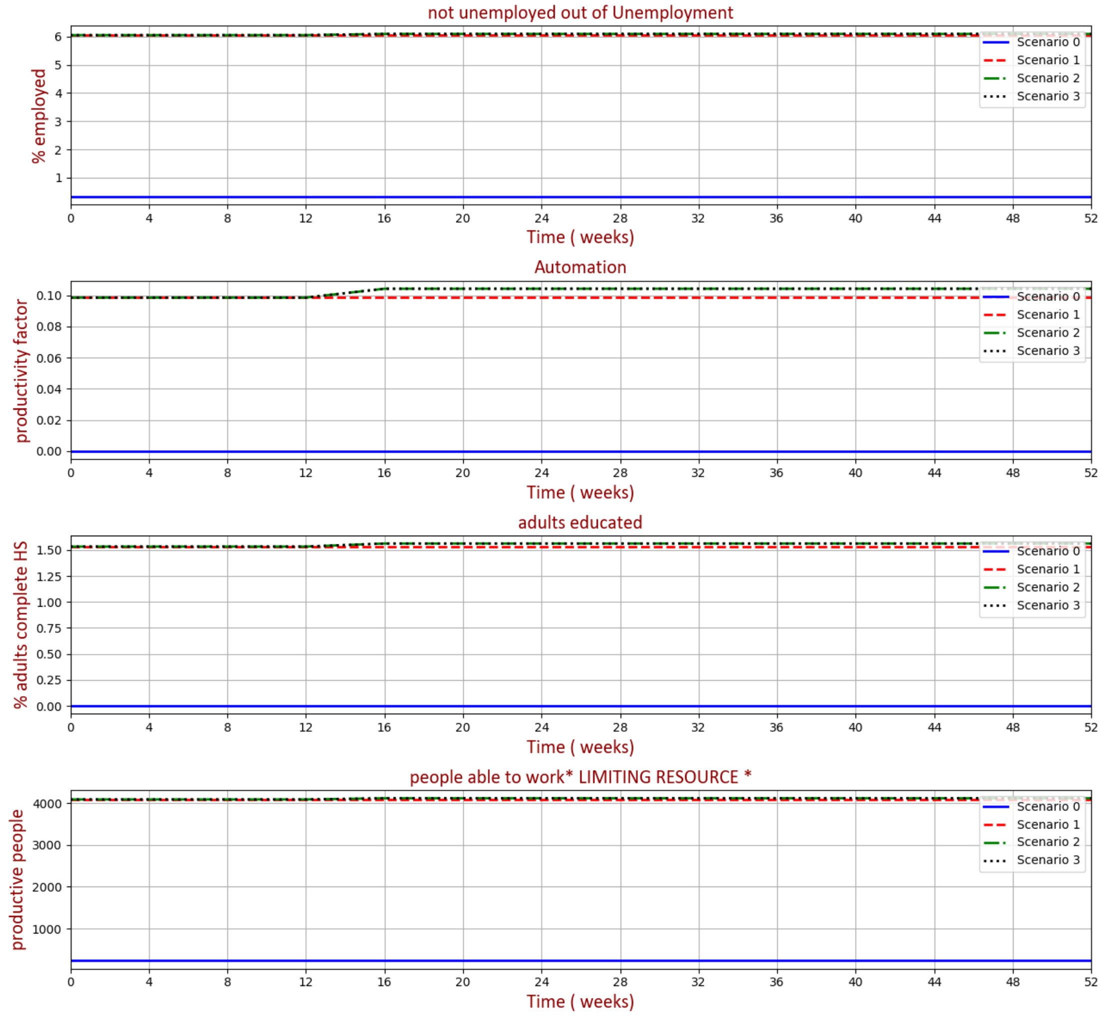
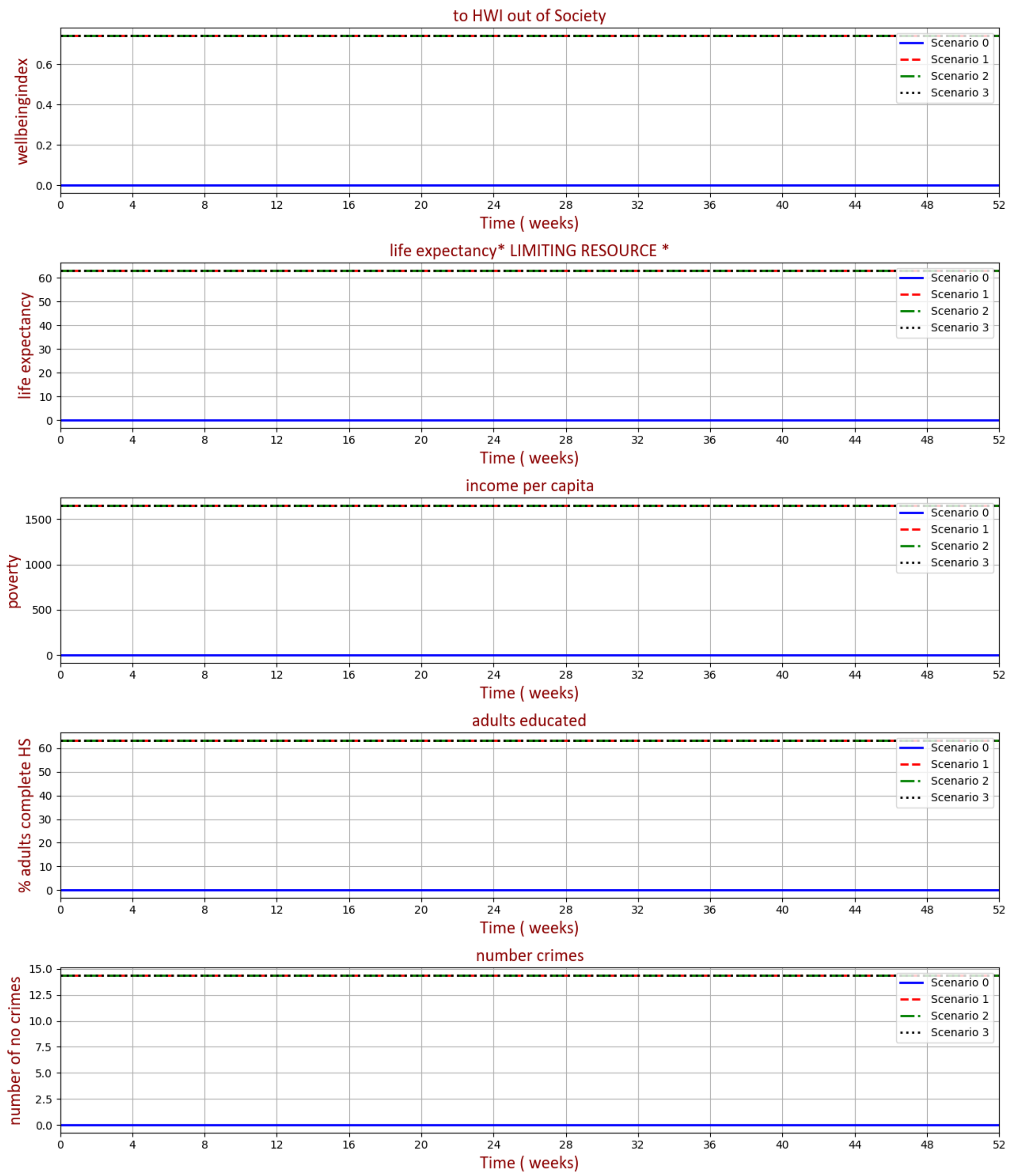


Figure 5-45 - Scenario 2.3 - Society Cell



5.6.4.1. ANALYSIS

The results showed that even though the health situation was addressed, quality of education became the main limiting factor for the improvement of Society's development, which remained at level 3.

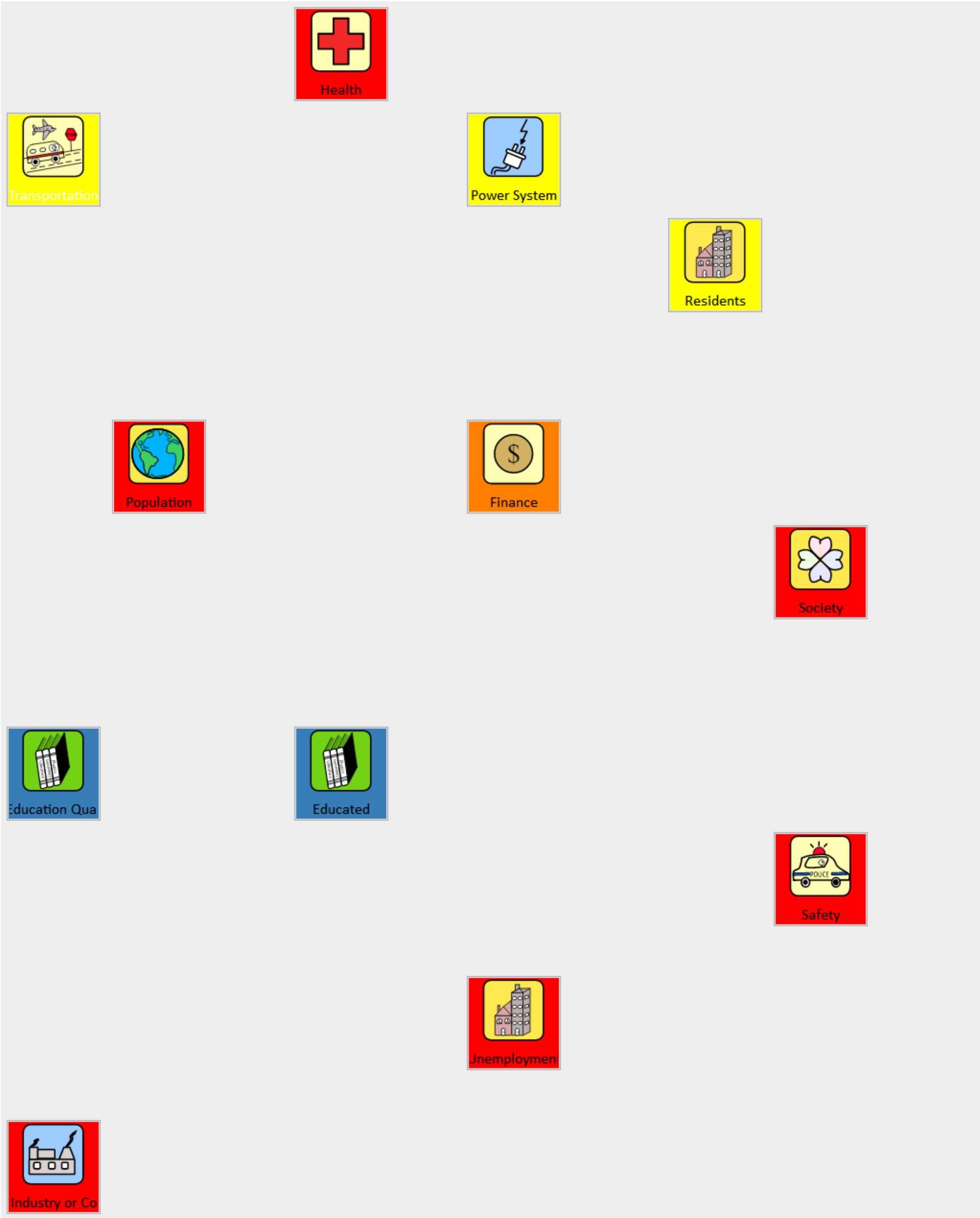
5.7. MODEL 2 - RESULTS & ANALYSIS

Here are presented the results of the simulations and their respective analysis for Model 2.

5.7.1. SCENARIO 0 - BASE SCENARIO - 2022

The base scenario represents the current scenario in the city. This way, the percentage of PV penetration was kept to 5.25%, EV was maintained at 0%, and the reliability of public transportation was 20%. Similar to Model 1, It uses current data on the modeled city on the 50% percent operability level. For 100% operability, the numbers used were references of the maximum possible number for each indicator. The following figures show the results obtained from this simulation. They serve as a reference for further scenarios and also give an idea of the behavior of the system and its relationships between cells and decision points.

Figure 5-46 - Model 2 - Base Scenario - I2SIM Interface



5.7.1.1. ANALYSIS

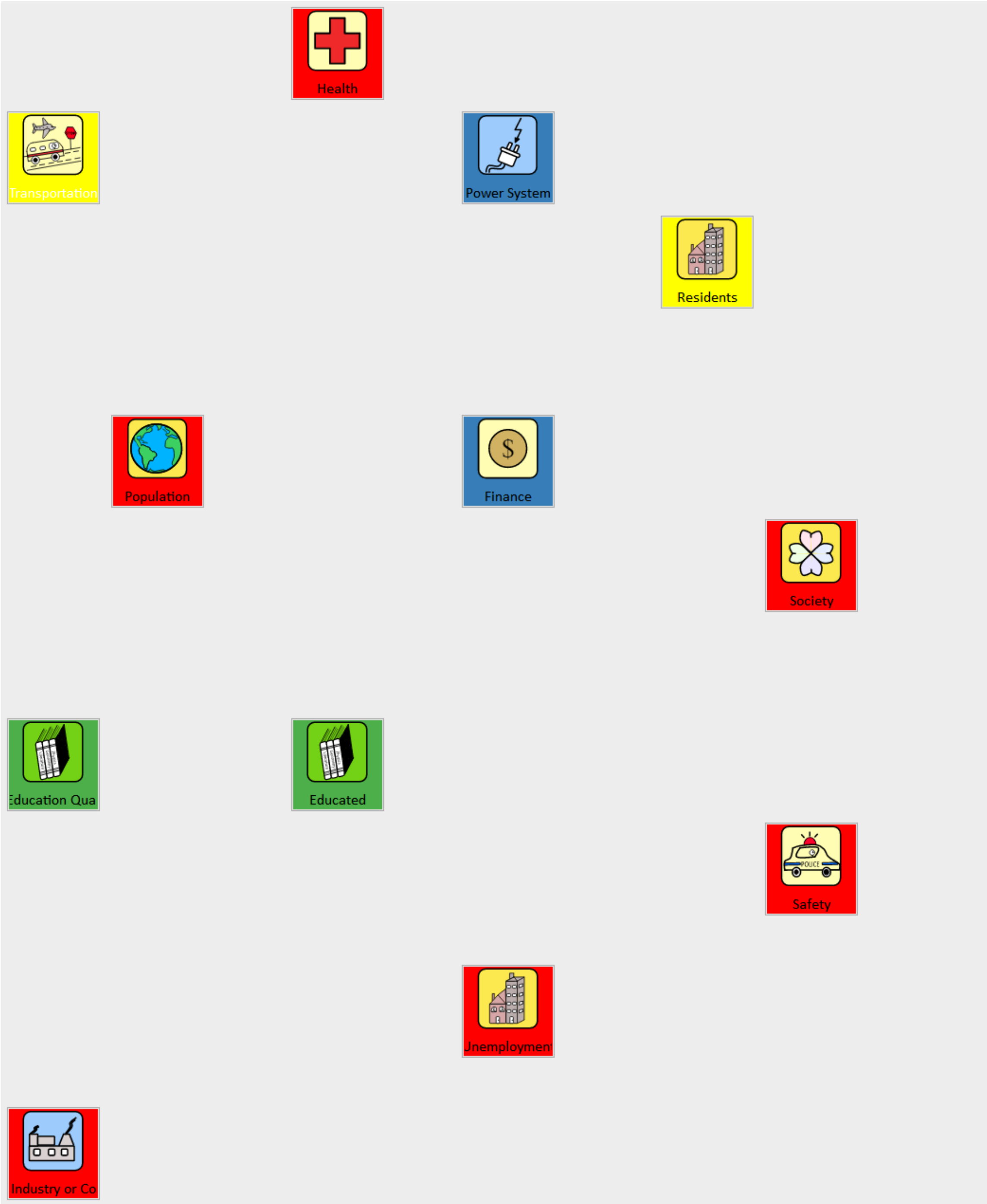
In this scenario, under no circumstance was it possible to make the Society Cell operate at a higher level. It was possible to identify the Health system as one of the main limiting resources, which cascades to limiting Population, Industry, and

Unemployment cells. Therefore, it is possible to say that with the current data on the city, there is no better way to allocate resources and improve the development of society.

