FEDERAL UNIVERSITY OF ITAJUBÁ
POSTGRADUATE PROGRAM IN ELECTRICAL ENGINEERING
ELECTRICAL POWER SYSTEMS

MASTER'S THESIS

PHOTOVOLTAIC PLANTS, RAINWATER STORAGE AND NATURE-BASED SOLUTIONS TO GENERATE ENERGY AND COMBAT SOCIOENVIRONMENTAL PROBLEMS: A CASE STUDY IN THE CITY OF ITAJUBÁ

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Itajubá
2025

PABLO ENRIQUE ANTUNES GUEDES

Ficha catalográfica elaborada pela Biblioteca Mauá
e Seção Técnica de Informática, ICMC/USP,
com os dados inseridos pelo(a) autor(a)

A924u

Antunes Guedes, Pablo Enrique
Usinas fotovoltaicas, armazenamento de água da chuva e soluções baseadas na natureza para geração de energia e combate a problemas socioambientais: um estudo de caso na cidade de Itajubá / Pablo Enrique Antunes Guedes; orientador Antonio Carlos Zambroni de Souza; coorientadora Eliane Valança Nascimento de Lorenci. -- Itajubá, 2025.
91 p.

Dissertação (Mestrado - Programa de Pós-Graduação em Engenharia Elétrica) -- Universidade Federal de Itajubá, 2025.

1. sistemas dinâmicos. 2. energias renováveis. 3. geração fotovoltaica. 4. captação de água da chuva. 5. soluções baseadas na natureza. I. Zambroni de Souza, Antonio Carlos, orient. II. Valança Nascimento de Lorenci, Eliane, coorient. III. Título.

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Thesis presented as a partial requirement for obtaining the degree of Master's in electrical engineering in the area of electrical power systems
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Itajubá
2025

ACKNOWLEDGEMENT

First and foremost, I would like to thank my mother, Geralda, and my father, Cláudio, whose support, wisdom, and encouragement made it possible for me to pursue this master's degree and complete this dissertation. They continually inspire me, challenge me, and motivate me to give my best in everything I do and to become a better person.

With all my love and gratitude, I thank my dear friend, mentor, and supervisor, Professor Dr. Antonio Carlos Zambroni de Souza. His passion for life is inspiring, and it is evident in everything he does, in his lectures, in our conversations, and in everyday life. To me, he is what an engineer should be, and he encourages me to be the same. His expertise and knowledge of the subject, combined with his dedicated way of teaching, make learning a true pleasure. Above all, he treats people with respect and kindness, seeing everyone as they are: human beings worthy of dignity and care. I am deeply grateful for the time we shared and for his guidance, not only throughout this dissertation, but also in life, helping me grow both as a student and as a person.

I also extend my sincere thanks to the other members of the examining committee—Eliane (my co-supervisor), Bruno, and Cláudia—for their valuable contributions to my dissertation, as well as for their mentorship and generosity in sharing their knowledge. They are, and will always be, an inspiration in my pursuit of learning.

I am grateful to my wife, Renata, who shares life with me and is always by my side supporting me, comforting me in difficult moments, keeping me company, and giving me her love. Without her, I would not be who I am.

Last, but certainly not least, I would like to thank all my friends who, directly or indirectly, supported me throughout this master's program and helped me remain happy and confident in life, knowing I have people close to me who wish me well, cheer for my success, and share their affection with me. In particular, I am especially grateful to Luís, who – beyond being a dear friend – went out of his way to be there on the day of my defense, sharing that moment with me. I record his name here with an honorable mention in my acknowledgments.

“We don't own this place, though we act as if we did
It's a loan from the children of our children's kids
The actual owners haven't even been born yet
But we never tend the garden and rarely we pay the rent
Most of it is broken and the rest of it is bent
Put it all on plastic and I wonder where we'll be when the bills hit
(...)
I'm dumpin' my trash in your back yard
Makin' certain you don't notice really isn't so hard
You're so busy with your guns and all of your excuses to use them
Well, it's oil for the rich and babies for the poor
We got everyone believin' that more is more
If a reckoning comes, maybe we will know what to do then
(...)
All these complications seem to leave no choice
I heard the tongues of billions speak with just one voice
Saying, "Just leave all the rest to me I need it worse than you, you see"
And then I heard the sound of one child crying
Today I went walking in the amber wind
There's a hole in the sky where the light pours in
I remembered the days when I wasn't afraid of the sunshine
But now it beats down on the asphalt land
Like a hammering blow from God's left hand
What little still grows cringes in the shade till the nighttime
We can run but we can't hide from it
Of all possible worlds we only got one we gotta ride on it
Whatever we've done
We'll never get far from what we leave behind
Baby, we can run, run, run, but we can't hide
Oh no, we can't hide”

John Barlow / Brent Richard Mydland

ABSTRACT

In contemporary cities, constrained and unequal access to reliable, affordable energy limits opportunity and reinforces socio-environmental disparities. A broader view is therefore required—one that links energy access to regional economy, demography, and environmental quality—so that interventions can be designed to reduce vulnerability and improve welfare. Existing power-sector models capture capacity expansion or dispatch but seldom assess how cleaner supply interacts with population growth, economic output, and ecosystem conditions over long horizons. This dissertation develops an integrated framework that combines a unit-commitment–inspired energy layer with a Wonderland-style system-dynamics model, extending the model to represent renewable penetration, abatement, and nature-based solutions (NbS). Using Itajubá as the reference system (population 96,632; annual electricity demand 251,110.95 MWh), the analysis quantifies the growth of renewable energies and nature-based solutions. Three policy scenarios are simulated—No changes, intermediate renewable integration, and full integration with smart grid and NbS—over multi-decadal scales to reveal expected co-evolutionary patterns. Results show that moderate action bends the pollution trajectory and slows environmental degradation, while a comprehensive portfolio more clearly reduces emissions intensity, buffers natural-capital losses, and supports a higher, more stable economic path, even though total renewables remain below full self-sufficiency. A complementary economic appraisal indicates positive net present values, an atractive Internal Rate of Return (IRR) for photovoltaic (PV) and Rainwater Harvesting (RWH), and a Levelized Cost of Energy (LCOE) for PV (0.44 BRL/kWh) below the prevailing tariff, indicating feasibility. The evidence supports a portfolio of distributed renewables, NbS, and abatement as a credible route to a cleaner, more resilient, and socially inclusive urban system.

Keywords: system dynamics; renewable energies; photovoltaic generation; rainwater harvesting; nature-based solutions; sustainable development; system engineering

RESUMO

Nas cidades contemporâneas, o acesso limitado e desigual a energia confiável e acessível restringe oportunidades e aprofunda disparidades socioambientais. Torna-se, portanto, necessária uma visão mais ampla — que conecte o acesso à energia à economia regional, à demografia e à qualidade ambiental — para que intervenções sejam concebidas de modo a reduzir vulnerabilidades e melhorar o bem-estar. Modelos tradicionais do setor elétrico capturam expansão de capacidade ou despacho, mas raramente avaliam como uma oferta mais limpa interage, ao longo do tempo, com o crescimento populacional, a produção econômica e as condições dos ecossistemas. Esta dissertação integra um módulo energético baseado em *unit commitment* a um modelo Wonderland de sistema dinâmico, ampliado para representar a expansão de renováveis, o abatimento de emissões e Soluções Baseadas na Natureza (SbN). Utilizando Itajubá como referência (população de 96.632 habitantes; demanda anual de 251.110,95 MWh), a análise quantifica a expansão de energias renováveis e de SbN. Três cenários de política são simulados — Sem mudanças, integração intermediária de energias renováveis e integração plena com rede inteligente (smart grid) e SbN — por um período de 50 anos, para observar os padrões de evolução ao longo do tempo. Os resultados indicam que ações moderadas alteram a influência da poluição, reduzindo seu ritmo de crescimento e desacelerando a degradação ambiental, enquanto um conjunto integrado de medidas reduz de forma mais clara a intensidade de emissões, atenua as perdas de capital natural e leva a uma trajetória econômica mais elevada e estável — embora a participação de renováveis ainda não alcance a autossuficiência. A avaliação econômica realizada indica valores presentes líquidos positivos, uma Taxa Interna de Retorno (TIR) atrativa para energia solar e para captação de água de chuva, e Custo Nivelado de Energia (LCOE) para sistema fotovoltaico de 0,44 BRL/kWh, inferior à tarifa vigente, indicando viabilidade. As evidências indicam que a combinação de renováveis distribuídas, SbN e ações de redução de emissões é um caminho viável para um sistema urbano mais limpo, resiliente e socialmente inclusivo.

Palavras-chave: sistemas dinâmicos; energias renováveis; geração fotovoltaica; captação de água da chuva; soluções baseadas na natureza; desenvolvimento sustentável; engenharia de sistemas

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LIST OF ABBREVIATIONS

AC – Alternate Current
CadÚnico – Cadastro Único para Programas Sociais
CEMADEN – Centro Nacional de Monitoramento e Alertas de Desastres Naturais
CSP – concentrated solar power
DC – Direct Current
EM-DAT – Emergency Events Database
EU – European Union
FAO – Food and Agriculture Organization
IBGE – Instituto Brasileiro de Geografia e Estatística
IGAM – Instituto Mineiro de Gestão das Águas
IEA – International Energy Agency
IRR – Internal Rate of Return
IUCN – International Union for Conservation of Nature
kW – Kilowatt
kWh – Kilowatt-hour
LCOE – Levelized Cost of Energy
LID – Light Induced Degradation
NGO – Non-governmental Organization
NbS – Nature-based Solution
OECD – Organisation for Economic Co-operation and Development
PV – Photovoltaic
RWH – Rainwater Harvesting
UN – United Nations
WCED – World Commission on Environment and Development
WEO – World Energy Outlook
WMO – World Meteorological Organization

SUMMARY

1. Introduction

Among the many challenges facing the world today, few are as critical or as complex as the issue of energy. Meeting the growing demands of a rising global population, while maintaining improved living standards, presents a formidable task. Achieving this without further intensifying the risks of climate disruption poses an even greater challenge. It necessitates a substantial departure from the historical reliance on fossil fuels and a comprehensive transformation of the global energy system. The limited timeframe required for the transition to a low-carbon economy further heightens the difficulty of this endeavor (Kessides; Wade, 2011).

Currently, considering the development of smart devices, there is a great interest in integrating smart solutions and interfaces into the existing network and infrastructure to improve the quality of service, solve existing problems, diversify the matrix and guarantee access for everyone. The goal of smart devices is to share information with/from other devices to make smart decisions while having the ability to be integrated into current infrastructures as much as possible (Farmanbar *et al*., 2019). The world is going through a process of urbanization, and according to the World Cities Report 2022, published by UN-Habitat, 68% of the world's population lives in urban areas. Urbanization, however, occurs in an accelerated and disorderly manner. The lack of urban planning has caused the proliferation of serious structural and social problems, such as slums, lack of infrastructure, violence, pollution of all types, and unemployment, among many others. Smart cities have been highlighted in recent years and are suggested by several researchers as an optimal solution to overcome urbanization problems and the demands of this process. Intelligence has been approached as the desire to improve the quality of life in cities and the residents who live in them from various points of view, using information and communication technology; however, in this context, it refers not only to technological issues but also encompasses both the intelligent integration of all infrastructures and socioeconomic functions and the intelligent transition from its current state to its desired future (Meijer; Bolívar, 2015). This future can only happen through an intelligent utilization of human, financial, and technical resources, simultaneously addressing environmental, demographic, social, infrastructure, and economic challenges, along with all their interrelationships (Andersson, 2020; Vacca, 2020). This new vision and approach to the urban environment requires a holistic perspective of thinking where everything is related, and all areas must be thought of together and not individually. This is not only due to the need to integrate multiple points of view and different disciplines but also to the wide range of interested agents and users (individual citizens, companies, public authorities, common areas, administrators, among others). Therefore, a smart city is a vision of a sustainable, fair, and resilient urban area (Ferreira *et al*., 2023; Masera *et al*., 2018; Neffati *et al*., 2021; Samarakkody; Amaratunga; Haigh, 2022). Resilience, in this context, refers to the ability of systems, communities, or environments to anticipate, adapt, and recover from adverse conditions while maintaining essential functions and structure. It encompasses strategies that mitigate risks, enhance sustainability, and promote long-term stability in the face of challenges such as urbanization, environmental degradation, and climate change.

Cities can exacerbate some of the world's most pressing environmental and socioeconomic challenges, while urban infrastructure and citizens increasingly face vulnerability. In the context of smart cities, Nature-based Solutions (NbS) play a crucial role by addressing fundamental environmental issues through the reintegration of ecosystem services into urban spaces, restoring balance between cities and their surrounding areas. By incorporating NbS into the development of smart cities, decision-makers can help urban areas adapt more effectively to the impacts of climate change, reduce the urban heat island effect, lower cooling needs in buildings, improve air quality, and manage water resources sustainably (Moura; Hrysyki; Branco, 2024). This leads one to think this problem as a smart grid enabling smart cities. In this sense energy demand may implicate in a number of actions, including the management of garbage for environmental and energy purposes.

1.1. Justification

While urbanization brings significant advantages such as economic growth and innovation, it also presents a range of complex challenges. Rapid urban expansion increases resource demands, heightens energy consumption, raises greenhouse gas emissions, and accelerates the degradation of natural ecosystems (United Nations, 2014). As a result, cities often become hubs of environmental pollution, traffic congestion, and limited access to essential services, including clean water and sanitation (Intergovernmental Panel on Climate Change, 2007). Additionally, the growing risks of flooding and landslides, exacerbated by extreme weather events driven by climate change, highlight the urgent need for innovative solutions in urban development.