5.7.2. SCENARIO 1

For this round of the simulation, the system was fed with information based on Scenario 0, and DG was increased to 60%, regardless of its feasibility. It was done because any value lower than 55% would not change the input to the Power Systems Cell, and consequently, all the other cells would remain in the same state as scenario 0 due to their interdependency. In summary, DG was increased to 60%, EV remained at 0%, and public transportation reliability remained at 20%, just like the level of Automation and the Gini Index were kept the same as in Scenario 0. The results obtained are presented in the following Figure.

Figure 5-47 - Model 2 - Scenario 1 - I2Sim Interface



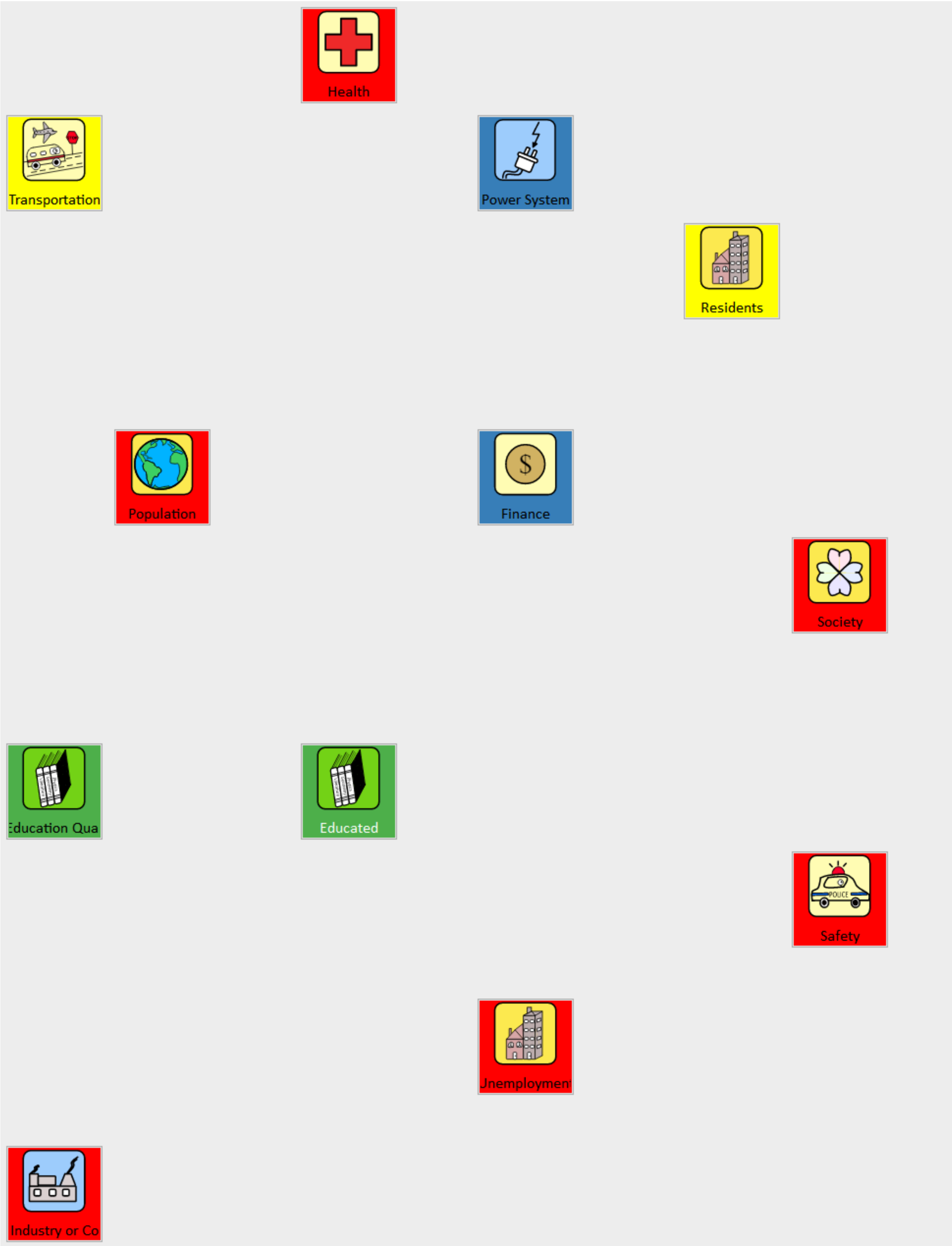
5.7.2.1. ANALYSIS

Looking at the I2Sim interface and analyzing the status of the cells through their colors, it is possible to see an improvement in the status of the finance cell. However, since the other resources were not improved, they continue to be limiting the cells, especially the society cell, from operating at a higher level. It indicates that the solo deployment of distributed generation would not be enough to improve the development of society as a whole. Also, it shows that financially it is a good tool, but it would only help the improvement of society if these avoided costs were reverted into investments in Education and Health (as Model 2 assumes).

5.7.3. **SCENARIO 2**

For this scenario, the penetration of DG was kept at 60%, and the EV was increased to 50%, as it was limiting the Health Cell and all the others after it. All the other inputs were kept the same as the Base Scenario. The result obtained is presented in Figure 5-48.

Figure 5-48 - Model 2 - Scenario 2 - I2Sim Interface



5.7.3.1. *ANALYSIS*

Interestingly, increasing the percentage of electric vehicles by the unfeasible amount of 50%, there was still no change in the system. This is due to the seemingly limiting reliability of the public transportation system. The results for this scenario remained the same as in Scenario 1.

5.7.4. SCENARIO 3

By observing the results from Scenario 2, for this round of the simulation, DG was kept at 60%, EV at 50%, and the reliability of the public transportation system was increased to 50%. All the other resources were kept the same as the Base Scenario.

5.7.4.1. *ANALYSIS*

Again, even with the changes made, there was no significant change in the operability level of the cells. Only there was a slight increase in the Transportation Cell, which is a direct effect of the change in reliability. It means that, no matter how DG, EV, and reliability increase, there are other factors that must be changed to have a significant increase in the development of society in the year 2022. An aspect that can be changed, though, is the share of DG that each infrastructure has. Currently, Commercial and Residential consumers hold the biggest shares.

5.7.5. SCENARIO 4

In this scenario, the source values were kept the same as in Scenario 3 (60% of DG; 50% of EV, and Reliability at 50%). The avoided energy costs were redistributed, taking 30% from Industry and reallocated to health. This is the percentage of the 60% DG penetration. The obtained results are exposed in the following figures.

5.7.5.1. *ANALYSIS*

It's possible to see that the Industry cell operating level increased to 50% due to the increase in productive people, which was caused by the increase in the Health cell. However, the society cell remained at its lowest operating level due to the current crime rate, which has become a limiting resource. This is caused by the percentage of unemployed people, which is further limited by Health. In any case, there was an improvement even with Health still being a limiting resource.

5.7.6. **SCENARIO 5**

For this simulation, the values of the sources were kept the same as in scenario 4, including the distribution ratio of DG, but electric vehicles were increased to 75%.

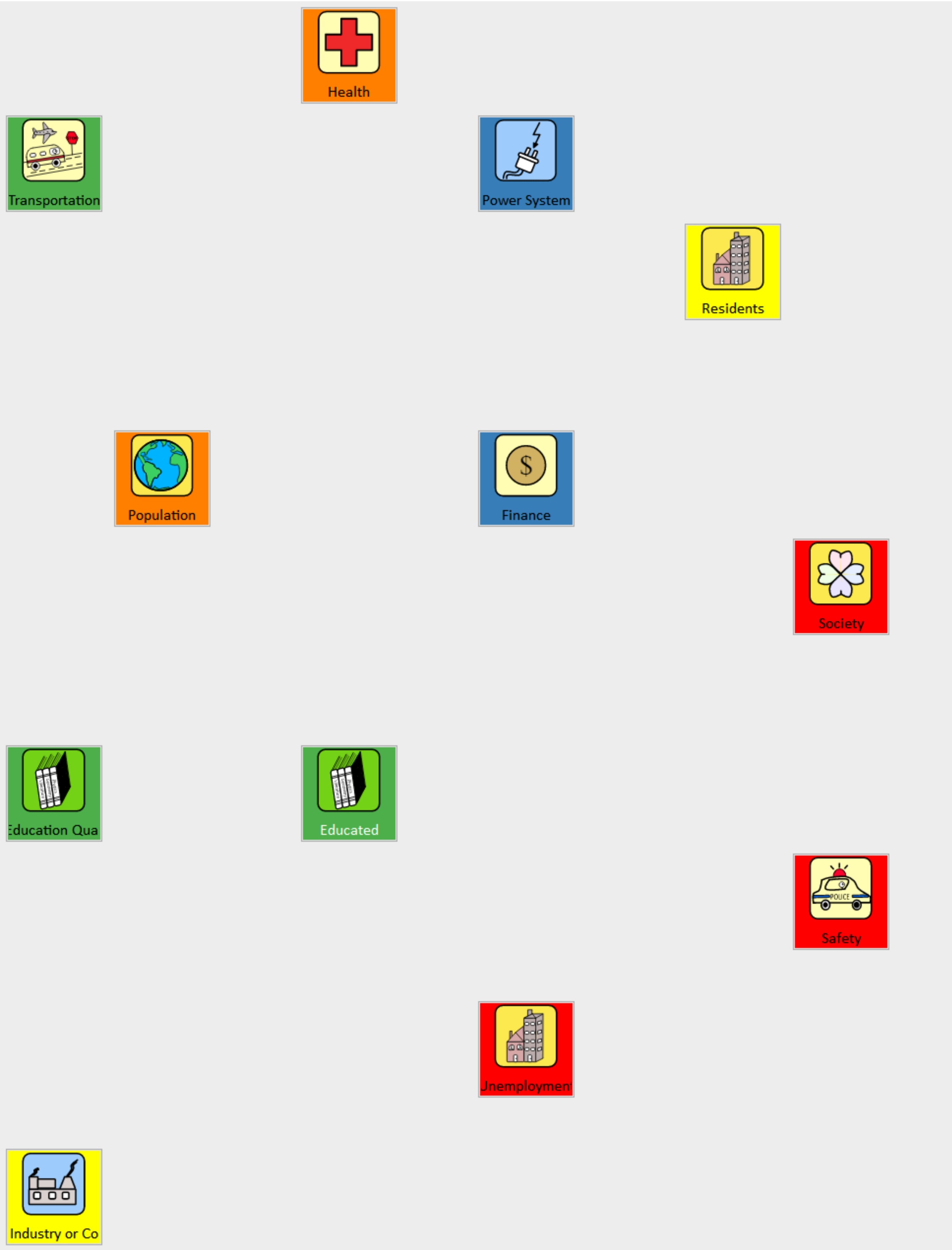
5.7.6.1. ANALYSIS

It is possible to see that the society cell still operates at its lowest level. However, taking a closer look, it is noticeable a slight improvement when compared to scenario 4. It means that improving Health is an effective way of improving society collectively, and the smart grid techs that decrease the impact on the environment have the potential to significantly contribute to this development.

5.7.7. **SCENARIO 6**

For this scenario, the source values were maintained as they were in scenario 5, and Electric Vehicles were increased to 90%. Regardless of its feasibility, it was performed for a better understanding of the Model and its limitations. The results are presented in the following figures.

Figure 5-49 - Model 2: Scenario 6 - I2Sim Interface



5.7.7.1. ANALYSIS

It is possible to observe that even though health does increase to 75%, that still corresponds to a population level below 50% because the Population HRT requires a health indicator of 78 and above to increase to a higher level. Therefore, this is the reason why Health is still a limiting resource for the Population Cell.

5.7.8. SCENARIO 7

From the previous scenarios, it was possible to identify that the current employment rate was a crucial limiting resource. It could be due to the number of citizens at productive age and also due to the number of people at this age that are not considered employed or unemployed. It happens because of how the census is performed. It considers that only the fact that a person is currently not working is not enough for this person to be statistically considered unemployed, which leads to a gap in the data of people at productive age. That being said, for Scenario 7, the distribution ratio for unemployment was changed to 20% employed; 20% gap; and 60% unemployed or available to work. The other sources were kept the same as scenario 6; reliability and EV were increased to 100%. The results obtained are presented in the following figures.