According to the International Energy Agency’s (IEA) World Energy Outlook (WEO) 2023, significant shifts currently underway are expected to result in a considerably different global energy system by the end of this decade. The rapid rise of clean energy technologies—

such as solar, wind, electric vehicles, and heat pumps—is transforming the way energy is used across industries, transportation, and households. The 2023 edition of the WEO envisions an energy landscape by 2030 where clean technologies play a much more prominent role. Projections include nearly 10 times the number of electric cars on the road, solar photovoltaic (PV) systems generating more electricity than the current entire U.S. power grid, and renewables approaching a 50% share of the global electricity mix, up from approximately 30% today. Furthermore, heat pumps and other electric heating systems are predicted to outsell fossil fuel boilers globally, while investment in new offshore wind projects is expected to triple that of new coal- and gas-fired power plants (International Energy Agency, 2023).

Scientific studies carried out since the second half of the 20th century have consistently demonstrated the accelerated consumption of non-renewable resources, the planet's inability to regenerate itself at the same rate and the serious problems resulting from this process for various ecosystems.

In order to address the pressing environmental and societal challenges facing the modern world, it is essential to understand and explore the potential contributions of renewable energy sources, smart cities, and nature-based solutions. Renewable energies offer sustainable alternatives to fossil fuels, significantly reducing greenhouse gas emissions while promoting energy security and mitigating climate change impacts.

By optimizing infrastructure, energy consumption, transportation, and public services, smart cities can greatly enhance resource efficiency and improve the overall quality of life for residents. Leveraging innovative technologies and data-driven systems, smart cities play a crucial role in transforming urban environments. Through the integration of digital technologies with urban planning, these cities can streamline energy use, develop more efficient transportation networks, and improve waste and water management. This leads to reduced pollution and lower resource consumption. Additionally, smart cities promote inclusivity, economic growth, and social equity, creating more efficient, livable, and adaptable urban spaces that support both environmental sustainability and the well-being of their citizens.

Nature-based solutions, which leverage natural processes and ecosystems to address societal challenges, play a vital role in fostering a more equitable and resilient society. These solutions improve air and water quality, mitigate the urban heat island effect, and enhance stormwater management, all while promoting biodiversity. Additionally, NbS strengthen resilience by offering protection against climate-related hazards, such as flooding and landslides, making them a crucial component in adapting to the impacts of climate change and supporting sustainable urban development.

By integrating renewable energy, smart city technologies, and nature-based solutions, societies can move toward a more resilient, sustainable, and fair future. These approaches collectively address critical issues related to climate change, resource depletion, and urbanization while promoting social equity and environmental justice for all.

1.2. Objectives

The general objective of this dissertation is to address problems related to unrestrained growth combined with a need for more urban planning using consolidated technologies and smart cities. The purpose is to combine different solutions such as solar power plants, rainwater harvesting (RWH) and Nature-based Solutions to mitigate the problems. Itajubá was used as a case study because the problems addressed can be observed in the city, such as power outages and floods. The city's accelerated urbanization has resulted in a significant expansion of its built environment, marked by the construction of taller buildings, alongside deforestation and emerging urban challenges. The proposed solutions seek to either mitigate these adverse effects or compensate for the environmental and infrastructural imbalances caused by this development.

1.3. Specific Objectives

1. Investigation of the potential for installing cisterns to capture Rainwater in existing buildings in Itajubá;
2. Assessing the potential for integrating photovoltaic systems in existing buildings to exploit solar energy;
3. Analyzing the capacity to store Rainwater, addressing flood mitigation, and evaluating its utility for non-potable needs;
4. Estimating the energy output from the photovoltaic systems within the available space in buildings;
5. Evaluating the feasibility of implementing both solutions.
6. Developing an integrated modeling framework that couples a simplified unit-commitment module with a Wonderland-style system-dynamics core (population, economic output, pollution, natural capital).

7. Calibrating the model with the data presented in this dissertation (population, demand, PV and RWH figures) and ensuring bounded/stable dynamics for meaningful long-run simulation.
8. Simulating policy scenarios (No Changes, Intermediate Renewable Integration, Full Integration with Smart Grid and NbS) to compare trajectories of economic output, pollution, and environmental quality and derive planning implications.

2. Literature Review

To meet the objectives outlined in this research, it is crucial to possess a thorough understanding of the real-world context surrounding the problem under investigation. The starting point is a deep exploration of the elements that define the issue, which is essential for identifying feasible strategies to address it. Consequently, the bibliographic review has been organized into five distinct segments: the first two sections focus on contextualizing the paradigm and challenges at both the global level and within the specific case of Itajubá. The final three sections concentrate on clarifying the concepts and characteristics of the proposed solutions, offering insight into their potential application.

Section 2.1 provides an overview on a global scale, as well as specific insights into Brazil and the city of Itajubá, establishing the problem context addressed in this dissertation. In turn, section 2.2, "Addressing the Problem", focuses on exploring the proposed solution concepts, presenting existing theories and practices that, when combined, offer substantial transformative perspectives given the complexity of the issues at hand.

This logical progression allows for identifying where the objects of study—smart cities, RWH, NbS, and renewable energies—along with their respective advantages and disadvantages, integrate into the analysis of the observed reality. Therefore, the literature review in this work seeks to explore the complexities of this reality, aiming to contribute to a deeper and more comprehensive understanding of the available strategies to address the challenges at hand.

2.1.Overview of the problem

2.1.1. World perspective

Population growth refers to the increase in the number of people on Earth. Throughout most of human history, the global population remained relatively stable. However, innovations in industry, energy production, food, water availability, and medical care have led to significant population increases. This rapid growth continues today, with profound impacts on global climate and ecosystems. Technological and social innovations will be essential to support the world's population as we adapt to and mitigate environmental changes (United Nations, *[S.d.]*).

Population forecasts and scenarios serve as critical tools for planning and risk management for governments, businesses, NGOs, and individuals. Governments rely on short- and mid-term scenarios to project the need for public services, such as schools and hospitals, and to inform infrastructure investments with long-term benefits. These forecasts also help plan for future workforce needs and guide investments in all areas. Long-term population scenarios are crucial for understanding potential environmental, geopolitical, and societal risks, allowing for the implementation of preventive or mitigation strategies (Mahtta *et al*., 2022).

Human population growth affects the Earth's systems in multiple ways:

- It increases the extraction of natural resources such as fossil fuels, minerals, trees, water, and wildlife, especially from the oceans. This extraction process often releases pollutants that degrade air and water quality, harming both human health and ecosystems.
- It amplifies the burning of fossil fuels for electricity, transportation, and industrial processes, contributing to greenhouse gas emissions.
- It raises freshwater use for drinking, agriculture, recreation, and industry, leading to higher extraction rates from lakes, rivers, and underground reservoirs.
- It disrupts ecosystems through the construction of urban infrastructure, including homes, businesses, and roads. As urban areas expand, more land is converted for agriculture to meet the food demands of growing populations, reducing biodiversity and altering species interactions.
- It intensifies fishing and hunting activities, decreasing species populations and indirectly affecting ecosystems by altering resource availability.
- It increases the transportation of invasive species, either through trade or travel. These species often thrive in disturbed environments, outcompeting native species and altering local ecosystems.
- It accelerates the transmission of diseases, particularly in densely populated areas. With modern transportation, diseases can spread rapidly across regions.
- It leads to increased waste generation, contributing to environmental pollution and the degradation of ecosystems.

The global population has more than tripled since the mid-20th century, rising from approximately 2.5 billion in 1950 to 8 billion by mid-November 2022. The population is projected to increase by nearly 2 billion more by 2050, reaching 9.7 billion, and is expected to peak at 10.4 billion by the mid-2080s. This dramatic growth is largely due to improved survival rates to reproductive age, longer lifespans, increasing urbanization, and accelerating migration. Changes in fertility rates have also played a significant role, with far-reaching societal implications for future generations (Mahtta *et al*., 2022; United Nations, *[S.d.]*). While developed regions, such as Europe, face an aging population and a rise in its median age, many lower-income countries continue to experience rapid population growth. These contrasting dynamics present economic and social challenges, affecting labor markets, healthcare systems, and resource distribution on a global scale.

Today, most of the global population lives in urban areas, a trend that is projected to reach 68% by 2050. Urbanization contributes to biodiversity loss, increased material consumption, and climate change. Moving forward, urban planning must be inclusive and responsive to local communities' needs, incorporating participatory approaches that engage marginalized groups while ensuring access to essential services like water and sanitation. Achieving sustainable cities will require breaking down barriers between different levels of government, strengthening urban-rural linkages, and promoting decarbonization across the energy, transport, and construction sectors (Bansard, 2022).

As climate change increases the risks of more extreme events, making societies even more resilient will be crucial to prevent our recent progress from reversing. Achieving this requires a comprehensive understanding of how disaster events are evolving, identifying the most vulnerable populations, and determining effective strategies to protect them.

Energy production, closely linked to population growth, affects land productivity, land cover, and migration patterns. This underscores the importance of understanding the complex interactions between energy, urbanization, and population dynamics when planning for sustainable development (Avtar *et al.*, 2019). Addressing population growth in urban planning is crucial for building resilient, sustainable cities that accommodate growing populations while protecting the environment and enhancing quality of life.

In 2023, the World Meteorological Organization (WMO), responsible for monitoring Earth's land, water, and atmosphere, reported a fivefold increase in the number of natural disasters per decade from 1979 to 2019 (WMO, 2023). While many of these disasters remain unpredictable and unavoidable, the WMO highlights that global warming—largely driven by human activities, particularly the emission of greenhouse gases from burning fossil fuels—is intensifying the frequency of climate-related disasters. These include droughts, heatwaves, stronger hurricanes, and flooding exacerbated by rising sea levels. Warmer temperatures lead to more extreme weather patterns, with some regions experiencing heavier rainfall and snowfall, increasing the risk of floods, while other areas face heightened drought due to reduced precipitation.

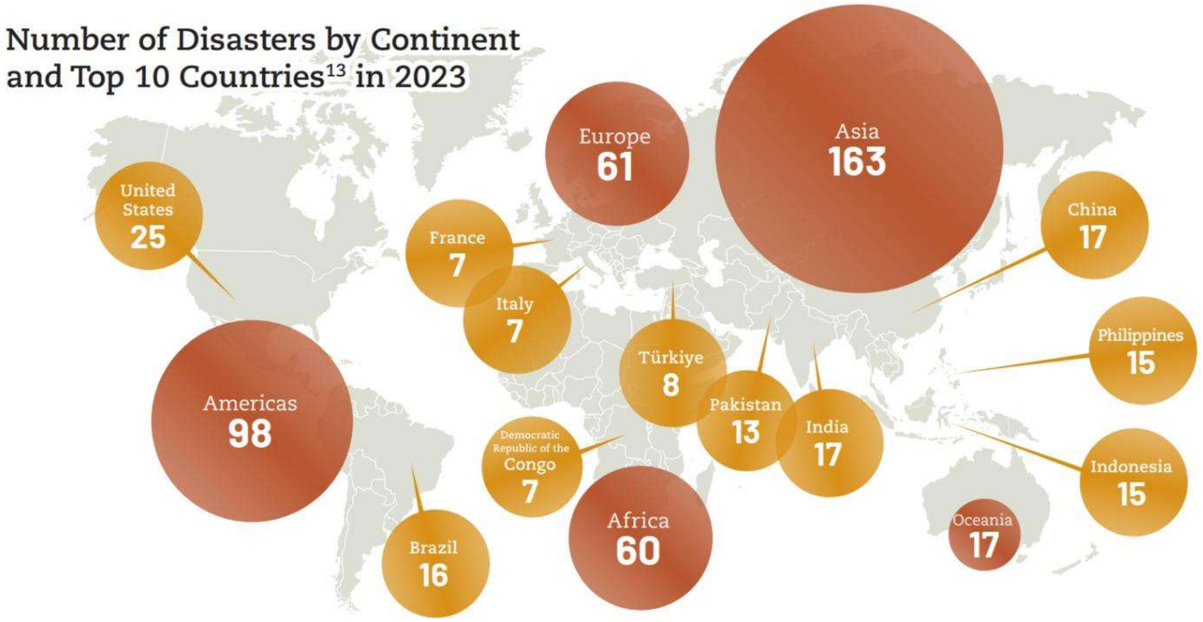
Despite global resilience remaining stable between 2021 and 2023, individual resilience declined significantly in nearly a third of the countries surveyed in the World Risk Poll

Resilience Index. This drop was largely attributed to a rise in the number of people—from 36% to 43%—who feel they are powerless to protect themselves and their families during disasters, indicating a widespread sense of diminished agency (Lloyd's Register Foundation, 2024).

The percentage of the global population experiencing natural hazard-related disasters in the past five years increased from 27% to 30%, primarily due to the rising frequency of floods. Additionally, 30% of those affected by disasters in the last five years reported receiving no prior warning. Vulnerable groups—such as those living in rural areas, with lower levels of education, or less financial stability—were particularly less likely to be informed. However, over 77% of individuals who received no warning owned a mobile phone, presenting a critical opportunity to enhance early warning systems through mobile and cell-broadcast technologies (Lloyd's Register Foundation, 2024).