Figure 5-50 - Model 2 - Scenario 7 - I2Sim Interface

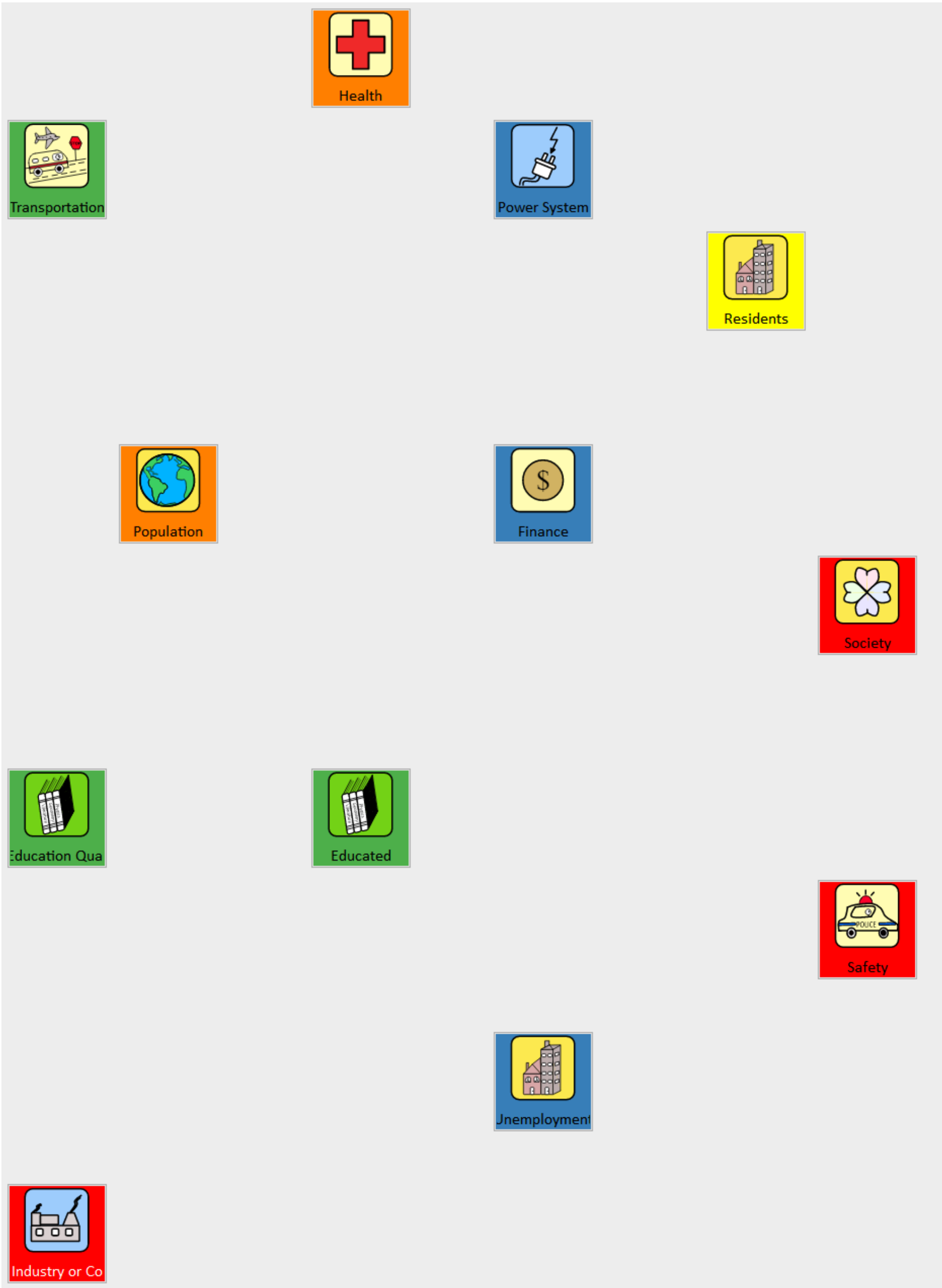


Figure 5-51 - Model 2 - Scenario 7 - Safety Cell

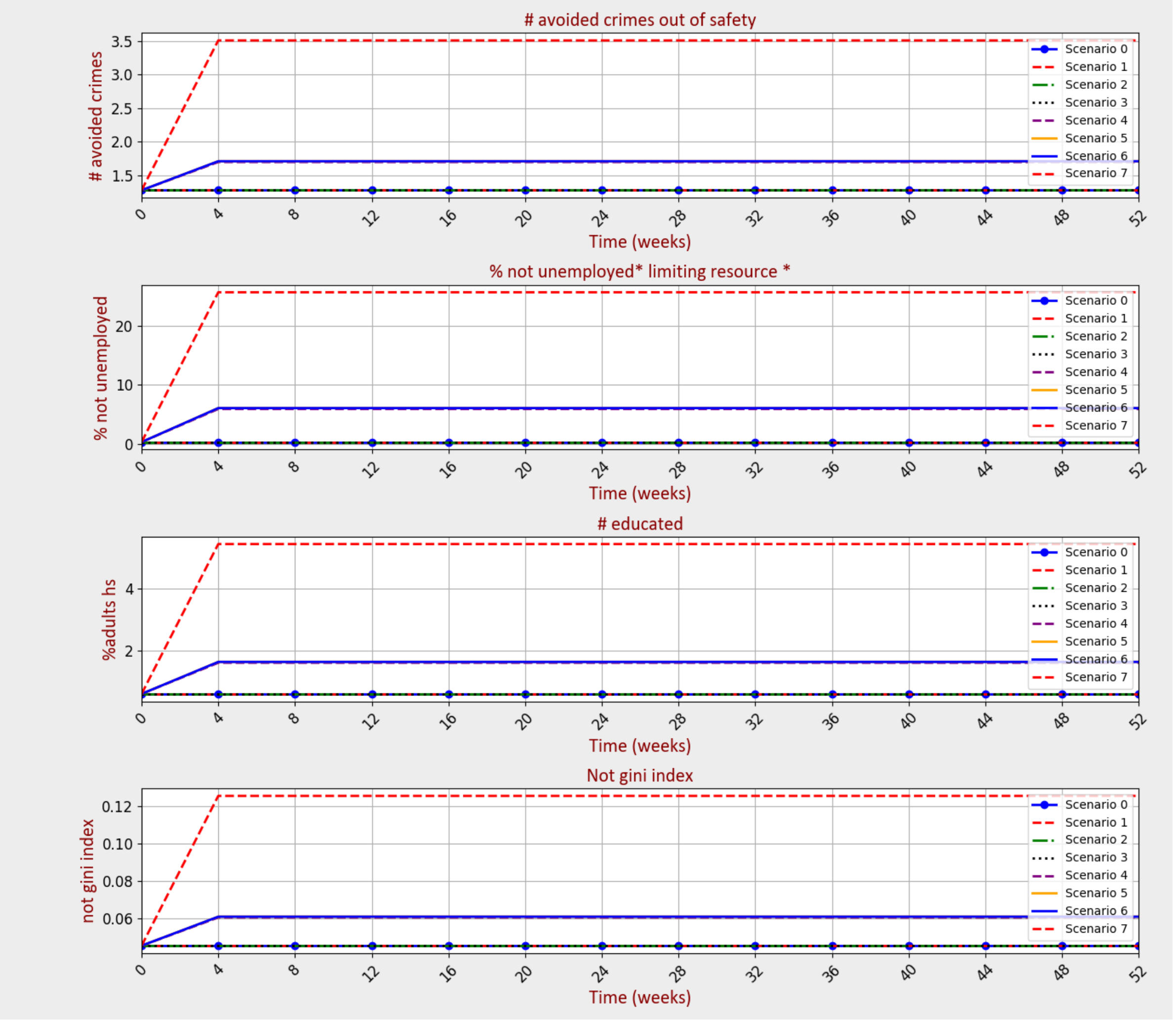
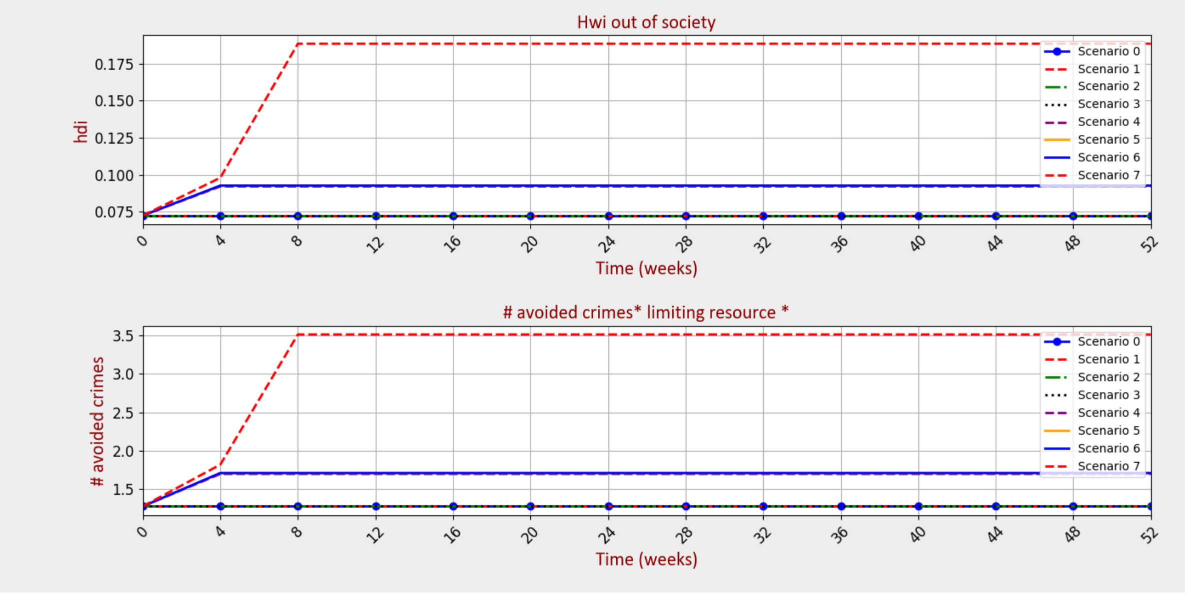


Figure 5-52 - Model 2 - Scenario 7 - Society Cell



5.7.8.1. ANALYSIS

From the plots, it is possible to see that the society cell was still limited by the safety cell, which was originally limited by the percentage of people not unemployed (a reverse indicator for unemployment), which was limited by the number of productive people. However, even with the limitations observed, values have slightly improved, showing that along with the deployment of PV generation and all the other measures, decreasing the unemployment rate is crucial for the system to develop cooperatively.

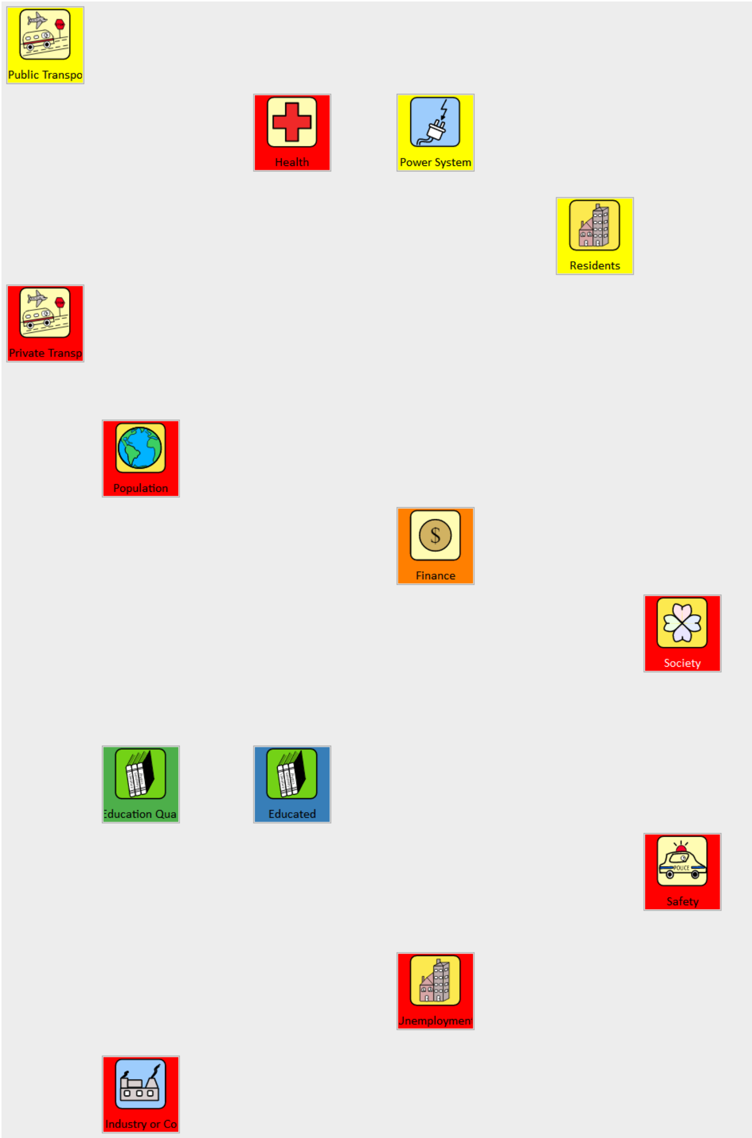
5.8. MODEL 3 - RESULTS & ANALYSIS

Here are presented the results of the simulations and their respective analysis for Model 3. From all the scenarios that were simulated as described in item 5.4.4, the scenario with the best results was chosen to be explored in this section, Scenario 4.

5.8.1. BASE SCENARIO

This is the base scenario for all Model 3 simulations. The inputs used here are the ones described under the topic “Cells” added the changes mentioned in the “Model Development” topic. For most of the cells, like the previous models, It uses current data on the modeled city on the 50% percent operability level. For 100% operability, the numbers used were references of the maximum possible number for each indicator. The Health, Public and Private Transportation cells, were run with the initial operability level at 0%.The following figures show the results obtained from this first simulation.

Figure 5-53 - I2Sim Interface - Base Scenario - Model 3



5.8.1.1. *Analysis*

Through this simulation it was possible to see that the adjustments that were made reflected in a more precise and representative model. It is also possible to identify that Private Transportation remains a limiting resource that consequently limits the Health cell.

5.8.1. **Scenario 4**

This scenario, among all the others not mentioned in this section, was the one that presented the best results. It considers that 60% of the load is covered by DG, 50% of the fleet is electric and the reliability of the public transportation system is at 50%. The results are presented in the following figures.