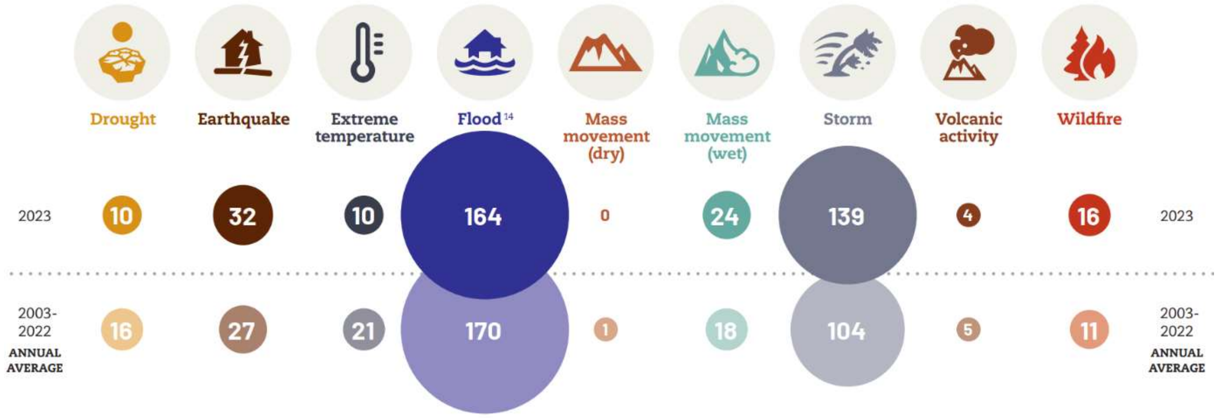
In 2023, the Emergency Events Database (EM-DAT) reported 399 disasters globally, all associated with natural hazards, excluding biological and extraterrestrial hazards, and recorded at the country level. These disasters caused 86,473 fatalities and impacted 93.1 million people worldwide, with economic losses totaling US$202.7 billion (Centre for Research on the Epidemiology of Disasters (CRED), 2024). Figure 1 illustrates the distribution of disasters by continent and highlights the top 10 countries with the highest disaster occurrences in 2023. Meanwhile, Figure 2 breaks down the disasters by type and compares the number of incidents to the annual average registered between 2003 and 2022.

Figure *1*: Number of disasters by continent and top 10 countries in 2023.



Source: CRED, 2024, p. 4

Figure 2: Occurrence by disaster type: 2023 compared to the 2003-2022 annual average.



Source: CRED, 2024, p. 4

Global climate change has recently become one of the most discussed topics by the international scientific community, mainly due to its profound environmental, economic, political and social implications. Concern about this issue can be attested to by the numerous studies published in recent years addressing the impacts and consequences of climate change, the main associated vulnerabilities and possible ways to minimize and adapt to the resulting scenarios (Cote, 2009).

2.1.2. Brazilian perspective

Overpopulated regions frequently experience social and economic pressures that can lead to the rise of conflicts. High population densities strain infrastructure, housing, and public services, often resulting in limited access to healthcare, education, and employment opportunities (UN-Habitat, 2022).

As of August 1, 2022, Brazil's population had reached 203,062,512 (IBGE, 2022). In the 150 years since the first census, the country's population has grown more than 20 times, representing an increase of 193.1 million inhabitants.

By 2022, 124.1 million people resided in urban concentrations, which include population arrangements or isolated municipalities with over 100,000 inhabitants. These arrangements consist of highly integrated municipalities, often overlapping to form larger spatial units. São Paulo, for example, serves as the core of a major urban concentration, encompassing 37 municipalities. Other examples include Belo Horizonte in Minas Gerais (23 municipalities) and Rio de Janeiro (21 municipalities) (IBGE, 2023).

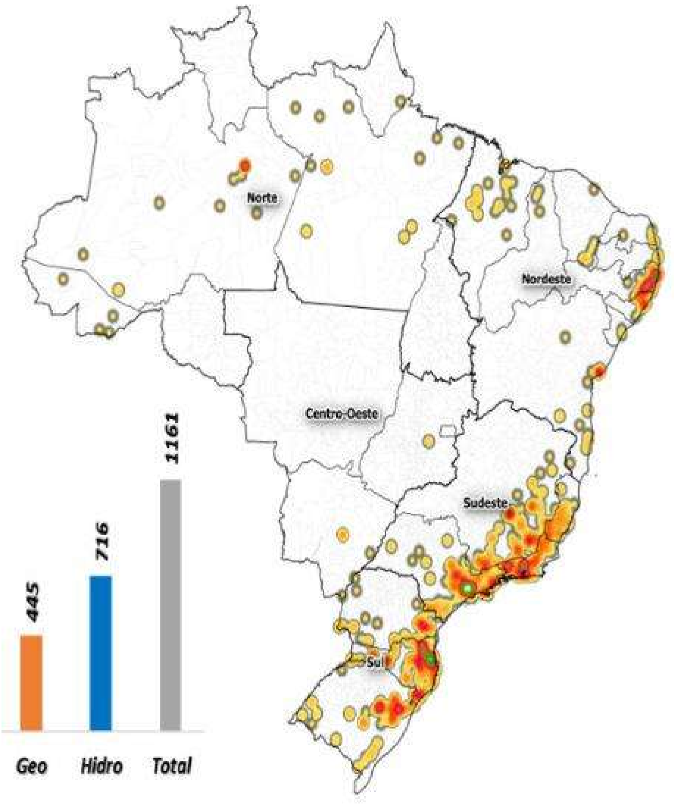
Since 1970, Brazil's demographic profile has shifted significantly from a predominantly rural and traditional society, characterized by large families and high infant mortality, to a largely urban society with smaller families and a restructured family dynamic (Leone; Maia; Baltar, 2010). These rapid changes demand swift and effective responses, which cannot be achieved without state intervention through the creation and implementation of essential public policies (Brito *et al.*, 2007).

In Brazil, around 85% of disasters are attributed to three main events: flash floods, landslides, and extended droughts (Pivetta, 2024). These occurrences are relatively common in tropical regions and their impacts can be significantly mitigated through the implementation of public policies aimed at reducing damage. Over the past five decades, more than 10,225 Brazilians have lost their lives to natural disasters, with most fatalities resulting from floods and landslides (Pivetta, 2016).

Climate simulation studies conducted by Brazilian researchers suggest that the risk of these water-related disasters will likely increase by the end of the century in most regions already affected. Additionally, new areas adjacent to those currently impacted by these events are expected to become vulnerable to similar risks. The effects are anticipated to intensify in the future due to climate change, urban expansion, and the increasing occupation of high-risk areas (Almeida; Welle; Birkmann, 2016).

Between January 2013 and December 2023, a total of 5,233 Brazilian municipalities were impacted by disasters, resulting in 64,742 declarations of a State of Emergency or Public Calamity. The majority of these declarations, 45,100 in total, were prompted by disasters related to either excessive or insufficient rainfall. Over this 11-year period, disasters caused an estimated 639.4 billion BRL in losses across Brazil (Confederação Nacional De Municípios, 2024).

Figure 3: Disaster ocurrencies in 2023.



Source: Brasil, 2024

In 2023, Brazil set a record for the number of hydrological and geohydrological disasters, with a total of 1,161 events reported. Of these, 716 were hydrological in nature, including river overflows, while 445 were of geological origin, such as landslides. These incidents largely followed the pattern of alert notifications, with a concentration in capital cities and metropolitan regions. Most of the disasters occurred in the eastern part of the country, as highlighted by Figure 3. The reported figures encompass events of varying magnitudes, without specific classification. Municipalities directly suffer the negative impacts of disasters, facing a range of human consequences including fatalities, injuries, homelessness, displacement, illnesses, and other detrimental effects on the physical, mental, and social well-being of affected populations. Additionally, the material damage is extensive, leading to the destruction of property, suspension of essential services, economic setbacks, and widespread environmental degradation.

2.1.3. Itajubá perspective

Itajubá is a municipality located in the southern region of Minas Gerais, Brazil, within the Southeast region of the country. As of July 2024, estimates from the Brazilian Institute of Geography and Statistics (IBGE) place its population at 96,632 inhabitants, with the vast majority (92%) residing in urban areas and only 8% in rural settings (IBGE, 2022). The city’s origins trace back to the 17th century during the expeditions of the bandeirantes in search of gold. Itajubá evolved from a small settlement into a village, eventually being officially founded as a city on March 19, 1819. Located along the Sapucaí River in the Serra da Mantiqueira, the city covers a territorial area of 294.835 km², with an urbanized portion of 19.51 km². Its strategic location between two major highways in Brazil, the Fernão Dias Highway and the Presidente Dutra Highway, allows Itajubá to exert a strong regional influence (Portal Itajubá, s.d).

The city is well-known across the country for its industrial contributions, boasting one of the largest industrial districts in the southern part of Minas Gerais. Itajubá also stands out for its educational excellence, home to notable primary and secondary schools, and highly regarded universities. Among its higher education institutions, the Federal University of Itajubá (UNIFEI), originally established as the School of Engineering on November 23, 1913, is particularly renowned (UNIFEI, s.d). This strong educational foundation has made Itajubá a center of academic distinction in Brazil.

The city’s urban development has been shaped by both political, sociocultural, and economic factors, as well as the unique characteristics of its natural environment. Itajubá's central area was founded at an elevation of 845 meters, slightly above the bed of the Sapucaí River, the main waterway for the municipality and the surrounding region. The landscape is further defined by the Serra da Mantiqueira mountain range, which reaches elevations of up to 1,900 meters at Pedra de Santa Rita (Portal Itajubá, s.d). The city's expansion has occurred both on the flat floodplains along the Sapucaí River and its tributaries—the Piranguçu and Anhumas streams on the left bank and the José Pereira stream on the right bank—as well as in the hilly areas with steep inclines.

Itajubá also exhibits notable socio-spatial inequalities throughout its urban landscape. These disparities stem from various factors that influence the valuation of specific areas, such as landscape quality, environmental conditions, access to infrastructure, proximity to key locations, and social status. Urban verticalization—initially prevalent in Brazil’s larger cities like São Paulo and Rio de Janeiro in the 1920s—began primarily with commercial and administrative buildings. It wasn’t until the 1940s that residential high-rises proliferated in the most desirable urban areas. In medium-sized cities like Itajubá, however, verticalization only began to intensify in the 1980s, reflecting broader urban development trends in Brazil (Andrade; Cunha, 2023). The city is currently experiencing a construction boom, reshaping its architectural landscape and creating a need for new infrastructure.

According to IBGE, it is estimated that the city of Itajubá has 11,23% of its properties verticalized, with approximately 3500 buildings in the city (residential, commercial, and public), with an average of 4 floors per building (approximately 12 meters high) and an average area of 200 m^2 per building (IBGE, 2022).

This resulted in an increase in the city’s economic wealth, the speed of expansion of the urban fabric, and the implementation of urban infrastructure in the region. With the introduction of neoliberal policies, from 1980 onwards, this process gained even more strength, marked by a policy of privatization and the concentration of wealth and services, which ended up socially destabilizing peripheral countries and releasing millions of people in informality. In Itajubá, the reality is no different. Unemployment rate, growth of informality, real estate speculation, lack of housing policy for the low-income population, and precarious public transport system are just some examples of the reasons for the growth of inequalities and slums in Brazil (Ferreira, 2019).

This shift has led to a systematic disorganization of public action, rendering the state ineffective in its role as a redistributive and development-promoting entity. By prioritizing pro-market logic, neoliberalization has further restricted public initiatives aimed at social welfare and equity.

Neoliberal policies have undermined the state's governance, leading to declines in economic, political, institutional, and moral dimensions. Subordinated to market forces, state actions have exacerbated socio-spatial inequalities and impeded the provision of essential public services. This has intensified the region's historical challenges and frequently misaligned public policies with the needs of the population. The neoliberal framework has thus legitimized actions that favor private interests over public welfare, further diminishing the state's ability to promote social justice and equity (Oliveira; Brandão; Werner, 2022).

Itajubá is a city characterized by stark economic and social contrasts, with significant disparities between affluent and low-income residents. According to the 2022 census conducted by the Brazilian Institute of Geography and Statistics (IBGE), 33.2% of the population lives on an income equivalent to half the minimum wage.

The *Cadastro Único para Programas Sociais* (CadÚnico) serves as the primary tool for identifying and profiling low-income families across Brazil, enabling their inclusion in federal assistance programs (Brasil (MDS), s.d.). As of January 2025, Itajubá had 12,409 registered families in the system (Brasil (MDS), s.d.). Among these programs, Bolsa Família stands out as the country's largest and most internationally recognized cash transfer initiative, credited with lifting millions of families out of poverty. Beyond providing direct financial aid, Bolsa Família aims to integrate public policies, ensuring beneficiary families have access to essential services such as healthcare, education, and social assistance. To qualify for the program, families must be registered in Cadastro Único and have a per capita income of no more than 218 BRL per month (Brasil (MDS), s.d). In January 2025, 4,610 families in Itajubá were receiving benefits through the program (Brasil (MDS), s.d.).

The rapid and unplanned urban expansion has led to several persistent challenges, one of the most severe being recurrent flooding. A notable example occurred in 2000 when over 70% of the city was inundated by a severe flood. Heavy rains that January caused the Sapucaí River and its tributaries to overflow, submerging the lower parts of the city and surrounding regions. In some areas, floodwaters reached depths of over three meters, resulting in widespread damage, including the destruction of buildings, road closures, damaged bridges, landslides, and interruptions to economic activities. Tragically, the event claimed four lives and left thousands of people homeless (Barbosa, Oliveira, Oliveira, 2015). It should also be noted that many people who could keep their houses, were forced to manage an extremely poor condition after the flood, since they lost appliances and basic furnitures.

This was not an isolated incident, as the city has a history of major floods. According to Minas Gerais Institute of Water Management (IGAM), significant floods also occurred in 1874, 1881, 1905, 1919, 1929, 1936, 1940, 1945, 1957, 1962, 1979, and 1991 (IGAM, 1999). The National Center for Monitoring and Alerts of Natural Disasters (CEMADEN) estimates that 26,801 residents of Itajubá live in areas at risk of flooding and landslides.

2.1.4. Itajubá perspective - climate

Situated at the southern edge of the temperate climate zone and influenced by the region's high altitude, Itajubá experiences a temperate climate characterized by abrupt temperature variations and predominantly northeastern winds (Reboita *et al.*, 2014). In Itajubá, the summer is characterized by being long and hot, with a large volume of rain and partly cloudy skies for much of the season, while the winter is short and cold, with lower temperatures, a humid climate, and clear skies for most of this period. The temperature throughout the year varies from 10 °C to 30 °C, with this limit being exceeded in brief periods (Weather Spark, s.d.).

The hottest period is observed between November and March, with an average maximum temperature recorded above 30 °C, while a milder period is observed between the months of May and August, with an average temperature below 23 °C (Weather Spark, s.d.).

Precipitation is when liquid or frozen water forms in the atmosphere and returns to Earth. It can occur in various forms, such as rain, hail, and snow, and in Itajubá, it is mostly characterized by precipitation in the form of rain. A day with precipitation is one with a minimum liquid precipitation of 1 millimeter. The probability of wet days in Itajubá varies significantly but occurs every month throughout the year, ranging from a 10% probability at its minimum in July to 75%, observed in December (Weather Spark, s.d.).

Accumulated monthly rainfall data provides valuable insights into the average precipitation levels and allows for a comprehensive analysis of the annual rainfall profile. This precipitation varies significantly throughout the year, ranging from a low of 21 mm in August to a peak of 236 mm in January. These fluctuations highlight distinct seasonal patterns and climatic changes experienced over the year. Similarly, the duration of daylight fluctuates annually. In the winter, the shortest days span approximately 10.46 hours, whereas in the summer, the longest days extend to about 13.31 hours (Weather Spark, s.d.).

To determine the amount of solar energy available in a given location, the total daily incident shortwave solar energy that reaches the ground surface throughout an area is considered. Shortwave radiation includes visible light and ultraviolet radiation and considers all seasonal variations during the duration of irradiation, absorptions by clouds and other elements in the atmosphere, and diffuse radiation in the plane studied (Villalva; Gazoli, 2012). According to the Brazilian Solar Energy Atlas, Itajubá is positioned in a region where the total daily horizontal global solar irradiance varies between 4.1 and 6.3 kWh per square meter per day (Pereira *et al.*,2017).

The depiction of Itajubá's urban development, socioeconomic aspects, and climatic attributes provides the contextual framework for this study. This guides the methodological approach chosen to investigate the integration of rainwater harvesting and solar energy systems within the city. Such integration holds immense promise for mitigating environmental challenges and optimizing resource utilization, and are viable solutions to water scarcity, flooding management, and energy demands.

2.2. Adressing the problem

2.2.1. Sustainable development

The concept of sustainable development arose from the inclusion of sustainability in the global political agenda. Since the 1970s, environmental concerns have been at the forefront, initially driven by concerns regarding the depletion of raw material sources essential for industrial processes and consumer goods production, which sustain capitalist economies. However, other concerns entered the debate, such as environmental devastation and its negative consequences for ecosystems, pollution, and the sustainability of social and political relations.

Sachs introduced the notion that development and environmental protection could be reconciled through sustainability's multiple dimensions: economic growth, equitable social distribution, cultural belonging, and environmental preservation. He argued that environmental and social sustainability could be achieved through growth driven by decent employment, while aligning ethics between economics and politics to avoid the poverty trap (Sachs, 2008). In contrast, Serge Latouche suggests for immediate degrowth as a path to sustainability. Michael Redclift further highlighted the ongoing contestation surrounding the concept of sustainable development, which he suggested had been co-opted by capitalist advertising as an adaptive tool (Niederle; Radomsky, 2016).

The term "sustainable development" was officially defined in 1987 by the World Commission on Environment and Development (WCED), which described it as (WCED, 1987, p. 37) "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs."

Since the mid-20th century, numerous conferences and publications have emerged to address environmental and developmental challenges, with initial works, such as Rachel Carson's *Silent Spring* (1962), and initiatives like the establishment of the Club of Rome in 1968, marking pivotal moments. Other key milestones include the United Nations (UN) Conference on Human Environment in Stockholm (1972), the World Commission on Environment and Development (1987), Rio 92 (1992), the Kyoto Protocol (1997), and Rio +20 (2012) (Caccia *et al.*, 2017). Despite these efforts, reports continue to raise alarming concerns about environmental degradation, while little has been done to change the situation.

Alongside environmental sustainability challenges, the production and consumption chain and the industries that support it have distanced themselves from their intended social functions. This disconnect has fuelled real estate speculation, gentrification of restored areas, urban spatial segregation, and exposed vulnerable populations to low-quality materials and restricted access to essential services. Sustainable development thus emerges as a framework to counteract this trend.

Similarly, the concept of smart cities, while also debated, is seen as a potential tool to address unchecked urban growth and the associated challenges, offering a complementary approach to sustainable development.

2.2.2. Smart cities

The debate surrounding smart cities has gained significant traction over the years, with key organizations such as the UN, the Organization for Economic Co-operation and Development (OECD), and the European Union (EU) emphasizing how technological advancements can contribute to urban development (Visvizi; Mazzucelli; Lytras, 2017). Smart cities have emerged as a rapidly growing area of scientific research, much of which focuses on technological innovations (Silva *et al*., 2024).

As urbanization continues to expand, the concept of a "smart city" has become a prominent topic in academic discourse, though it remains somewhat diffuse and ambiguous. Smart cities are generally defined by their transformative processes, which are grounded in technology and characterized by interconnected governmental, economic, and political layers that include public and private sectors, individual and collective interests, infrastructure, and intangible elements (Matos *et al*., 2017).

There is broad consensus that the primary objective of smart cities is to stimulate economic growth and social development through technological innovations and enhanced collaboration (Sarma; Sunny, 2017). Research has shown positive correlations between smart cities and urban wealth, as demonstrated by data from urban audits in EU27 countries (Caragliu; Del Bo; Nijkamp, 2011).

Trencher (2019) highlights the evolution of the smart city concept into a second generation, termed "smart city 2.0." Unlike its predecessor, "smart city 1.0," which was predominantly techno-economic in focus and concerned with the diffusion of digital technology and the corporate potential of smart city initiatives, "smart city 2.0" adopts a more decentralized, human-centered approach. It emphasizes community involvement and collaboration, addressing critiques of the earlier model (Trencher, 2019). These critiques often argue that smart city strategies have prioritized neoliberal economic interests at the expense of social and environmental concerns. Furthermore, some critics suggest that the top-down, corporate-driven focus of many smart city projects has contributed to their failure, as they overlook the needs and preferences of citizens (Zhao *et al*., 2021).

A critical element of smart city development is the integration of smart energy and electricity networks, which are key to creating sustainable urban environments. These networks facilitate the incorporation of renewable energy sources, promote the electrification of transport, and offer new energy-related services (Masera *et al*., 2018). However, it is naive to believe that technological solutions alone can resolve the complex challenges cities face, since technology by itself is not a policy maker. This approach risks falling into a neoliberal framework that privileges business-led technological fixes over long-term political and urban planning strategies (Grossi; Pianezzi, 2017).

For smart cities to effectively address urban challenges, they must adopt comprehensive solutions. These should include not only technological advancements, such as renewable energy applications, energy-storage technologies, and smart water grids, but also robust water management systems, NbS, equitable access to public services, and thoughtful urban planning that prioritizes societal needs.

2.2.3. Solar energy

Solar energy is an alternative, renewable, and sustainable source of energy. It comes from electromagnetic radiation (light and heat) emanated daily by the sun. Different technologies can use this energy, such as solar heaters, photovoltaic panels, and heliothermic plants.

Solar energy is a highly sustainable and environmentally friendly technology, recognized as one of the most important renewable energy sources. It offers a significant contribution to sustainable energy solutions, making it an appealing option for electricity generation due to the vast amounts of solar energy available daily. Both concentrated solar power (CSP) and solar photovoltaic technologies continue to undergo continuous advancements to meet growing energy demands (Maka; Alabid, 2022).

Despite its potential, the contribution of solar energy (including both CSP and PV) to global electricity production remains relatively low, accounting for only 3.6%. However, solar energy has solidified its position among renewable energy technologies, representing nearly

31% of the total installed renewable energy capacity in 2023. This makes it the second most installed renewable resource globally, following hydropower (Pourasl; Barenji; Khojastehhnezhad, 2023).

Photovoltaic solar energy is the direct conversion of solar radiation into electrical energy. This conversion is carried out by so-called photovoltaic cells composed of semiconductor material, normally silicon. Upon reaching the cells, sunlight causes the movement of electrons in the conductive material, transporting them through the material until they are captured by an electric field (formed by a potential difference between the semiconductors). In this way, electricity is generated (Villalva; Gazoli, 2012).

The photovoltaic generator transforms solar radiation into electrical energy with direct current in a process regulated by its efficiency, which is characterized by the power value of the generator in the so-called standard test conditions (STC) and by a set of second-order phenomena related to operating conditions, such as cell temperature, spectrum and angle of solar incidence different from STC, air mass and soiling losses (dirt on the modules) (Zilles *et al.*, 2012).

This study analyzed solar data obtained from meteorological stations using the PVSyst© software version 7.1.8 to assess potential solar energy production in Itajubá.

2.2.4. Rainwater Harvesting

Although water supply systems have improved, population growth and ongoing development continue to drive demand, while available water resources remain limited or seasonal. This has intensified the search for solutions to address water scarcity, a challenge faced by many countries worldwide. Optimizing water usage and conserving water as a natural resource are essential strategies in overcoming shortages (Mohammed; Noor; Ghazali, 2006).

Rainwater harvesting and reuse, an ancient practice with systems dating back to the Neolithic period, has historically supported the development of civilizations by allowing the storage and planned use of rainwater. Today, RWH remains a primary water source for millions in developing countries and is increasingly promoted through regulations and laws in developed nations, offering a sustainable solution to enhance water supply resilience (Raimondi *et al.*, 2023).

Rainwater can be utilized for both potable and non-potable purposes. While potable uses typically require treatment to remove contaminants, non-potable uses do not. As a cost-effective and efficient means of better water management, RWH helps to compartmentalize urban water resources, contributing to the regulation of the hydrological cycle and integrated water management.

Forests regulate this cycle, minimizing impacts resulting from major rain events. Without required environmental analysis during urbanization, this cycle is deregulated, causing several problems in the urban environment, as discussed previously. Intervening with rainwater collection on a large scale can be seen as an analogy to the vegetal interception carried out by the forest, where it retains part of the Rainwater and is released more slowly to runoff. The same can occur in buildings, with Rainwater being stored and released more slowly and at specific times so as not to overload the drainage network.

2.2.5. Rainwater supply configurations

Rainwater can be used in two ways: indirectly, where the accumulated Rainwater is captured in a lower reservoir and pumped to a higher tank that will feed the water usage system through gravity, or directly, where a pressurizer is used directly from the lower tank to supply the water usage system.

2.2.6. Nature-based Solutions

Nature-based Solutions are increasingly recognized for their role in addressing the biodiversity and climate crises and, to a lesser extent, other societal challenges. The importance of the relationship between nature and society is intensifying as environmental changes more significantly impact food and water resources, income, and human health (Manes *et al.*, 2022).

NbS encompass actions aimed at protecting, sustainably managing, and restoring natural and modified ecosystems to address societal challenges in adaptive and effective ways. They contribute to human well-being while also benefiting biodiversity. Historically, concepts under the NbS framework have emphasized sustainable natural resource management and enhancing ecosystem function to reduce habitat loss and improve ecosystem service provision. More recently, NbS have gained prominence for their capacity to mitigate the climate crisis by reducing carbon emissions, minimizing disaster risks associated with climate-induced hazards, and reversing biodiversity loss (INTERNATIONAL UNION FOR CONSERVATION OF NATURE (IUCN), 2016).

According to the International Union for Conservation of Nature (IUCN), NbS can address seven primary societal challenges (IUCN, s.d):

- Climate change mitigation and adaptation,

- Disaster risk reduction,
- Economic and social development,
- Human health,
- Food security,
- Water security,
- Reversing environmental degradation and biodiversity loss.

Forests are one of the best examples of nature-based solutions, housing 80% of the world's terrestrial biodiversity. They provide essential ecosystem services such as clean air and water, erosion and landslide protection, and climate regulation by removing carbon from the atmosphere. Primary forests, like the Amazon, are crucial carbon sinks, sequestering vast amounts of carbon in their biomass and soils. Preventing deforestation and degradation, responsible for approximately 13% of global CO_2 emissions, can significantly mitigate carbon emissions and help avert severe climate change impacts (Seddon *et al*., 2020).

Urban development often replaces forests and wetlands with buildings and impervious surfaces, exacerbating stormwater runoff during heavy rains. This runoff can lead to severe flooding and wash pollutants into water bodies, harming drinking water quality and wildlife. Nature-based solutions, including green roofs, rain gardens, and constructed wetlands, can absorb stormwater, reduce flood risks and protect freshwater ecosystems (Seddon *et al*., 2020). Using natural infrastructure as part of this strategy can ensure smarter and more resilient cities for the future.

Emphasizing flood management via strengthening green infrastructure rather than solely relying on drainage systems is central to the concept of sponge cities. The idea behind sponge cities is that urban flooding, water shortages, and the heat island effect can be mitigated by increasing urban parks, gardens, green spaces, wetlands, nature strips, and permeable pavements. These features enhance ecological biodiversity for urban wildlife and reduce flash floods by acting as reservoirs that capture, retain, and absorb excess stormwater (GIES, 2018; World Future Council, 2016). Harvested rainwater can be repurposed for irrigation or treated for household use. This approach represents a sustainable urban drainage system that contrasts with traditional industrial management, where water is confined with levees, channels, and asphalt to expedite its removal. Instead, sponge cities seek to restore water's natural tendency to linger in places like wetlands and floodplains (Han *et al*.,2023).

These solutions can be integrated to better address urban challenges. Linear parks, for example, are extended green spaces with native vegetation that serve multiple ecological and social functions. They prevent erosion and silting of urban rivers, contain floods, and connect parks and other vegetative fragments within the urban network (Buratti; Merino-Pérez, 2023). When combined with green roofs, which reduce impermeable areas and slow surface runoff, the overall benefits of linear parks can be enhanced. This integration also helps mitigate urban heat islands and promotes thermal comfort by regulating temperatures (Mihalakakou *et al.*,2023).