Figure 5-54 - I2Sim Interface - Scenario 4 - Model 3

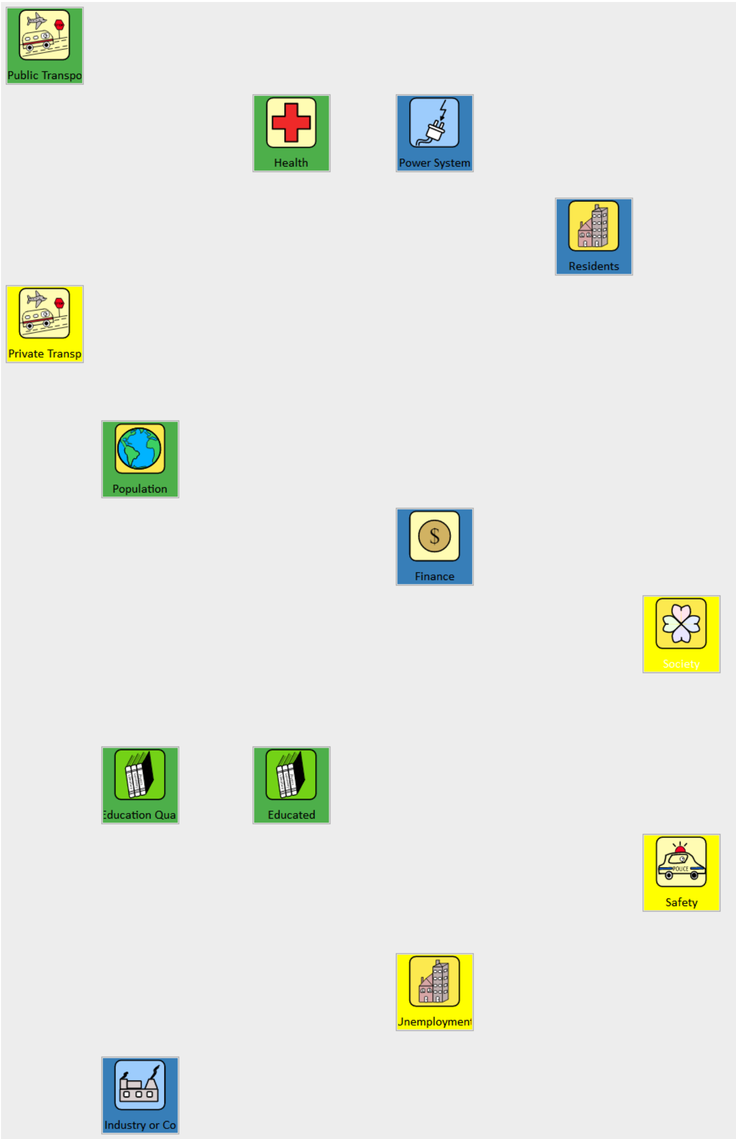


Figure 5-55 - Model 3 - Capacitation Cell

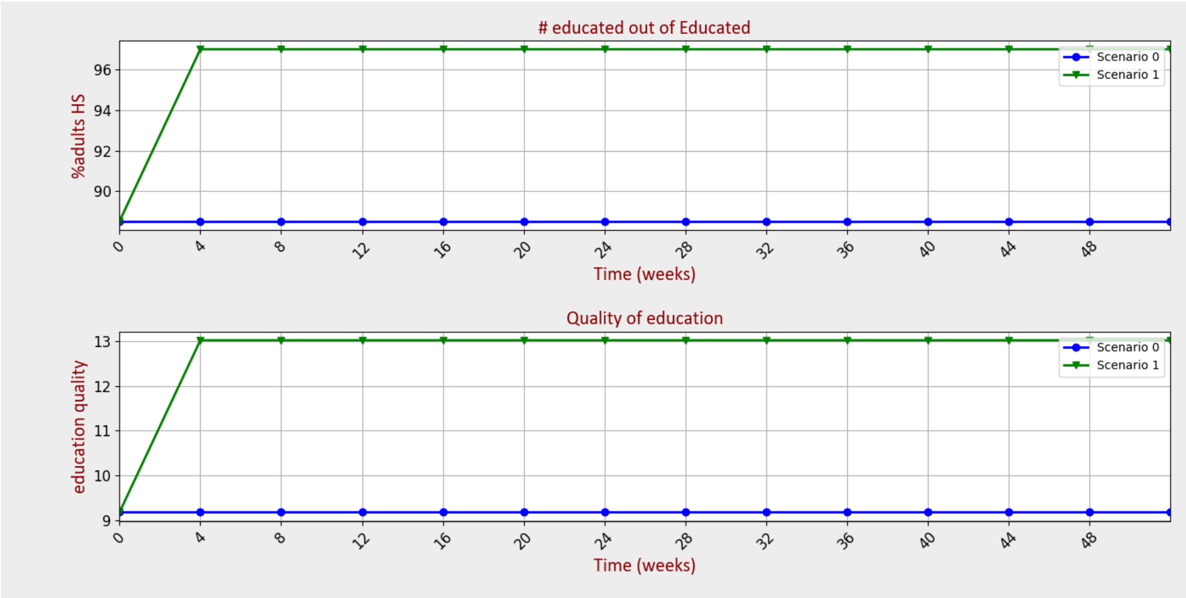


Figure 5-56 - Model 3 - Education Cell

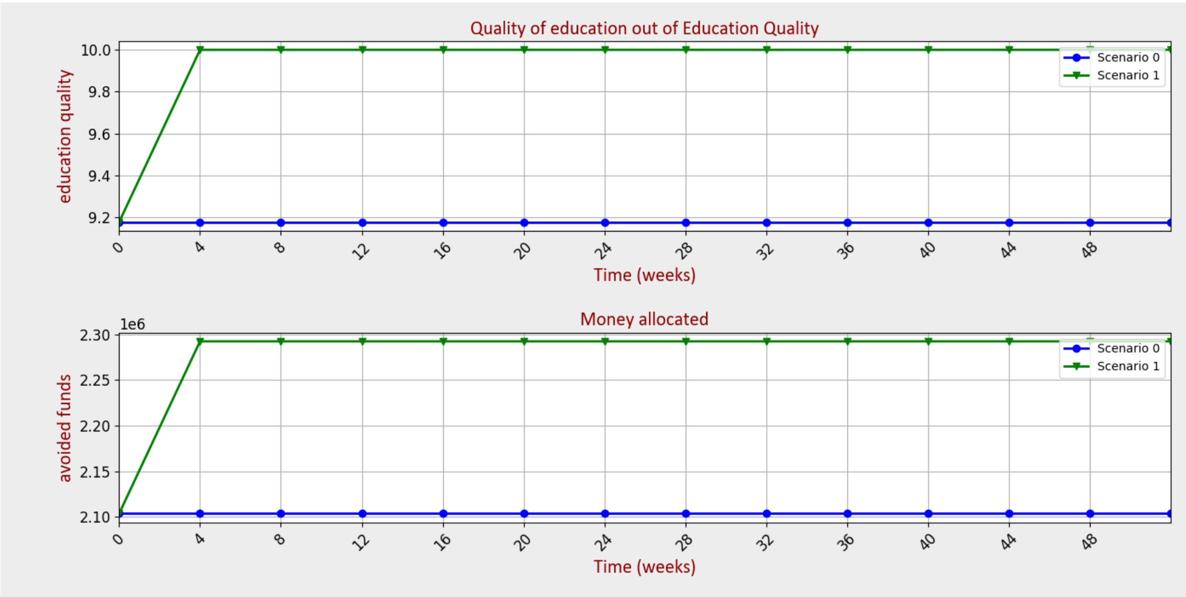


Figure 5-57 - Model 3 - Finance Cell

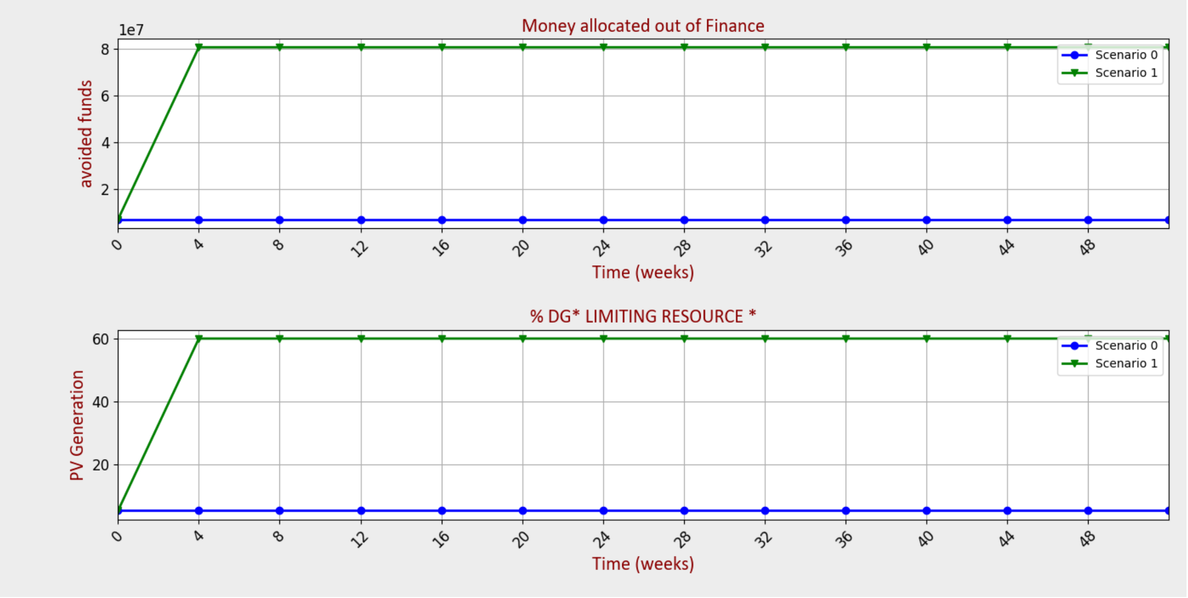


Figure 5-58 - Model 3 - Health Cell

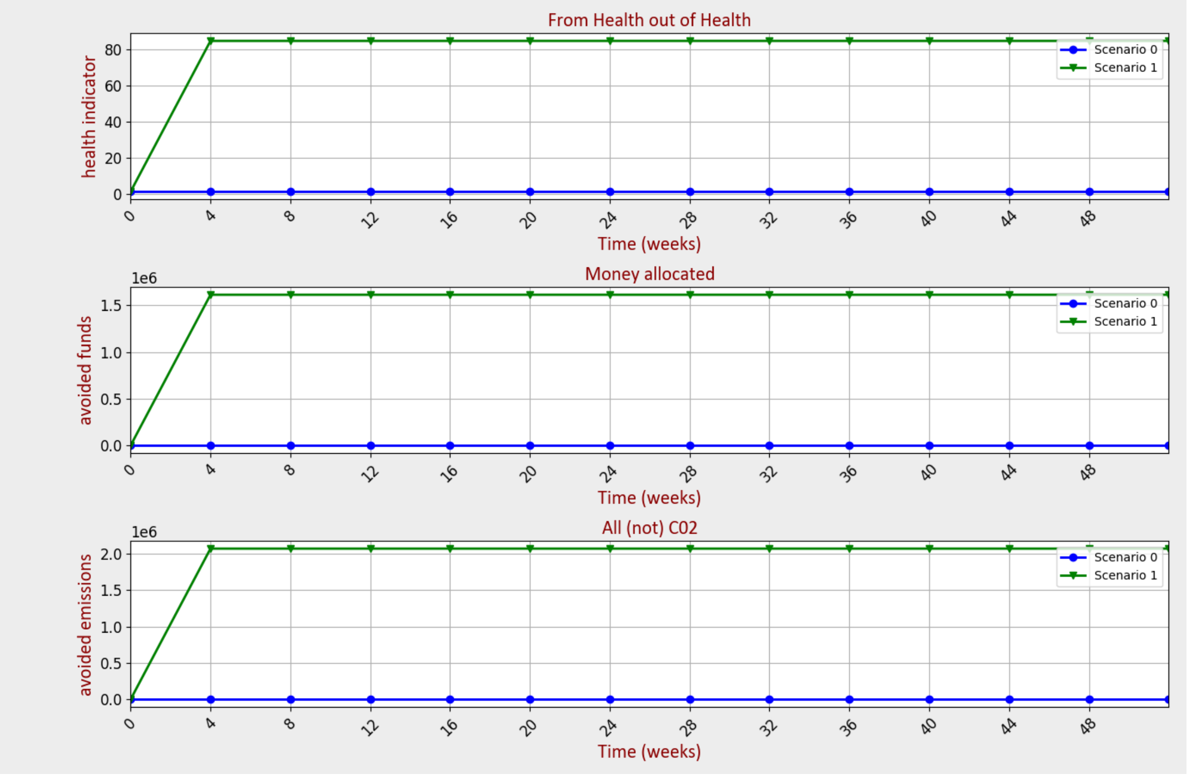


Figure 5-59 - Model 3 - Industry Cell

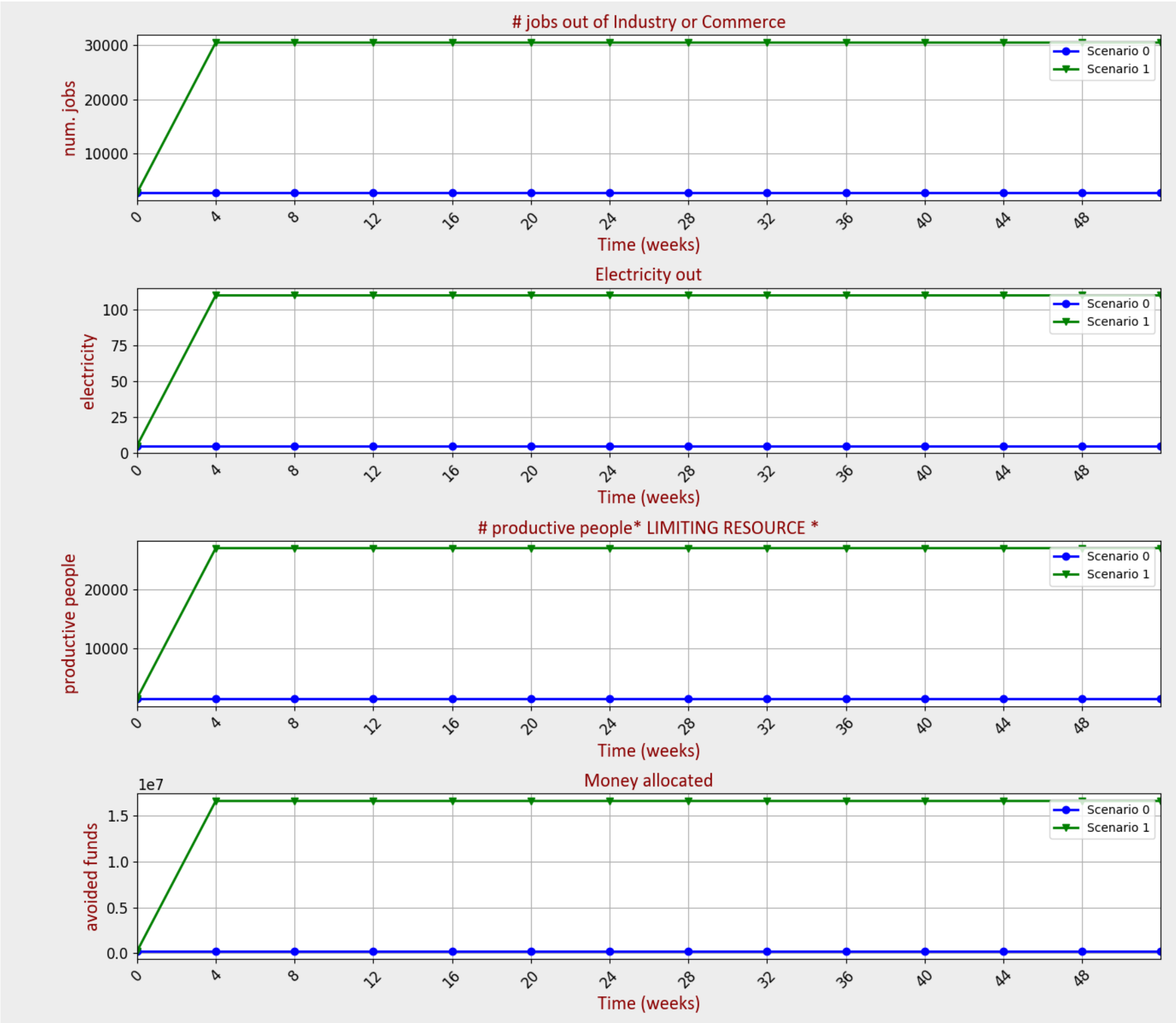


Figure 5-60 - Model 3 - Population Cell

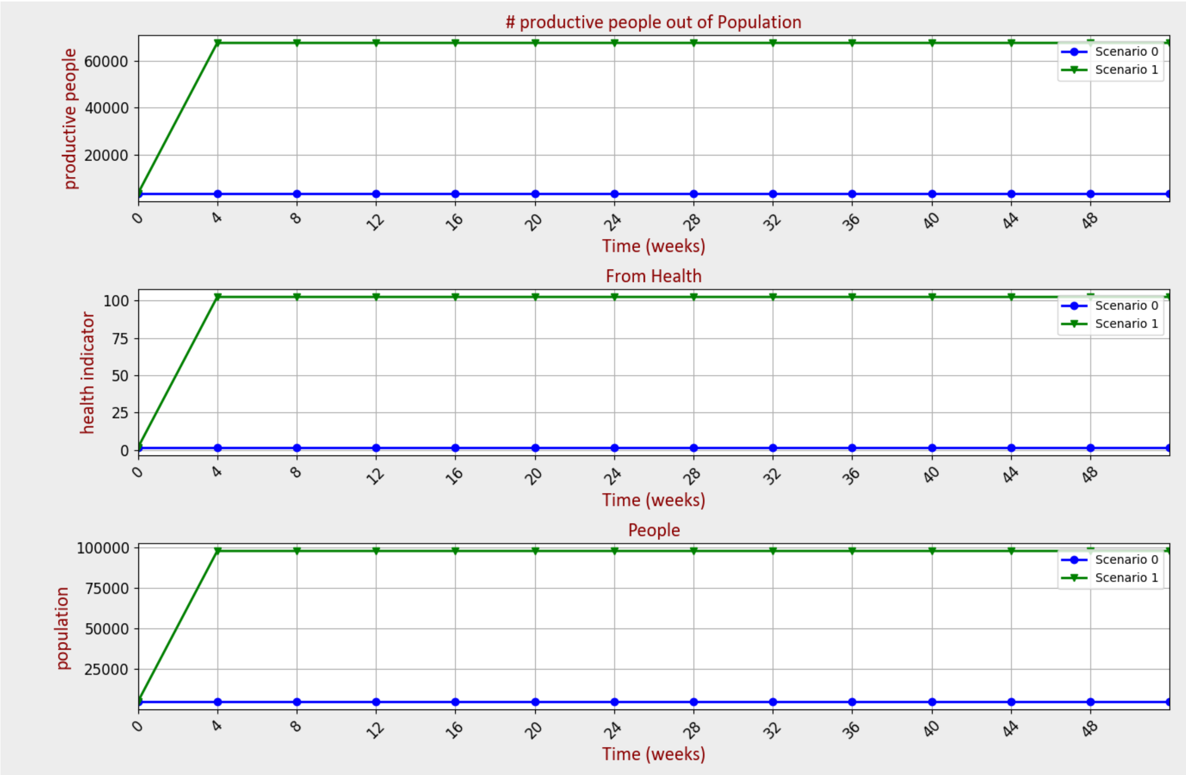


Figure 5-61 - Model 3 - Power Systems Cell

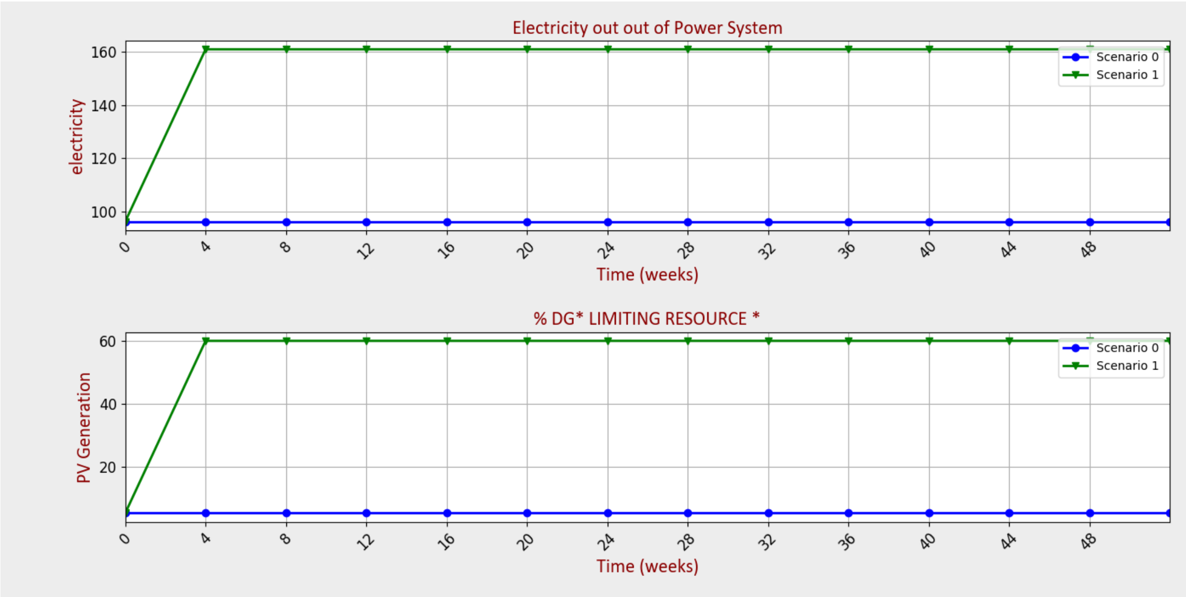


Figure 5-62 - Model 3 - Private Transportation Cell

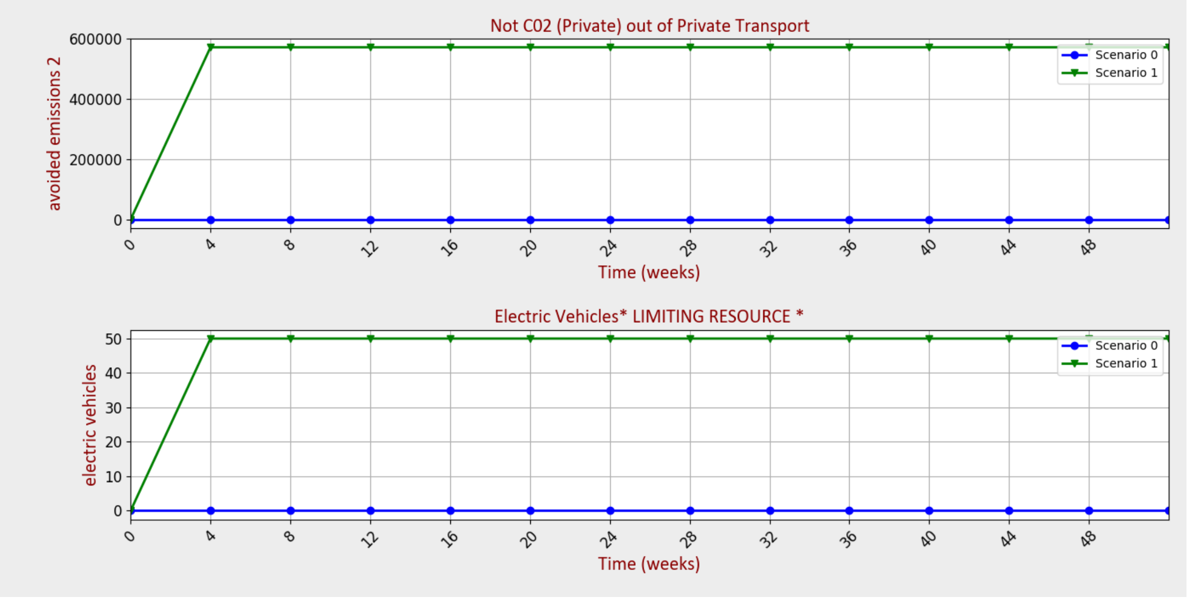


Figure 5-63 - Model 3 - Public Transportation Cell

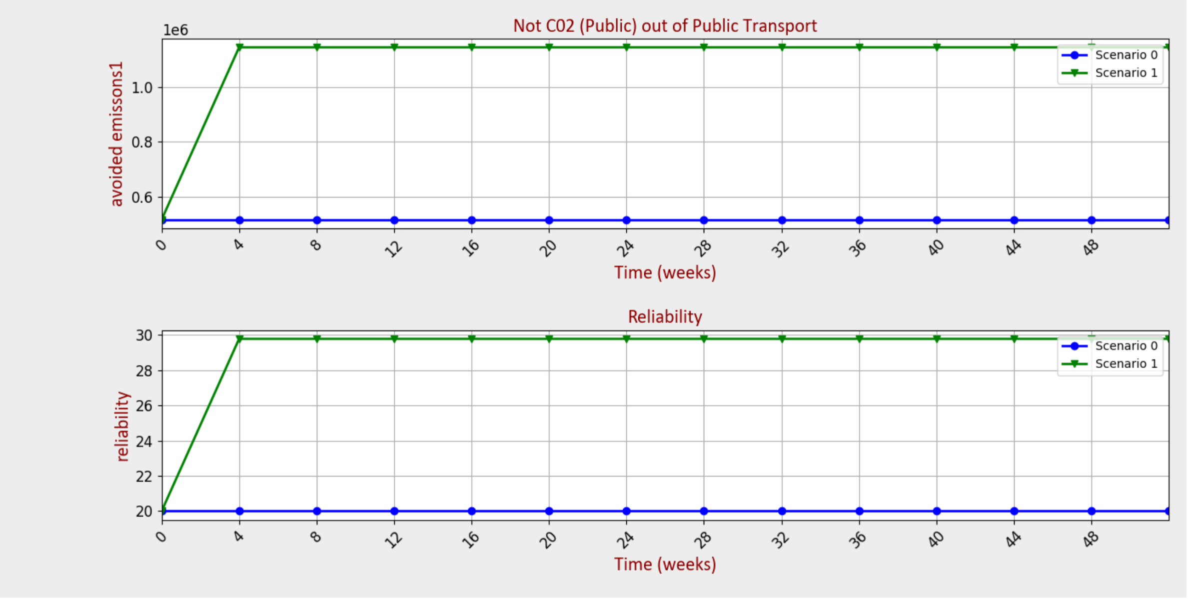


Figure 5-64 - Model 3 - Residents Cell

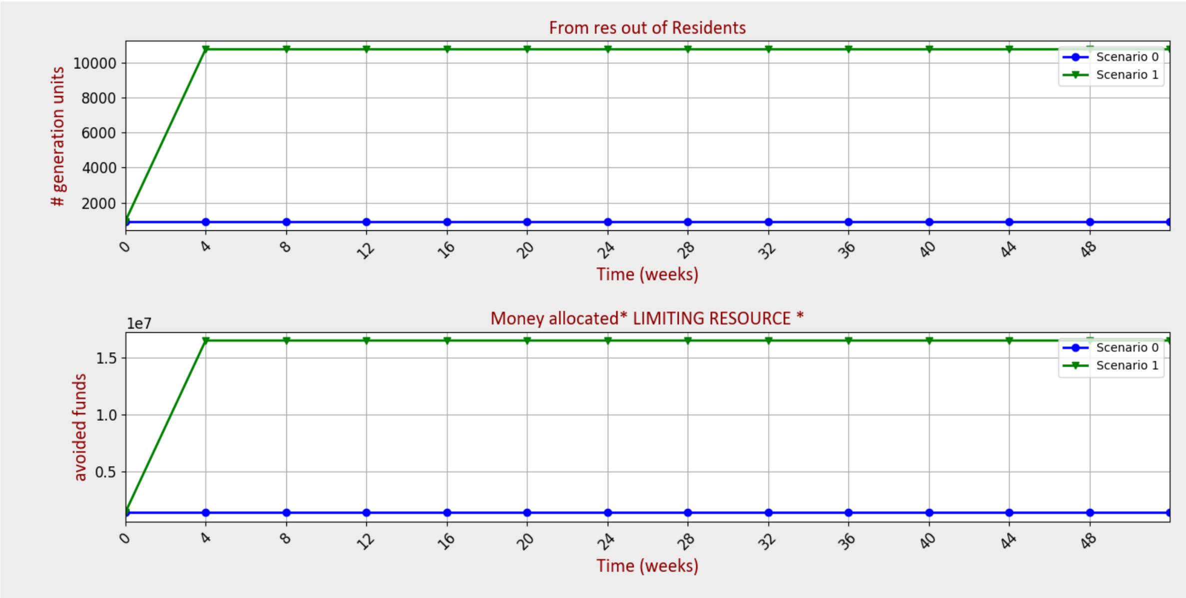