Another complementary solution is green ditches or vegetated swales—linear drainage depressions filled with substrate, vegetation, and other filtering elements. These swales receive rainwater or surface runoff, filter it, and direct it to other green infrastructures or conventional drainage systems. They are particularly effective for large paved areas, such as the sides of avenues or parking lots, and can significantly support other green infrastructure solutions (Duan *et al*., 2023).

Natural water retention ponds, organized into networks, can enhance connectivity and their collective benefits by addressing water issues. These ponds provide stormwater attenuation, improve water quality, and offer additional storage capacity to retain runoff, releasing it at a controlled rate to prevent flooding. Retention ponds can manage runoff from all storms by storing surface drainage and releasing it slowly once the flood risk has subsided. They can be implemented in both urban and rural areas, where large ponds can store water to prevent excessive amounts from entering rivers, thereby reducing the risk of urban flooding (Natural Water Retention Measures, s.d.; Staccione *et al*., 2021).

3. Methodology

This dissertation followed an applied research strategy aimed at assessing the feasibility and the system-level implications of combining distributed PV generation, RWH, and NbS in an urban context. The study adopted an exploratory–descriptive approach and employed a mixed-method design, integrating qualitative and structured evidence synthesis (literature review and bibliometric mapping) with quantitative assessments (resource potential estimation, techno-economic indicators, and computational modelling and simulation). The city of Itajubá (Minas Gerais, Brazil) was used as the case study to ground assumptions and to quantify the scale of deployable solutions.

To ensure transparency and replicability, the methodological procedures were organized into four complementary stages: (1) literature review and conceptual framing; (2) bibliometric analysis; (3) case-study quantification and feasibility assessment; and (4) integrated modeling and scenario simulation. These stages are described in the following subsections.

3.1.Research and methodological design

From the standpoint of purpose, the dissertation constituted applied research, as it translated established technologies (PV and RWH) and planning instruments (NbS and smart-city concepts) into a structured assessment framework for a specific case study. Regarding objectives, the work was exploratory because it investigated an under-integrated solution portfolio (PV + RWH + NbS) and how this portfolio could alter long-run trajectories; it was also descriptive because it quantified technical potentials and economic indicators for the Itajubá case. Concerning approach, the dissertation adopted a mixed-method design: qualitative steps supported the problem framing and the identification of solution mechanisms, while quantitative steps generated numerical estimates, indicators, and scenario trajectories.

The overall delineation combined:

- a case-study strategy (Itajubá as the empirical anchor);
- techno-economic estimation (energy/water potentials and feasibility indicators); and
- computational modeling (unit-commitment–inspired energy adequacy coupled to a Wonderland-style system-dynamics core).

3.2.Materials, tools, and data resources

The study relied on the following resources:

(a) Scientific literature and conceptual references. Peer-reviewed articles, technical reports, and institutional documents were used to define the conceptual background (smart cities, PV generation, RWH, and NbS), clarify mechanisms of impact, and support parameter choices when city-specific data were unavailable.

(b) Bibliometric toolchain. Bibliometric mapping and descriptive indicators were produced using the *Open Source Software Bibliometrix* package (Aria; Cuccurullo, 2017), allowing the identification of publication trends, thematic clusters, and connections between smart-city strategies, social economic data, renewable energy, and NbS research.

(c) Case-study datasets and secondary data. City characterization and numerical assumptions were supported by secondary sources used throughout the dissertation (e.g., local building stock and socio-demographic indicators, climate/rainfall characterization, and solar resource references), as well as tariff series and economic parameters used in the feasibility calculations.

(d) PV energy simulation software. PV generation potential under area constraints and stated technical assumptions was estimated using PVsyst©, providing specific yield outputs (kWh/kWp/year) for the adopted PV configuration.

(e) Computational modeling environment. The integrated dynamic model (unit-commitment–inspired energy module + Wonderland-style system dynamics) was implemented and executed in GNU Octave©. Intermediate calculations, tabulation, and plotting were supported by standard spreadsheet workflows when needed.

3.3. Procedures for data generation, treatment, and analysis problem

In this stage, the study operationalized the research design by specifying how evidence and numerical inputs were obtained and transformed into comparable indicators. The procedures were organized to move from conceptual grounding to quantitative estimation and assessment, ensuring traceability between assumptions, datasets, and outputs.

3.3.1. Literature review and conceptual synthesis

A structured literature review was conducted to characterize global and Brazilian urban sustainability challenges relevant to the case study, consolidate definitions and operational mechanisms for smart cities, PV, RWH, and NbS, and extract practical insights to support model structure, assumptions, and parameterization. The synthesis was used to derive the dissertation’s conceptual architecture and to justify why an integrated portfolio (rather than isolated measures) was a meaningful planning object.

3.3.2. Bibliometric analysis

Bibliometric analysis was carried out to complement the narrative review with a quantitative overview of the research landscape. The procedure involved compiling a literature corpus, processing metadata in Bibliometrix©, and extracting indicators such as publication growth, citation structures, thematic evolution, and keyword co-occurrence. The resulting maps supported the identification of research gaps and the positioning of the dissertation within the broader discussion on urban resilience, social economic impacts, renewable energies, and NbS.

3.3.3. Case-study quantification

The city of Itajubá was analyzed to estimate the deployable scale of the proposed solutions. For PV, the available rooftop area and the adopted PV configuration were translated into an installed capacity estimate, and PVsyst© was used to obtain an annual generation potential consistent with local solar resources and system assumptions.

The analysis considered installing 550 Wp solar modules on existing buildings. At nominal power, these modules have a current of 13.12 A, a voltage of 41.95 V, and dimensions of 1.13 meters by 2.25 meters.

The PVSyst© accounts for all system losses, with most losses being input by the user and some automatically calculated based on the location and installation site, such as temperature-related PV losses. Key user-input losses include the soiling loss factor set at 1.5%, Light Induced Degradation (LID) set at 2.0%, DC and AC wiring losses, including transformation losses totaling 1.48%, and mismatch losses from both modules and strings amounting to 2.1%. Additionally, the system has an annual degradation rate of 0.27%. Losses related to shading were excluded, as it was assumed that installation sites would be ideal, with sufficient space and no shading from objects or buildings.

This approach makes it possible to verify the relationship between the city's specific production given by kWh/kWp/year and the solar index, which was reached at 1,321 kWh/kWp/year.

For RWH, simplified storage and use assumptions were applied to estimate water capture potential and its contribution to flood mitigation and resource savings.

To use Rainwater, the technical norm ABNT NBR 15.527 'Use of roofs in urban areas for non-potable purposes' was applied, specifying the requirements and listing the primary objectives as follows:

- encourage the population to use Rainwater correctly;
- ensure that every urban home has at least one simple Rainwater Harvesting system;
- minimize the runoff of high volumes of water into storm drains during heavy rains;
- use the water for irrigation in gardens and washing external floors. Thus, this water will infiltrate the Earth and go to the water table, preserving its natural cycle;
- use water to wash floors, cars, and machines, and flush toilets.

The standard uses the Equation (1) for calculating the volume of water catchment:

$$V = A * p \tag{1}$$

where A represents the available area for rainwater harvesting (measured in m^2), and p is the precipitation (measured in mm).

In this study, to make the feasibility analysis, the indirect exploitation model will be used. The indirect model uses a submersible pump, that is a device designed for underwater operation, which allows them to push fluid to the surface rather than pulling it, which can be more efficient, especially for deep wells or bodies of water. It features a sealed motor and pump unit encased in a waterproof housing. The compact size and submerged operation make submersible pumps ideal for installations where space is limited or where continuous and reliable pumping is required.

To evaluate the energy generation potential (Batchelor, 2000) with the stored Rainwater, Equation (2) is used:

$$P = Q * g * h \tag{2}$$

where P denotes potential energy (measured in kW), Q represents the fluid flow rate (measured in m^3/s), g stands for the acceleration due to gravity (measured in m/s^2), and h indicates the fluid's height above a reference point (measured in meters). This equation demonstrates the relationship between the energy stored within a fluid and its fluid velocity, the gravitational force acting upon it, and its elevation relative to a defined point. In practical applications, such as hydroelectric systems, understanding this equation allows for assessing the potential energy available for conversion into usable forms, like electrical power, by harnessing the gravitational force acting on elevated fluid masses.

3.3.4. Techno-economic assessment

Economic feasibility was evaluated using standard project indicators and tariff series. Costs and operational horizons were defined according to the assumptions stated in the dissertation, and financial metrics such as net present value (NPV), internal rate of return (IRR), payback, and levelized cost indicators were computed when applicable. The purpose of this step was not to produce site-engineering budgets, but to provide consistent, order-of-magnitude evidence of feasibility under transparent assumptions.

3.4. Integrated modeling and simulation

After the case study quantification and feasibility assessment, an integrated modeling stage was implemented to link the estimated potentials to long-run socio-environmental dynamics. This step established the structure of the coupled framework (energy adequacy and system dynamics), defined how parameters were set and interpreted under the dissertation's boundaries, and specified how scenarios were constructed for comparative analysis. The subsections that follow therefore present the model architecture, the implementation and calibration choices, and the design of simulation experiments used to generate the results discussed.

3.4.1. Conceptual architecture

To connect the quantified solution potentials to long-run urban sustainability outcomes, an integrated modeling framework was developed. A unit-commitment–inspired module represented energy adequacy through a clean-share channel (renewable generation relative to annual demand), while a Wonderland-style system-dynamics core represented population, economic output, pollution, and natural capital through coupled feedback loops. This architecture enabled an interpretable bridge between near-term renewable penetration and long-term socio-environmental trajectories.

3.4.2. Implementation and calibration

The model was implemented in GNU Octave©. Parameters were calibrated using the values quantified in the dissertation for Itajubá, while canonical values from the reference Wonderland structure were retained when direct local calibration was not feasible. Calibration was used to ensure internal consistency and stable, bounded trajectories for scenario comparison, rather than to reproduce historical time series or to generate precise forecasts for

Itajubá. Accordingly, validation was treated as structural and mechanism-based, and results were interpreted as indicative trajectories under transparent assumptions and stated limitations.

3.4.3. Scenario design and simulation

Three policy scenarios were simulated to compare trajectories under increasing integration intensity: a reference case (no changes), intermediate renewable integration, and full integration including smart-grid practices and NbS reinforcement. To preserve comparability, demographic assumptions were held constant across scenarios, and the analysis emphasized relative differences among trajectories (economic output, pollution, and natural capital) rather than exact numerical forecasts.

3.5. Model Validation and Robustness

Given the dissertation's purpose, model credibility was established through verification steps and plausibility checks rather than through predictive fitting to historical time series. Verification procedures included unit and consistency checks of equations, parameter ranges, and variable bounds; inspection of the model's feedback behavior under extreme yet plausible parameter settings to prevent non-physical trajectories; and confirmation that scenario ordering remained coherent, such that stronger intervention levers did not systematically produce deteriorations in environmental state variables.

Model validation was therefore treated as structural and mechanism based. The framework was calibrated to the case study context to ensure internally consistent, bounded, and numerically stable trajectories that preserved the intended causal logic of the coupled system. As a result, the outputs were interpreted as indicative trajectories suitable for scenario comparison, not as precise forecasts for Itajubá. To address parameter uncertainty, the analysis explicitly discussed limitations and robustness by identifying the most influential parameters and by explaining how variations in these inputs could affect the direction and magnitude of the conclusions.

In summary, the methodology combined evidence synthesis (literature review and bibliometric mapping), case study quantification, techno-economic treatment, and integrated simulation to compare long term socio-environmental trajectories across policy scenarios under consistent assumptions and clearly stated boundaries.

4. Bibliometric study

In this dissertation, a key focus lies in examining the holistic approach to the complex interplay among the concept of smart cities, the technologies implemented to achieve this goal—whether through technological solutions or nature-based approaches—and their outcomes in urbanization, socioeconomic challenges, and climate change mitigation. To explore these multifaceted connections, robust data analysis tools are essential to uncover deep insights and relevant information. In this context, the Open Source Software *Bibliometrix* was applied.

As an open-source platform, *Bibliometrix* facilitates the quantitative analysis of scientific publications, allowing for the exploration of trends, patterns, and connections on an unprecedented scale.

This software's significance lies in its ability to enable researchers to identify the current knowledge landscape within each domain, assess academic contributions, and pinpoint areas needing innovative approaches. Additionally, *Bibliometrix* facilitates cross-regional comparisons, offering a global perspective on the trends and challenges surrounding these topics.

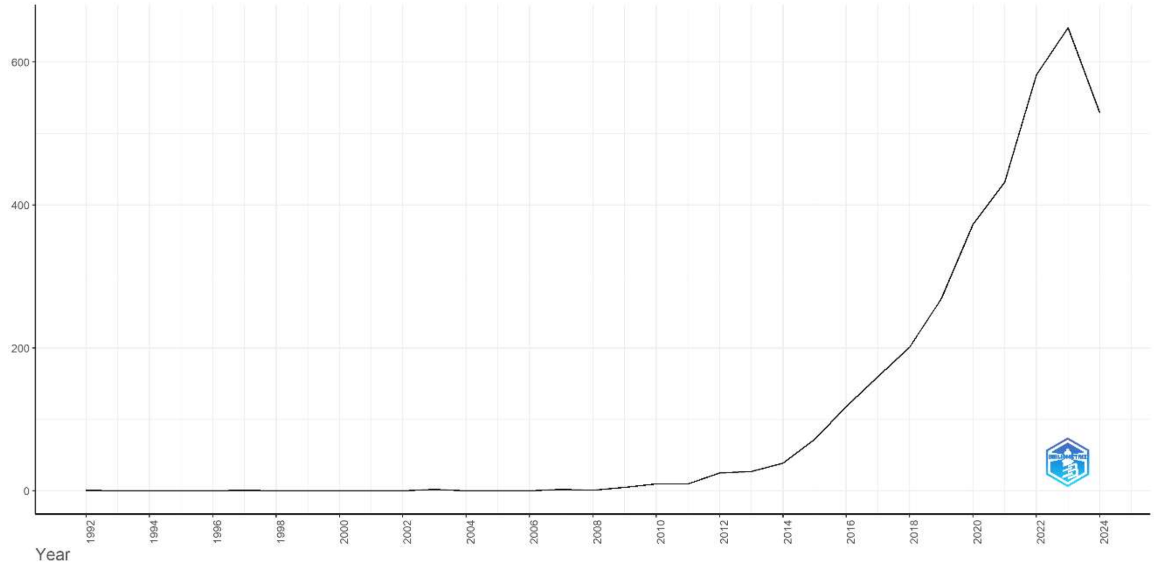
Recognizing the academic landscape in these fields is essential, especially given that, like other scientific areas, technologies aimed at addressing these complex issues are developed within a capitalist framework, as discussed in *Chapter 5. Literature Review*. Examining the breadth of research on smart cities and related discussions on urban growth and climate adaptation is crucial, as these technologies and ideas are central to understanding the core issues addressed in this dissertation.