Figure 5-65 - Model 3 - Safety Cell

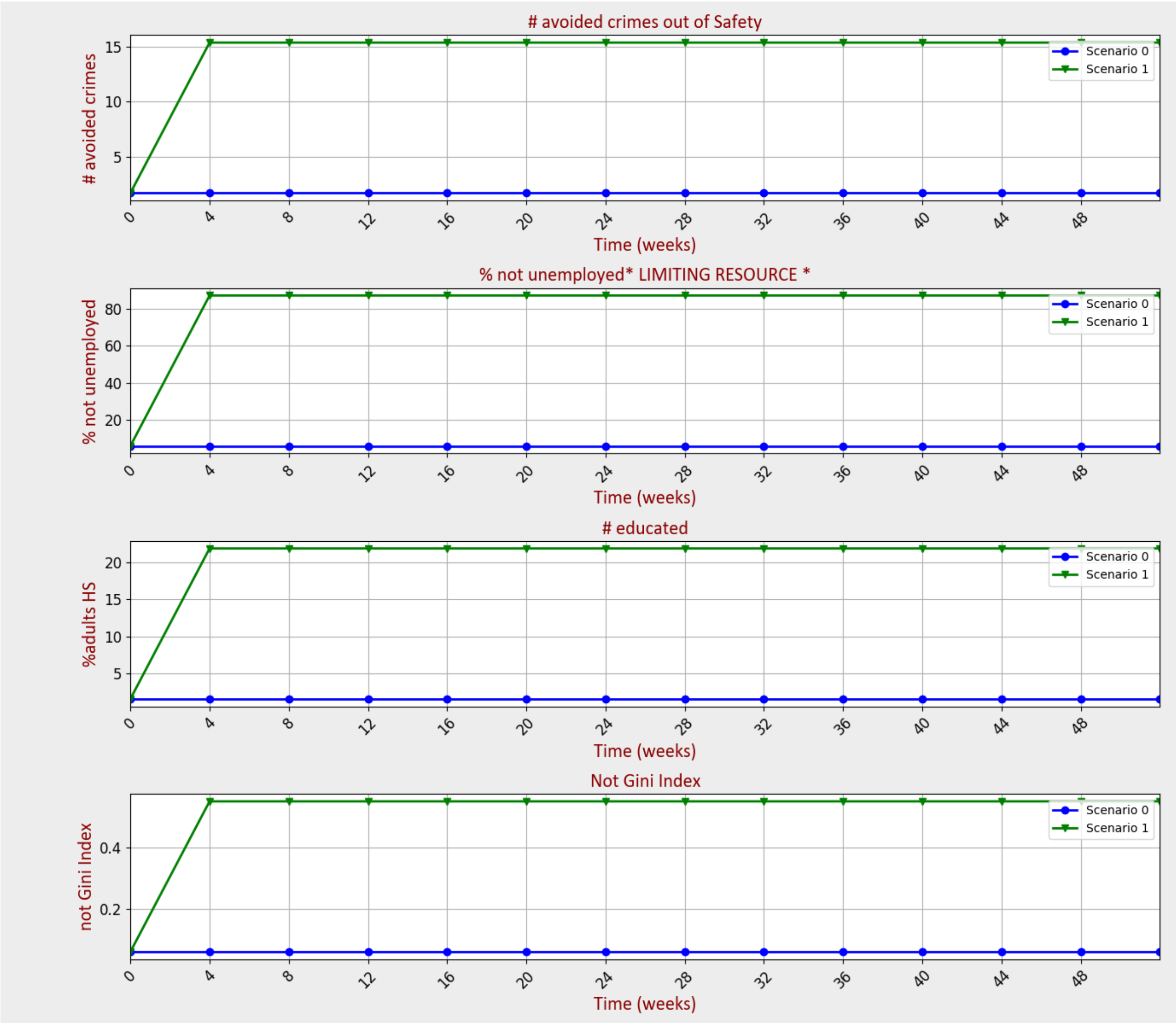


Figure 5-66 - Model 3 - Unemployment Cell

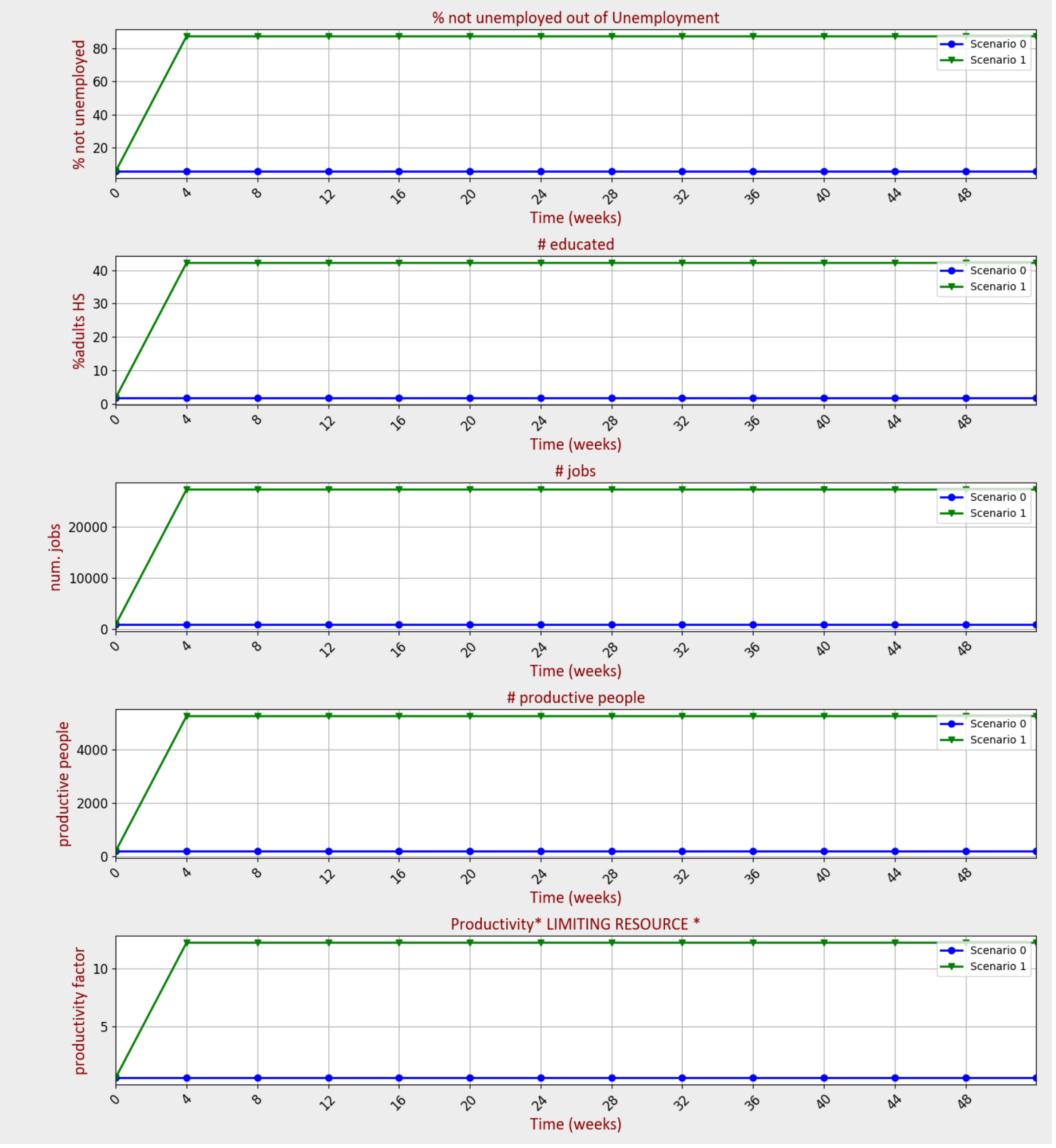
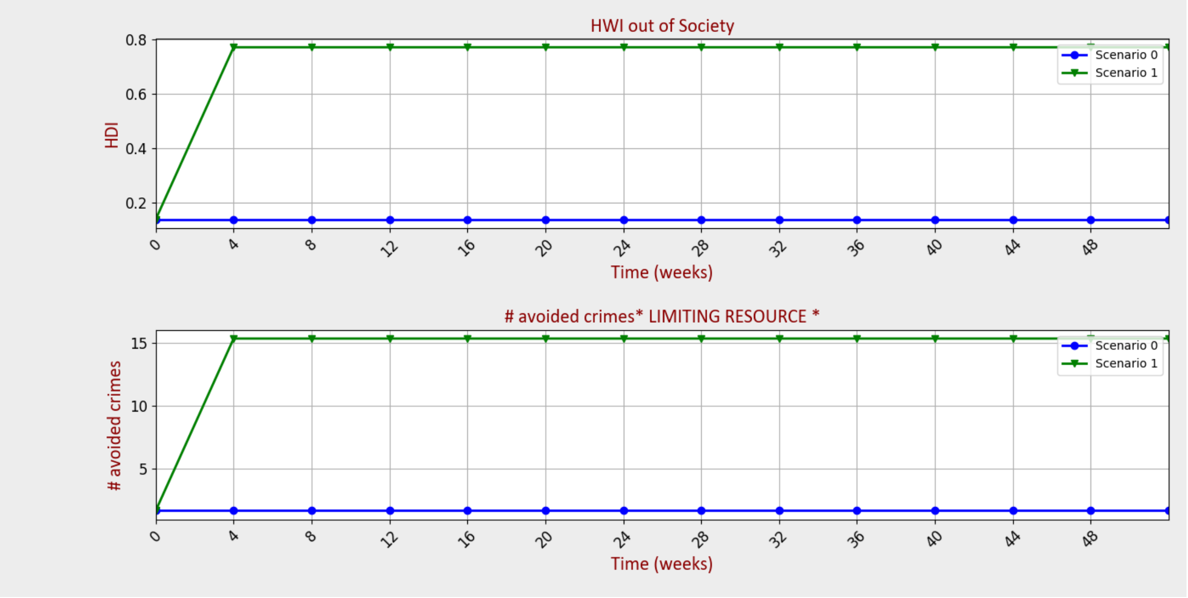


Figure 5-67 - Model 3 - Society Cell



5.8.1.1. Analysis

So far, this has been the best scenario. It is possible to see that all of the cells were able to operate at a higher operability level. The inputs of the system were increased to a point where they do not seem too unfeasible and at the same time they are able to induce significant changes in all the cells through interdependency. In other words, it was possible to make the Society cell work at 50% with the least amount of EVs. However, the limiting resource now is the productivity factor.

5.9. Model 3 – 2023

Since the results from the last simulation have proven to be very satisfying, the same scenario and model were projected to the year of 2023. For this, the values used to populated the HRTs were projected following the predicted population increase for this year.

5.9.1. Base Scenario - 2023

For the Base scenario, the results obtained are presented as follows:

Figure 5-68 - I2Sim Interface - Base Scenario - Model 3 2023

5.9.1.1. ANALYSIS

It is possible to see that it does not differ much from the results of 2022. The model still works very representatively and Private Transporation remains a critical limiting resource that consequently limits most of the other cells due to interdependency.

***5.9.1.* SCENARIO 1 – 2023**

Since the results of Scenario 4 for the 2022 model was satisfying, it was chosen to be simulated again but with 2023 projected values. It considers that 60% of the load is covered by DG, 50% of the fleet is electric and the reliability of the public transportation system is at 50%. The results are presented in the following figure.