To achieve this, four studies were conducted using the LENS.ORG© database. The LENS© database was selected for this research due to its extensive coverage and integration of diverse open knowledge sources. It aggregates, merges, and links multiple datasets, including academic publications and patents, drawing from reputable databases such as Microsoft Academic, Crossref, and ORCID, among others. This comprehensive approach ensures access to a vast and multidisciplinary repository of scientific and technological information. Additionally, Lens.org provides advanced analytical tools that facilitate in-depth bibliometric analysis, enabling a more robust and data-driven foundation for the research conducted in this study. The inquiries employed different keyword combinations and subsequently analyzing the results in *Bibliometrix*. These studies aim to assess trends and identify knowledge gaps in academic literature on these topics, as detailed in the analysis below.

4.1. Inquiry 1

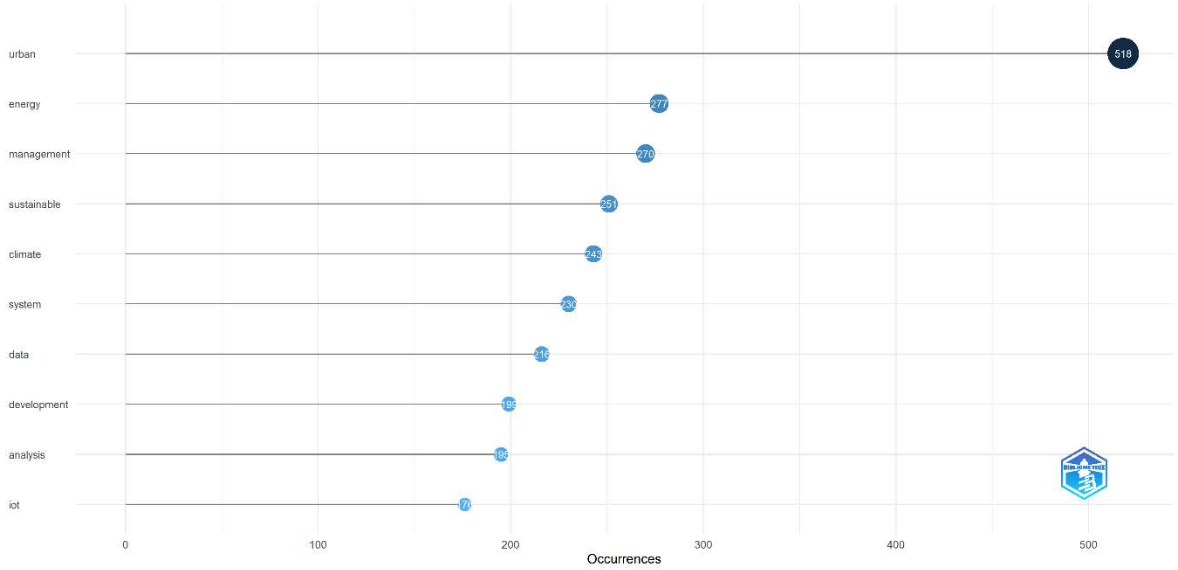
The analysis conducted in *Bibliometrix* was based on a search in the LENS.ORG database, using the following keyword combination, which identified 3,618 relevant documents: ("smart cities" OR "smart city") AND ("climate change" OR "flood" OR "Global warming" OR "natural disaster" OR “environmental impact" OR "environmental damage"). This search aimed to assess the volume of research and publications that link the application of smart city concepts to addressing climate change challenges and its impacts. The evolution of annual scientific production indicated a sustained increase over time, as presented in Chart 1, suggesting the progressive consolidation of smart-city research in climate related contexts. In terms of vocabulary, the most frequent keywords were dominated by broad urban and techno-managerial terms such as “urban”, “energy”, “management”, “sustainable”, “climate”, “system”, and “data”, as highlighted in Chart 2, reinforcing a technology and governance oriented framing. This tendency was consistent with the trend topics output shown in Chart 3, where recurrent anchors such as “smart” and “urban” coexisted with more operational and monitoring-related terms, including “sensor”, “detection”, and “enhance”. The thematic structure displayed in Chart 4 further supported this reading by placing “management”, “energy”, and “system” among motor themes, while “cities”, “smart”, and “urban” appeared as basic themes.

Chart 1: Inquiry 1 - Annual Scientific Production



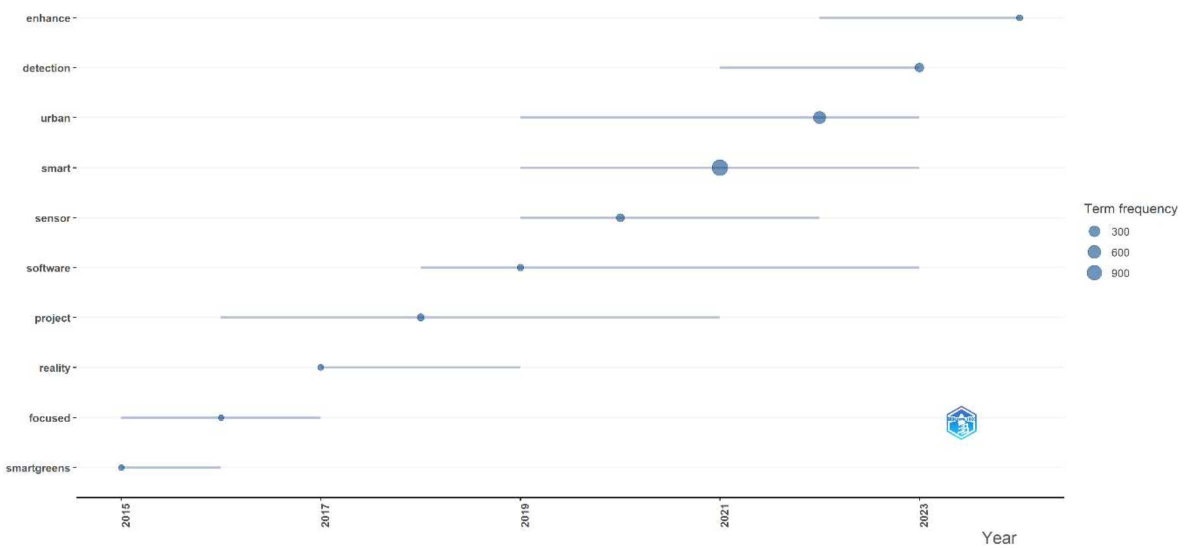
Source: Open Source Software Bibliometrix, author search, 2024

Chart 2: Inquiry 1 – Most relevant words



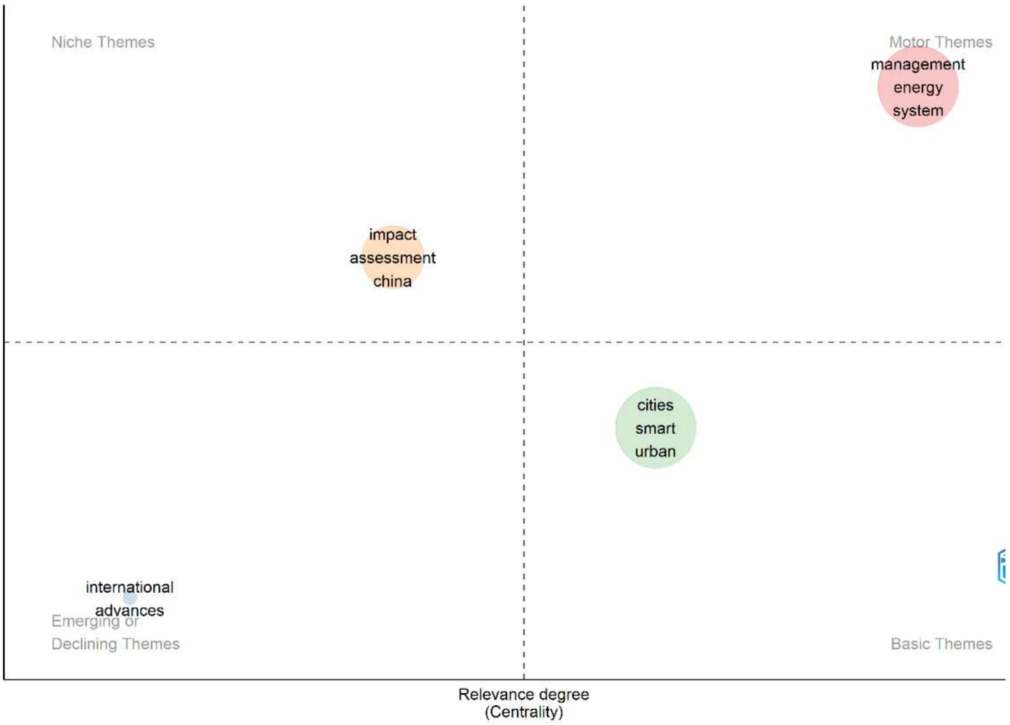
Source: Open Source Software Bibliometrix, author search, 2024

Chart 3: Inquiry 1 – Trend topics



Source: Open Source Software Bibliometrix, author search, 2024

Chart 4: Inquiry 1 – Thematic map

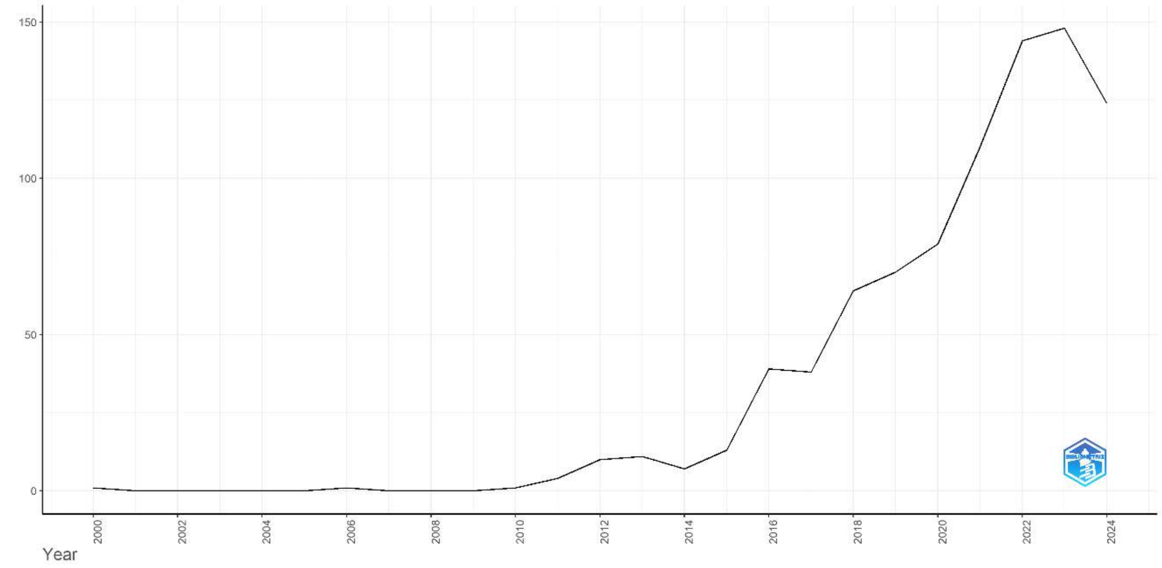


Source: Open Source Software Bibliometrix, author search, 2024

4.2. Inquiry 2

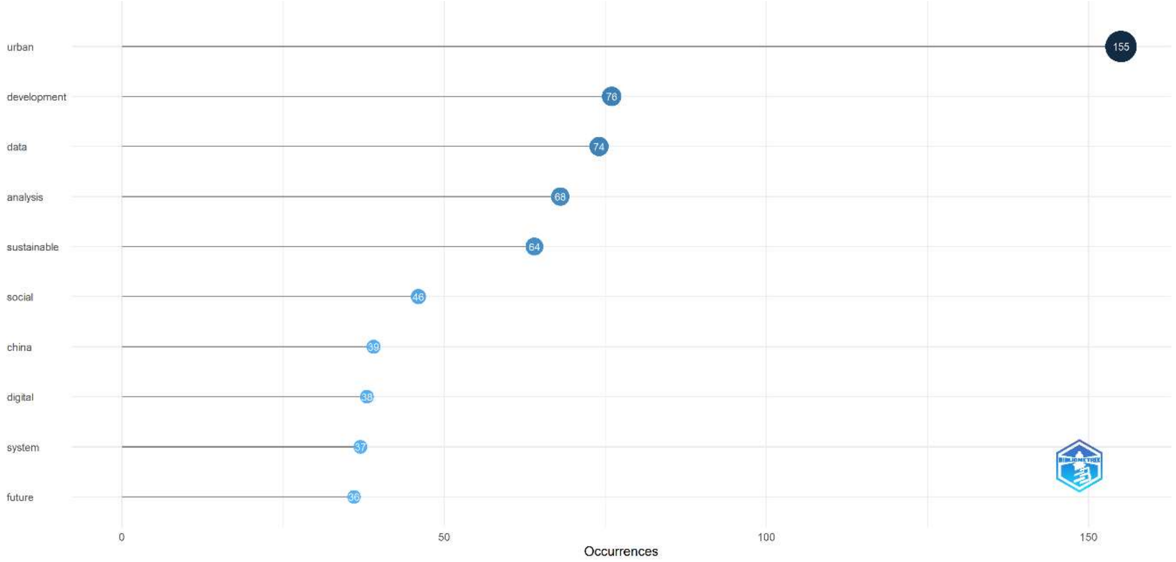
The second search used the following keyword combination, resulting in the identification of 865 relevant documents: ("smart cities" OR "smart city") AND ("socioeconomic" OR "social problem"). This search focused on understanding the relationship between smart cities and the addressing of social issues. Charts 5 to 8 illustrate the results obtained. A similar growth pattern in research output was observed in Inquiry 2, as shown in Chart 5, indicating increasing academic attention to socioeconomic issues within the smart city literature. However, the keyword profile still emphasized general urban and analytical terms, particularly “urban”, “development”, “data”, and “analysis”, as highlighted in Chart 6, whereas “social” appeared comparatively less prominent, suggesting that socioeconomic discussions were often embedded within data and development driven perspectives. This interpretation aligned with the trend topics timeline presented in Chart 7, in which more recent topics increasingly incorporated “green” and “ai”, while terms such as “urban” and “data” remained central across the period. The thematic map displayed in Chart 8 reinforced the predominance of technology centered narratives by positioning “future”, “research”, and “technology” as motor themes, while clusters linked to “social”, “digital”, and “economy” appeared as less consolidated.

Chart 5: Inquiry 2 - Annual Scientific Production



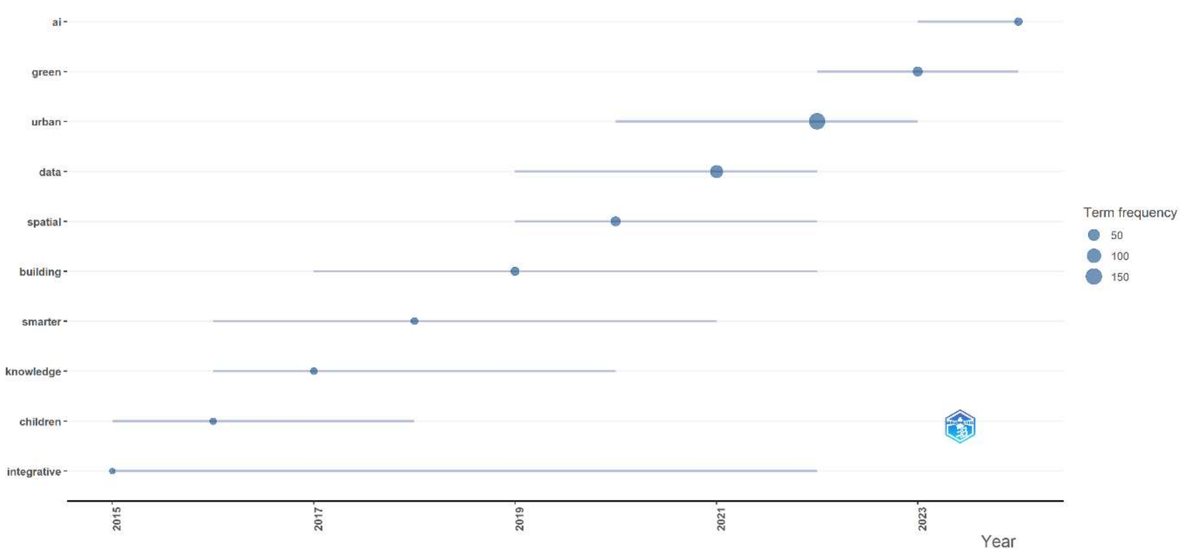
Source: Open Source Software Bibliometrix, author search, 2024

Chart 6: Inquiry 2 – Most relevant words



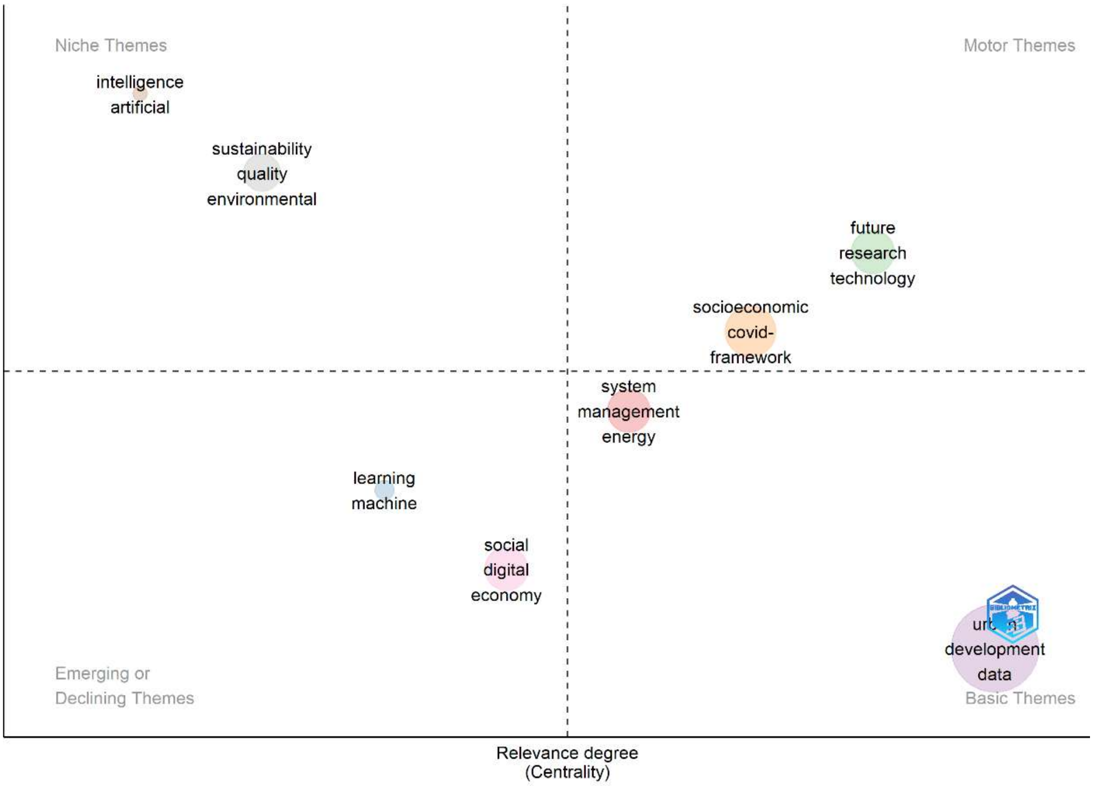
Source: Open Source Software Bibliometrix, author search, 2024

Chart 7: Inquiry 2 – Trend topics



Source: Open Source Software Bibliometrix, author search, 2024

Chart 8: Inquiry 2 – Thematic map



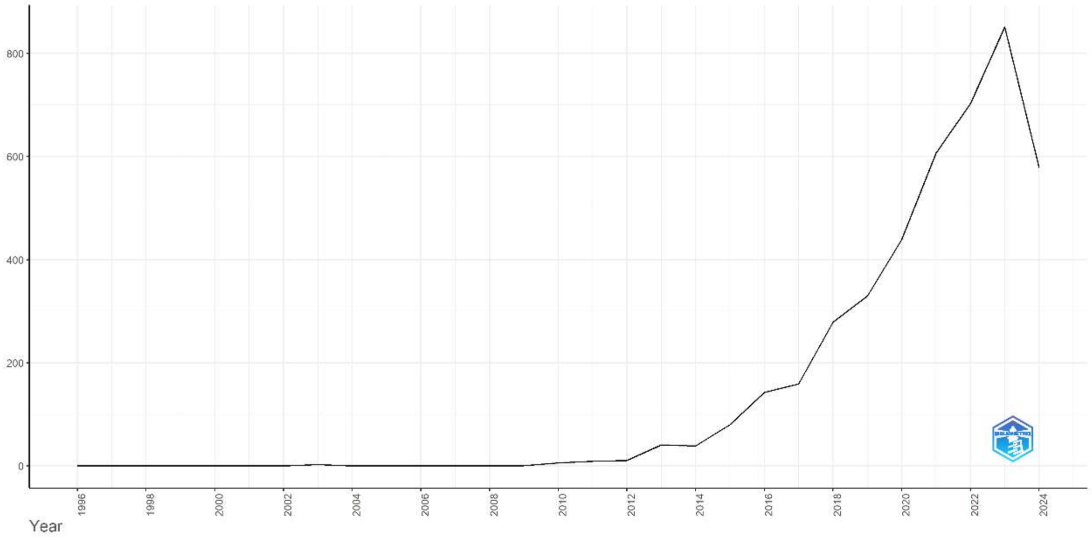
Source: Open Source Software Bibliometrix, author search, 2024

4.3. Inquiry 3

Finally, a third search was conducted using the following keyword combination, resulting in the identification of 4,297 relevant documents: ("smart cities" OR "smart city") AND ("rainwater harvesting" OR "RWH" OR "Nature-based solution" OR "NBS" OR

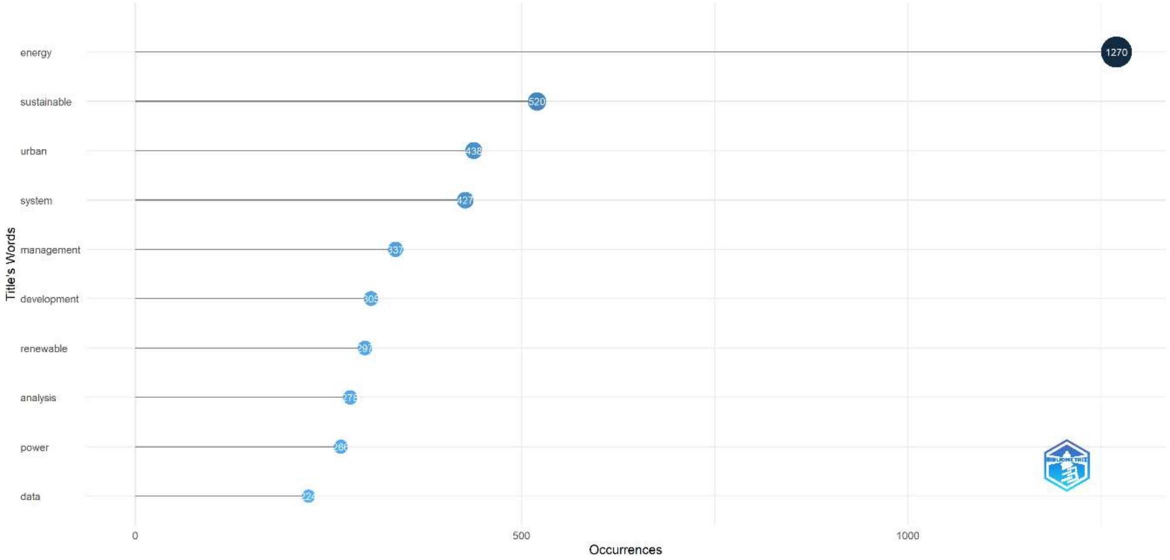
"Renewable energy" OR "solar energy"). This search aimed to analyze the influence of smart cities on the types of solutions proposed in this study. Inquiry 3 also presented a continued increase in annual scientific production, as presented in Chart 9, confirming the growing relevance of solution oriented smart city research. The dominance of energy related terminology was evident in Chart 10, reinforcing the central role of renewables and system level perspectives within this scope. Recent emphasis on data driven approaches was captured by the trend topics “predictive” and “digital”, as presented in Chart 11, while “system” and “energy” remained persistent anchors throughout the period. Finally, the thematic map displayed in Chart 12 positioned “system”, “power”, and “solar” as motor themes and “energy”, “management”, and “renewable” as basic themes, indicating that solar power systems and renewable energy management formed the conceptual backbone of this inquiry.