Figure 5-69 - I2Sim Interface - Scenario 4 - Model 3 2023

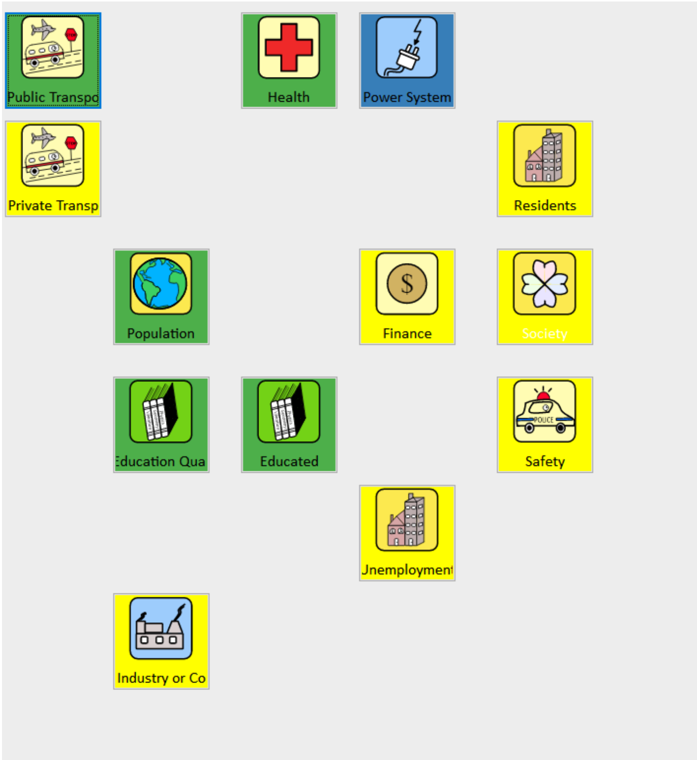


Figure 5-70 - Model 3 - 2023 - Finance Cell

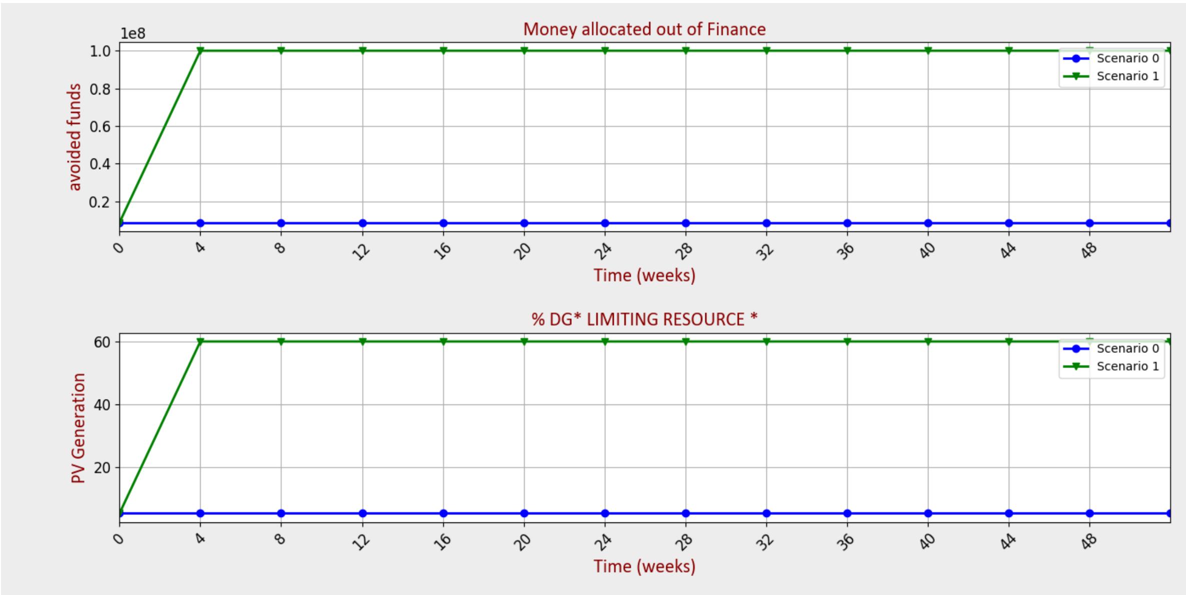


Figure 5-71 - Model 3 - 2023 - Health Cell

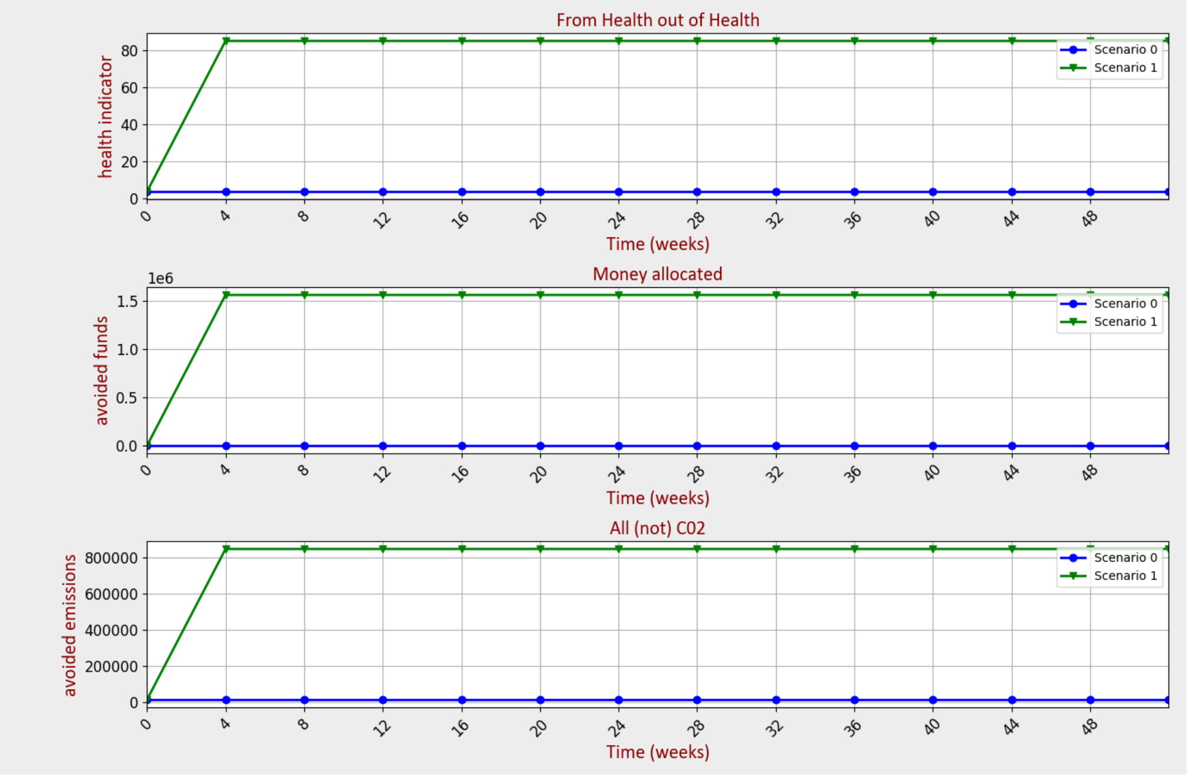


Figure 5-72 - Model 3 - 2023 - Industry and Commerce Cell

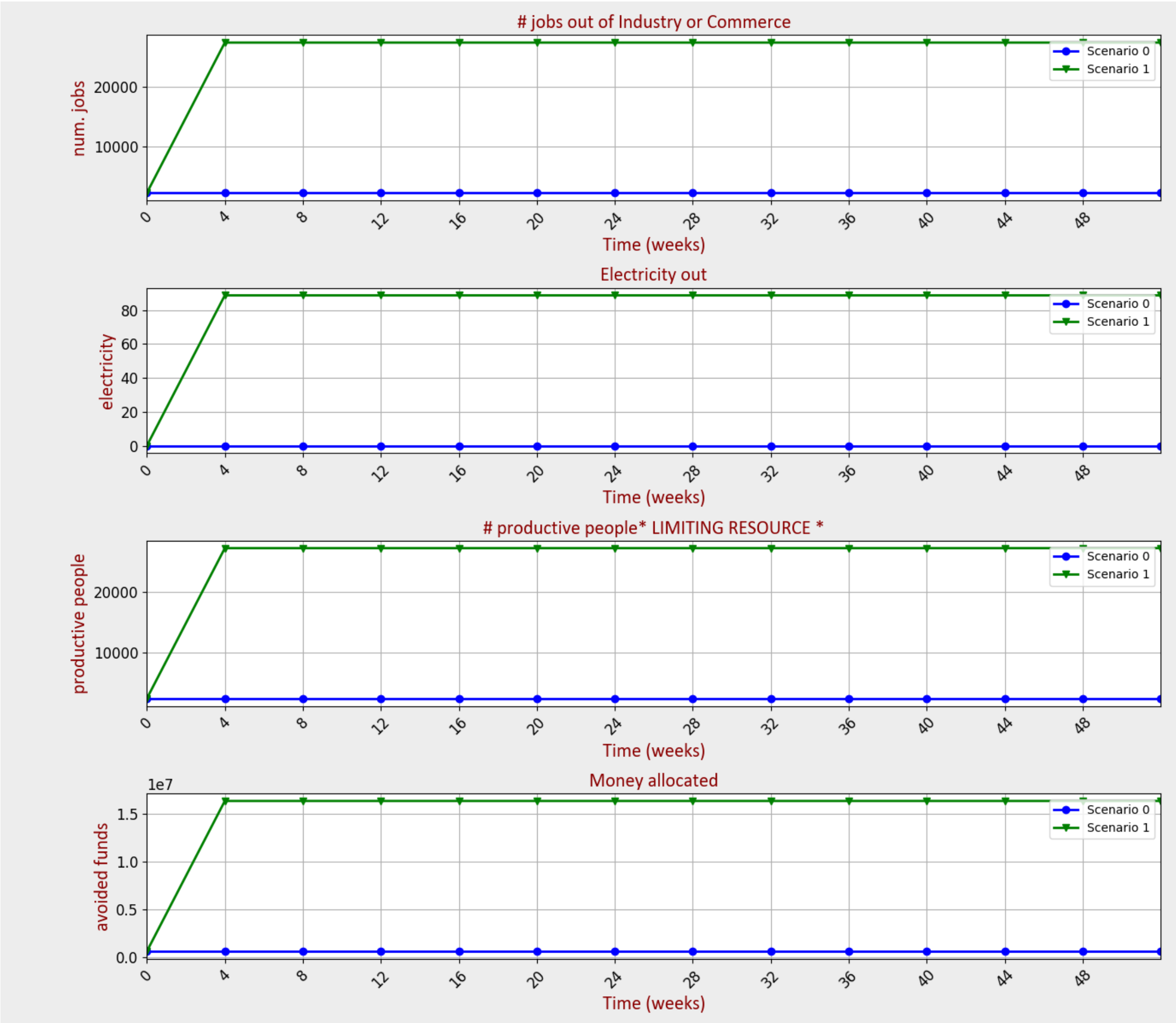


Figure 5-73 - Model 3 - 2023 - Population Cell

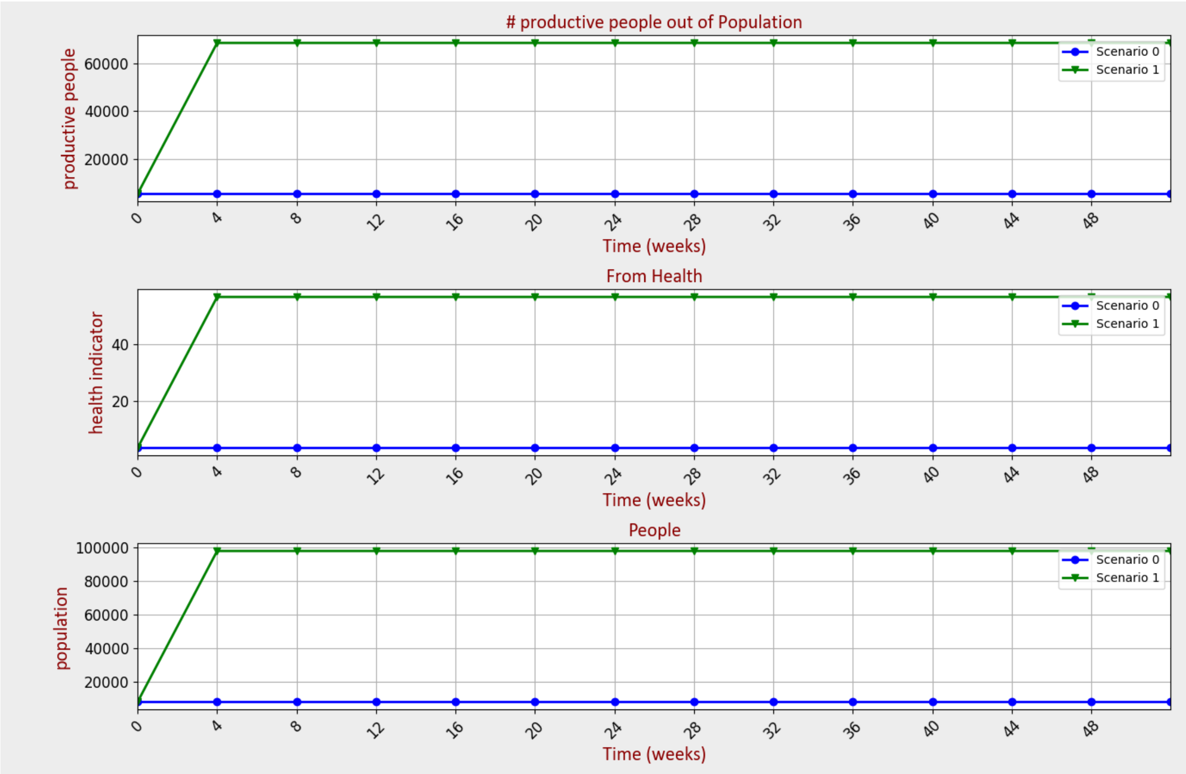


Figure 5-74 - Model 3 - 2023 - Power Systems Cell

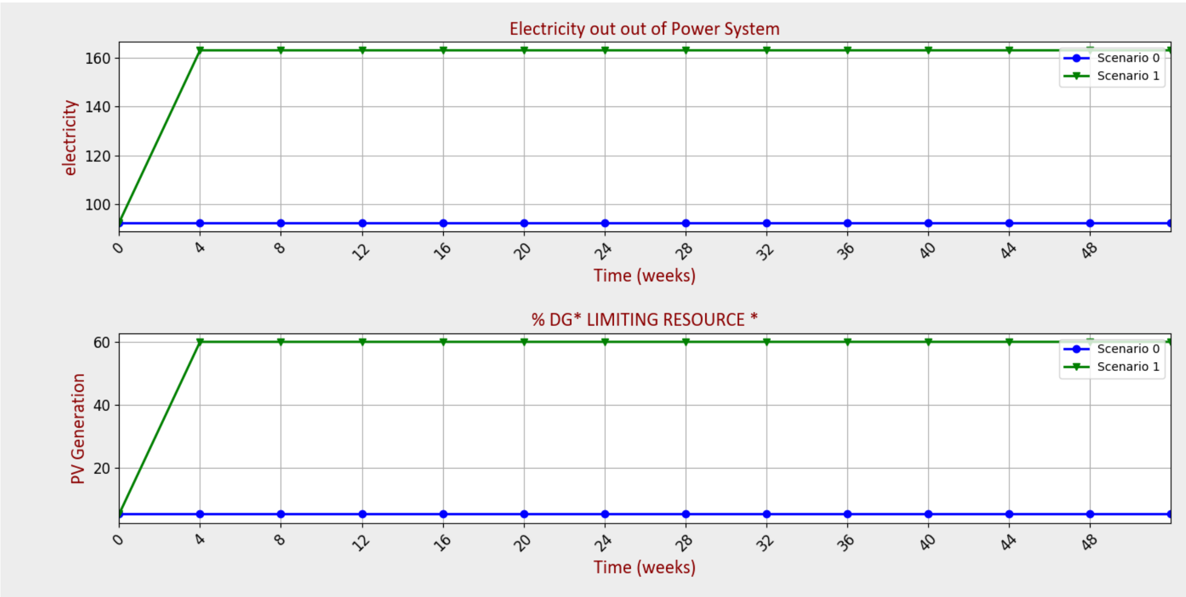


Figure 5-75 - Model 3 - 2023 - Private Transportation Cell

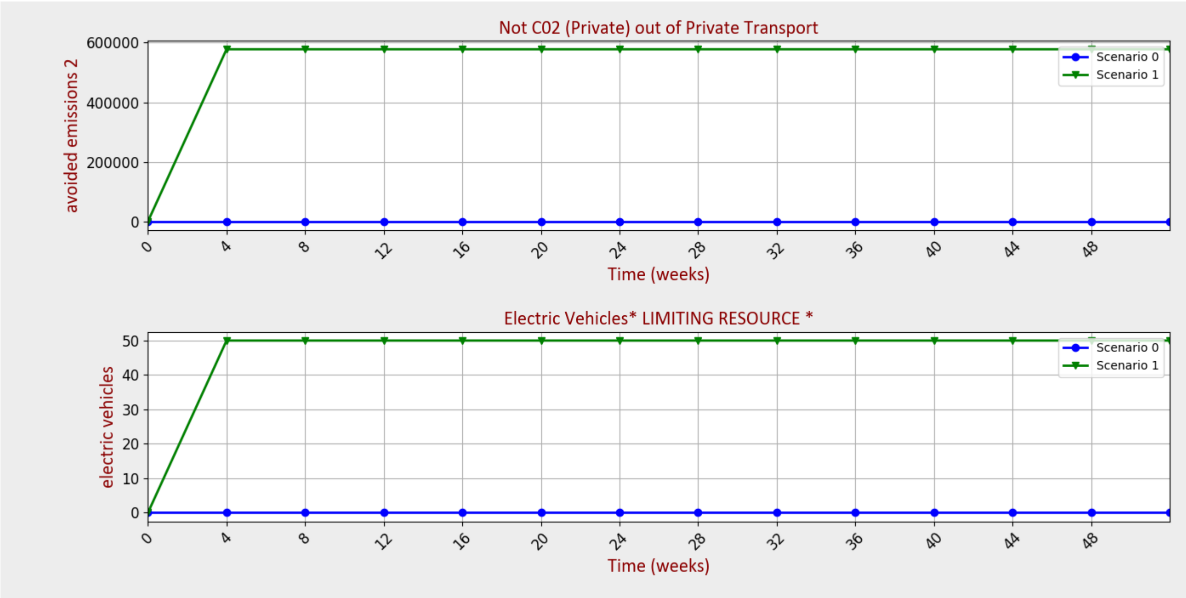


Figure 5-76 - Model 3 - 2023 - Public Transportation Cell

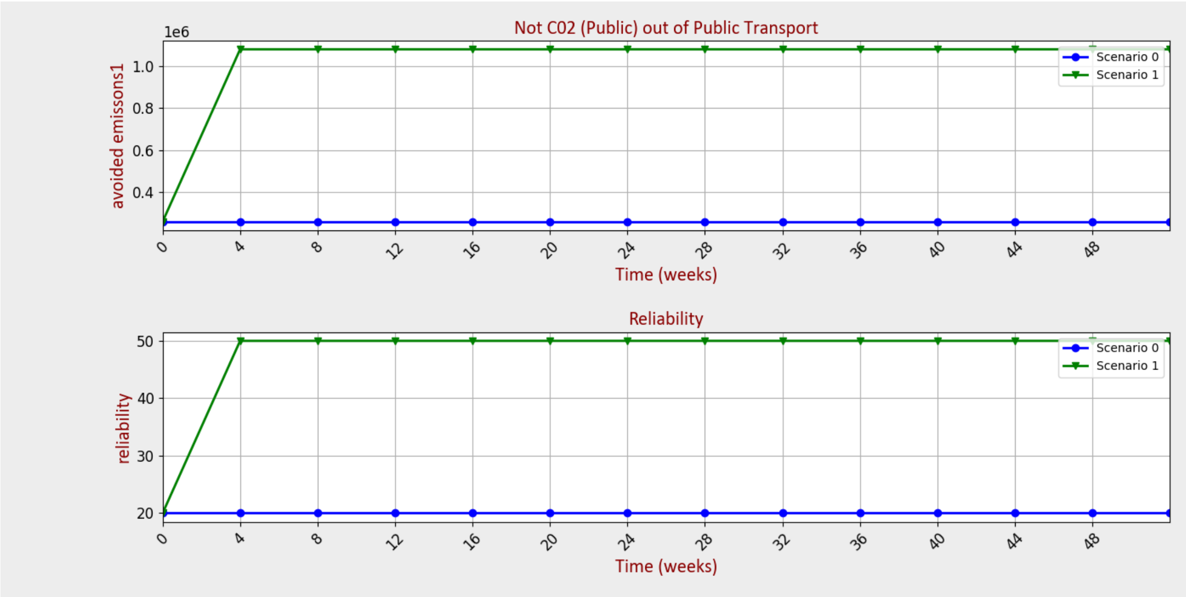


Figure 5-77 - Model 3 - 2023 - Safety Cell

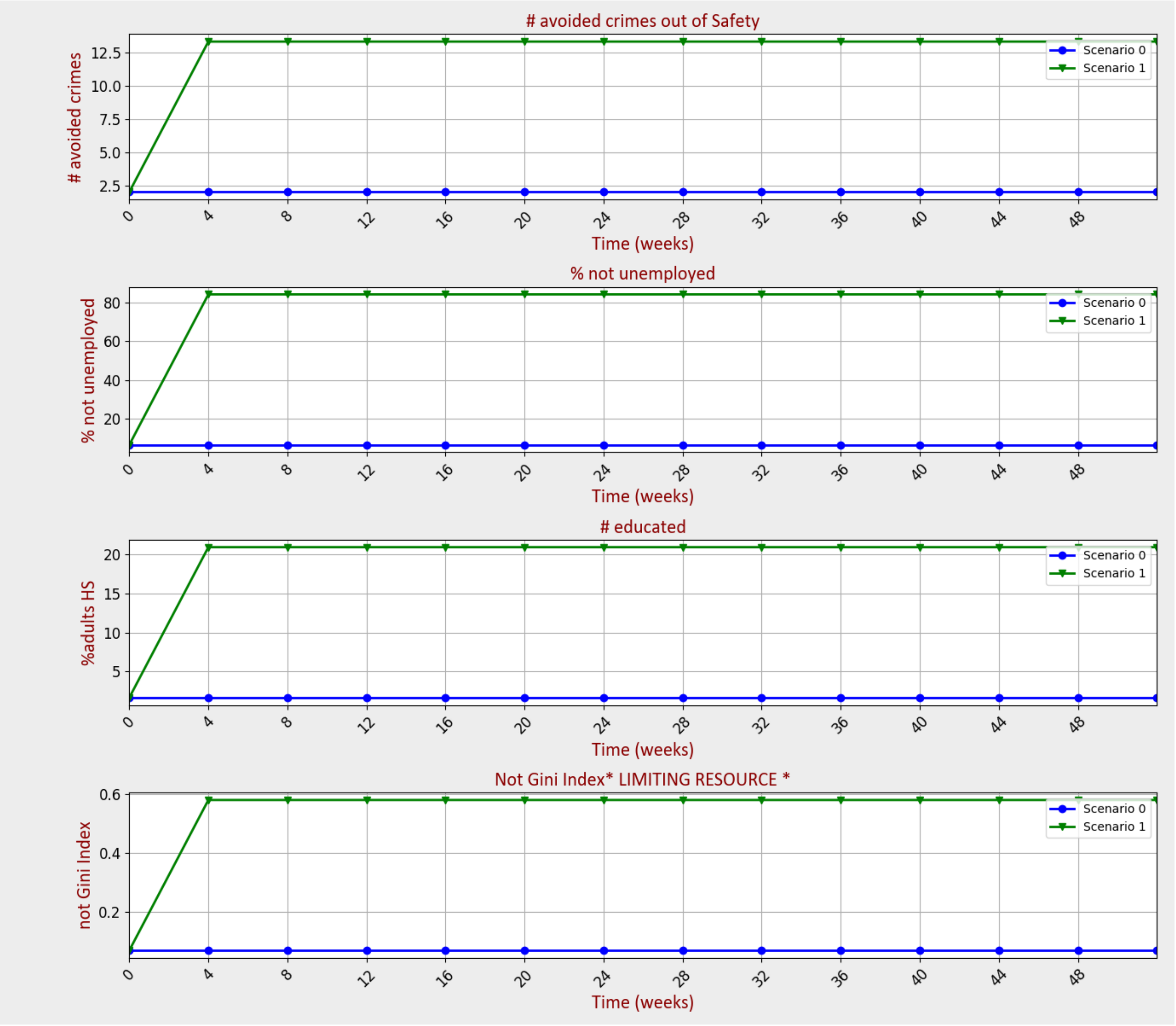


Figure 5-78 - Model 3 - 2023 - Unemployment Cell

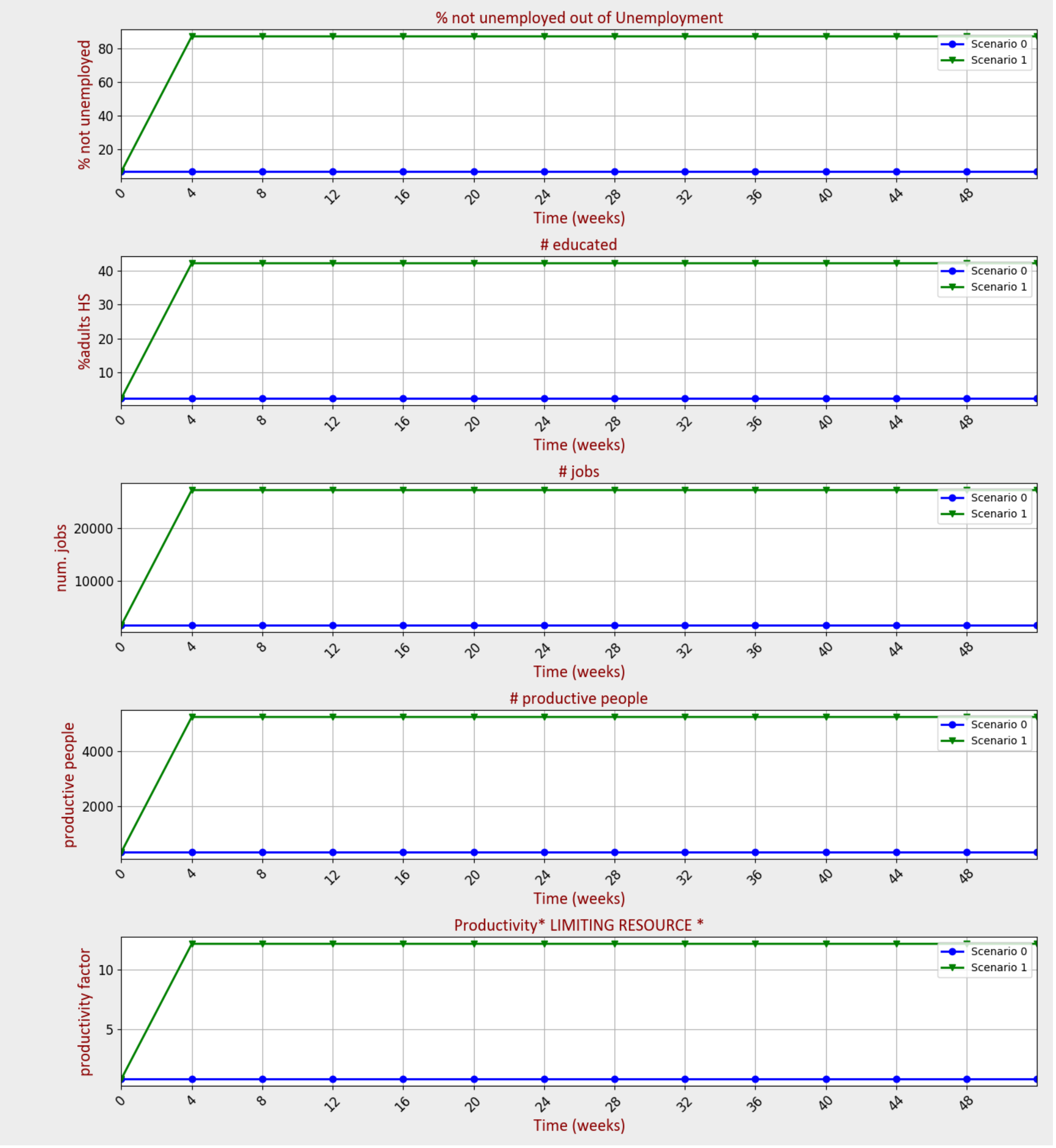
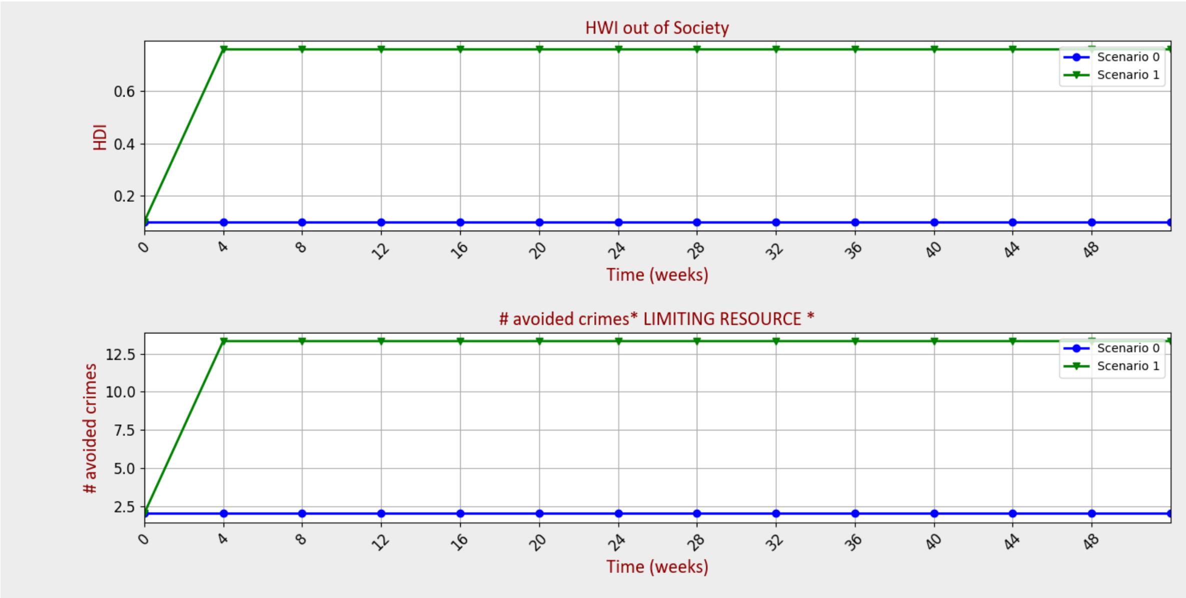


Figure 5-79 - Model 3 - 2023 - Society Cell



5.9.1.1. Analysis

It is clear that the operability level of the cells increased considerably. However, the limiting resource in this case becomes the safety cell, that is limited by the Gini Index. In other words, if the income distribution does not improve over time the overall society development is limited by it. Therefore, equality is as important as the other measures adopted to promote development.

5.10. Conclusion

In this chapter, through evaluating different scenarios with different levels of distributed generation, electric vehicles, distribution rates among the critical infrastructures, and also many other socioeconomic indicators, a methodology was proposed to help decision makers of public policies to incentive the increasing rates of PV generation in the system, by evaluating the impact that it has on the many distinct aspects of society that compose the Human Development Index.

To summarize, the behavior of the model led to the following conclusions:

- If the penetration of PV generation increases, the number of jobs increases, leading to an increase in employment and a decrease in crime rates;

- Also, by increasing the percentage of EVs, CO_2 emissions decrease, increasing the quality of health and increasing the people able to work, which also increases employment and, therefore, decreases crime rates;

- By deploying PV Generation, it increases the avoided energy costs, and this money can be reinvested to increase the quality of education, consequently increasing the percentage of adults educated, which increases employment and decreases crime;

- Broadcasters work as if other sources were created to repeat the information from that distributor. In this case, they were actually decoupling the model and creating inherent linear dependency throughout the system.

In conclusion, the decisions of allocating DG throughout the system are not only technical but also socio-economic. Furthermore, the best method for evaluating the optimal assessment of PV deployment should be based on a holistic approach, considering infrastructure interdependency for decision-making.

6. CONCLUSION

This chapter reviews and summarizes the research carried out, identifies the main methods used and discusses their implications for the study.

The study and modeling of the interdependent relationships among cities´ critical infrastructures can provide not only optimal action plans for extreme events scenarios but also provide effective and strategic long-term planning to optimize the system towards the desired goal, which is the case of this research. This work provides a reliable model of the systems in a developing city using the software I2SIM that aims to represent the interdependent relationships in it, along with its variables, inputs, outputs, and possible modifiers. This plan will hopefully pave the way for the economic and energetic development of the city towards making it a smarter city and also showing that it is possible to make smart the existing, not planned, developing cities

This dissertation, for example, focused on developing a sophisticated understanding of the close interconnections between energy and development for incentives for Distributed Generation and Electric Vehicles. The model was based on the investigation of the interdependency existing among Critical Infrastructures Systems. The developed system can be used by policymakers and help them throughout the decision-making process.

In summary, it was possible to get to the following conclusions:

- The Reliability of the Public Transportation System is a vital factor for Health Indicators in the long term. Therefore, it also affects the number of people available to work since some health conditions are strictly related to GHG emissions. This means that improving the quality, optimizing travel fares, and broadening the range of routes (all drivers of reliability) are essential aspects that can work as transition tools to the process of achieving the actual benefits of Electric Vehicles and Distributed Generation;
- Observing the current percentage of PV deployment in each of the systems, it was possible to conclude that if the current ratio of PV generation in each infrastructure remains the same, in other words, if the PV generation just increases enough to follow the load increase predicted, the

infrastructures with less penetration of DG will become limiting resources and consequently prevent the society from benefit from the gains that the Smart Grids Techs have to offer. For this specific case, increasing the share of Health Systems of DG was a step towards the solution;

- The quality of Education was an expected limiting resource since the current indicators show a very constrained rate. The path to improving education quality using the avoided costs from electricity seems a viable one; however, it would have to be addressed now in order to get long-term results;
- The current people available to work were also a limiting factor. To put it differently, the current unemployment rate was a crucial limiting resource. It means that if the current rate persists, the lack of human resources for the implementation of full penetration of PV could only be overcome by the increase in population over the years. The improvements in Health indicators through the adoption of Electric Vehicles and the increase in the reliability of public transportation could increase this number slightly;
- Even the models showing a high penetration of DG or EV as the optimum way for decision-makers, the scenario must fit the city's reality; That is to say, it is crucial to evaluate the feasibility of such measures and then decide on the optimal path between its constraints, that in the case of developing countries are much bigger than others. Those could be the infrastructure necessary for the adoption of such technologies and also technical aspects such as control of frequency stability and measures to avoid grid congestion;
- In brief, it suggests that the link between renewable energies and structural changes are key elements for a just transition. Moreover, there is an urgent need for a holistic approach to the deployment of DG and Electric Vehicles, so the long-term results can be optimized.

After those considerations, it is intended that this work can be a tool to shed light on the complexity of this group of combined systems. Only when systems are broken down into their core natures and the connections among these pieces become more transparent the root of the troubles can emerge. It is only through finding this root that one can begin to diagnose and rebuild the system [44].

6.1. FUTURE RESEARCH

For further research, it is suggested the following branches of this work:

- Investigate the possible use of optimization methods in I2SIM to identify development drivers, limiting resources, and major restrictions;
- Investigate the possible use of stochastic methods in selected parameters of I2SIM to calculate risks;
- Investigate the possible overall calculation of economic impacts of selected decisions on public policies and their associated risks;
- Adapt the modeled schematic for a disaster scenario simulation (flood, lightening, etc.), changing the timescale of events to optimize the system to minimize losses and lives;
- Decrease the timescale of this study to analyze the impact that smart lighting has on public safety;
- Include other varieties of renewable deployment;
- Continue the simulations to observe the long-term behavior of the system in the following years.

6.2. PUBLISHED PAPERS BY THE AUTHOR

- Barros Scianni Morais, Lucas; Costa, Vinicius; Freire, Paulla; Vilas Boas Pappi Maciel, Natália; Silva, Patricia; Bonatto, Benedito Donizeti; Ribeiro, Paulo. Smart Optimization of Power System Operation with Renewables and Energy Storage Systems. In: ANAIS DA XIV CONFERÊNCIA BRASILEIRA SOBRE QUALIDADE DA ENERGIA ELÉTRICA, 2021, online. Campinas-SP: Galoá-SBQEE,2021. v. 1.

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- Vilas Boas Pappi Maciel, Natália; Zambroni de Souza, Antonio Carlos; Ribeiro, Paulo Fernando. “ELECTRIC GARBAGE TRUCKS: A STEP TO SMARTEN CITIES”, International Conference “Advances in Renewable and Clean Energy Technologies” – ARCT, Online. Itajubá-MG, June 7th to 10th, 2022.

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