Chart 9: Inquiry 3 - Annual Scientific Production



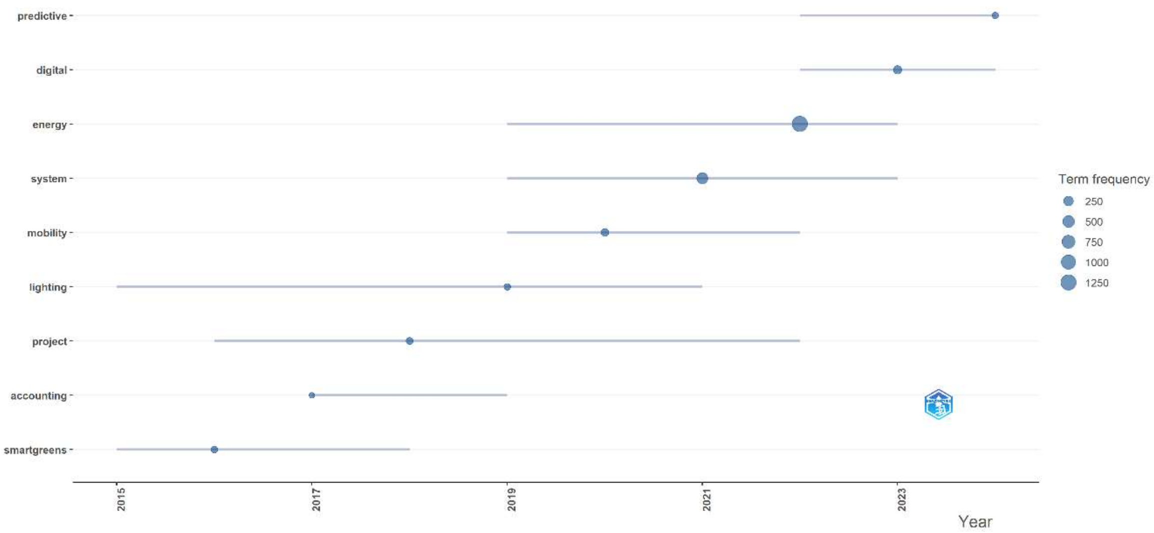
Source:
Open Source Software Bibliometrix, author search, 2024

Chart 10: Inquiry 3 – Most relevant words



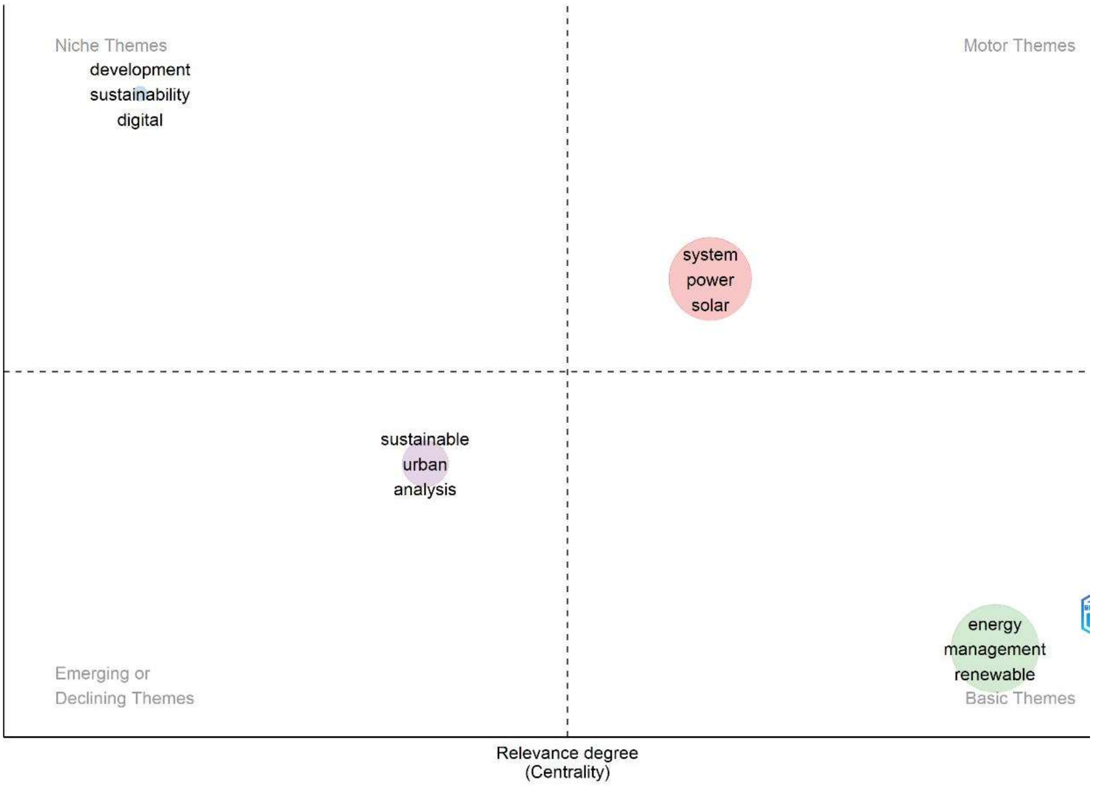
Source: Open Source Software Bibliometrix, author search, 2024

Chart 11: Inquiry 3 – Trend topics



Source: Open Source Software Bibliometrix, author search, 2024

Chart 12: Inquiry 3 – Thematic map



Source: Open Source Software Bibliometrix, author search, 2024

4.4. Analysis

The analysis of the conducted studies revealed a notable panorama: smart cities were increasingly explored as a means to address climate change, as an approach to tackle social issues, and as a way to incorporate new ideas and technologies to solve complex problems. Across the three inquiries, the annual scientific production curves exhibited a similar growth pattern, as presented in Charts 1, 5, and 9. From around 2010 onward, the marked increase suggested a sustained rise in academic relevance and interest in this topic.

A cross inquiry comparison of the most recurrent terms indicated a strong persistence of technology and data oriented language, reinforcing the interpretation that smart cities remained largely perceived as technology based solutions with an emphasis on systems and energy, as highlighted in Charts 2, 6, and 10. Even in Inquiry 2, which adopted an explicitly social focus, "social" emerged as one of the few terms directly representing this dimension, whereas the remaining high-frequency vocabulary remained predominantly aligned with urban development, data, and analytical framings.

The trend topics outputs further reinforced this technological association. Terms such as "system", "data", and "digital" appeared as recurrent anchors, as shown in Charts 3 and 11, suggesting the centrality of digitalization and data driven management in the smart city literature. When social issues were targeted, terms such as “children” and “integrative” gained visibility, and “ai” emerged as a recurring topic in the most recent period, as presented in Chart 7. In the third inquiry, the prominence of “predictive” and “accounting” in Chart 11 suggested an increasing emphasis on forecasting, monitoring, and quantitative reporting as mechanisms to anticipate and manage urban challenges.

The thematic maps provided an additional layer of interpretation by revealing how these concepts were structured within each inquiry. Motor themes, representing well developed and central clusters, were associated with “management”, “energy”, and “system” in Inquiry 1, as displayed in Chart 4. Inquiries 2 and 3 presented a similar centrality of system and energy related clusters, as shown in Charts 8 and 12, while also highlighting technology-oriented narratives. In Inquiry 2, “technology”, “future”, and “research” stood out as motor themes, as displayed in Chart 8, reinforcing the prominence of technology centered approaches even in socially oriented searches. In Inquiry 3, the emergence of “sustainable”, “urban”, and “analysis” as developing themes, as highlighted in Chart 12, suggested that integrative analytical work connecting sustainability and solution-oriented interventions remained an active frontier for further research.

Finally, in Inquiry 3, attempts to combine the keywords in a way that simultaneously captured all targeted terms did not yield results, indicating fragmentation across adjacent research streams. This gap reinforced the relevance of the present dissertation, which addressed the need for an interdisciplinary approach capable of linking smart city frameworks with renewable energy solutions and nature-based strategies to respond to multifaceted urban challenges.

5. Itajubá case study

A study was conducted to assess the opportunities within the entirety of the city of Itajubá to explore the capacity for rainwater harvesting, solar power generation and Nature-based Solutions. Considering the number of buildings, average area, average height, and climatological data, the amount of energy to be generated and how many liters of water could be stored are estimated. It is also proposed spaces to utilize NbS and the impacts it would have in the city planning.

5.1. Assessment of rainwater harvesting and power generation in Itajubá

For a conservative estimate of accumulated water, one-tenth of the total available area of buildings will be utilized, considering that 90% of the city's existing buildings do not have infrastructure to harvest Rainwater (lack of space, excess weight in the structure, inappropriate installation). Therefore, considering the average obtained, we have a total available area of 70,000 m^2. Using the precipitation data available and Eq. (1), Table 1 presents the total Rainwater harvested and the corresponding daily average.

Table 1: Amount of water stored in Itajubá's buildings

Months	m^3 (monthly)	m^3 (daily)
January	12,285.00	396.29
February	9,324.00	333.00
March	9,114.00	294.00
April	6,223.00	207.43
May	4,312.00	139.10
June	3,122.00	104.07
July	2,625.00	84.68
August	2,436.00	78.58
September	4,564.00	152.13
October	6,307.00	203.45
November	10,234.00	341.13

December	12,516.00	403.74

Source: Created by the author

Given the precipitation data and the urban area of Itajubá, which spans 19.51 km², Equation 1 can determine the volume of water that falls on the city. Table 2 shows the volume of water that reaches the ground.

Table 2: Amount of water that reaches the ground in Itajubá city

Months	m³ (monthly)	m³ (daily)
January	3,424,005.00	110,451.77
February	2,598,732.00	92,811.86
March	2,540,202.00	81,942.00
April	1,734,439.00	57,814.63
May	1,201,816.00	38,768.26
June	870,146.00	29,004.87
July	731,625.00	23,600.81
August	678,948.00	21,901.55
September	1,272,052.00	42,401.73
October	1,757,851.00	56,704.87
November	2,852,362.00	95,078.73
December	3,488,388.00	112,528.65

Source: Created by the author

It is noticeable that this simple solution can reduce the volume of water entering the city by 0.36%.

The daily storage capacity will be considered to assess the potential for power generation and energy output. Assuming the operation of the hydraulic turbine for one hour per day, the resulting water flow reaching the turbine and the available power can be calculated using Eq. (2). As the operation was considered during one hour per day, the available potential energy is equal to the energy generated over the period of operation. The outcomes are presented in Table 3. For the calculations, the following factors were considered: an average building height of 12 meters, a gravitational acceleration of 9.8 m/s², and the daily volume of water accumulated, considering the flow during 1 hour of operation (measured in m³/s).

Table 3: Energy potential of the water stored in Itajubá

Q (m³/s)	Ph (kW) (daily)	Ph (kW) (monthly)
0.005	0.94	29.26
0.004	0.79	22.21
0.003	0.70	21.71
0.002	0.49	14.82
0.002	0.33	10.27
0.001	0.25	7.44
0.001	0.20	6.25
0.001	0.19	5.80
0.002	0.36	10.87
0.002	0.48	15.02
0.004	0.81	24.38
0.005	0.96	29.81

Source: Created by the author

To use solar energy, it was also considered that 90% of the city's buildings do not have the appropriate infrastructure to install a solar power plant due to multiple factors such as lack of space, excess weight in the structure, shading, and inappropriate electrical infrastructure, among others. Therefore, considering the average of 200 m^2 per building, we have a total area of 70,000 m^2. In this study, the analysis considers 550 Wp panels for dimensioning purposes, each covering an area of approximately 2.55 m^2 per module. Accounting for installation requirements, the available space accommodates approximately 27,450 photovoltaic modules, resulting in a total installed module power of 15,097.5 kWp. As the inverter interfaces with the grid, it is necessary to determine the power of this equipment. An overload of 40% on the inverters was considered, obtaining a power of 10,783.92 kW of installed power. PVSyst© software was used, as discussed, and energy generation can be obtained through the specific production given in kWh/kWp/year. Therefore, the generation potential is approximately 19,943.79 MWh/year.

Considering the energy potential generated through water storage and its use in the hydraulic turbine as well as the production of solar energy, the city of Itajubá's generation potential under this scenario is around 20,141.65 MWh/year.

5.2. Nature-based solutions in the city

In Itajubá, flood and inundation impacts are intensified by the city's urban layout, which constrains the natural river corridor, reduces buffer zones, and limits infiltration areas. Rather than relying on heavy technological investments, these challenges can be addressed through practical nature-based solutions (NbS) that expand permeable surfaces, slow runoff, and increase local retention capacity. Based on the city's hydrological constraints and the objective of expanding infiltration and local retention capacity, four complementary nature-based proposals were defined. The following subsections present each proposal, its rationale, an order-of-magnitude estimate of the area that could be created, and the main expected co-benefits.

Proposal 1 — Sapucaí riverbank widening and bioswales.

The Sapucaí River crosses the entire urban district of Itajubá and is frequently channeled; along substantial portions of its route, the banks offer limited space for infiltration and natural runoff regulation. The river corridor within the city extends for approximately 12 km (Comitê da Bacia Hidrográfica do Rio Sapucaí (CBH Sapucaí), [s.d]; Instituto Fernando Bonillo, 2021). By widening the banks by 1 meter on each side along this stretch and implementing bioswales and permeable surfaces, approximately 24,000 m² of additional permeable area could be created. This intervention would increase infiltration and provide a distributed runoff-control structure in areas currently dominated by impermeable surfaces.

Proposal 2 — Neighborhood permeable blocks.

A complementary strategy is the creation of permeable zones within neighborhoods by dedicating one block per neighborhood to a green, permeable use. These blocks could be designed as linear parks, community green corridors, or multi-use open spaces, thereby improving local permeability while also enhancing quality of life through public green areas with social and environmental co-benefits. According to Municipal Law No. 3353, Itajubá has 56 neighborhoods in its urban network, and city blocks are permitted a maximum face length of 200 m (Itajubá, 2019). If each neighborhood allocated a rectangular block of 100 m length for permeability-focused interventions, approximately 560,000 m² of permeable area could be added at the city scale.

Proposal 3 — Urban gardens.

Urban gardens, either open-air or indoor, are domestic scale cultivation spaces for vegetables, fruits, herbs, and other edible plants. By allocating 5% of the permeable blocks proposed above to urban gardening, Itajubá could add approximately 28,000 m² of garden area. According to the Food and Agriculture Organization (FAO), urban gardens can yield up to 20 kg of food per m² (Clemente; Haber, 2012; Silva; Patrício, 2022), which implies an annual production potential of approximately 560 tons of food. Urban gardening is also commonly associated with job creation, approximately one job for every 100 m² cultivated, potentially providing 280 local jobs, thereby supporting the local economy as well.

Proposal 4 — Urban gardens.

Urban gardens, either open air or indoor, are domestic scale cultivation spaces for vegetables, fruits, herbs, and other edible plants. By allocating 5% of the permeable blocks proposed above to urban gardening, Itajubá could add approximately 28,000 m² of garden area. According to the Food and Agriculture Organization (FAO), urban gardens can yield up to 20 kg of food per m² (Clemente; Haber, 2012; Silva; Patrício, 2022), which implies an annual production potential of approximately 560 tons of food. Urban gardening is also commonly associated with job creation, approximately one job for every 100 m² cultivated, potentially providing 280 local jobs, thereby supporting the local economy as well.

Taken together, these measures would increase infiltration and storage capacity across the city and its surroundings, reduce flood and inundation risks locally, and contribute to a more resilient “sponge city” behavior along the Sapucaí River corridor. The proposed interventions and their estimated areas and benefits are summarized in Table 4.

Table 4: Summary table of proposed interventions

Proposal	Description	Area created	Main benefits
Riverbank widening	Widen banks by 1 m on each side along ~12 km	~24,000 m²	Increased infiltration, reduced runoff peaks, improved river corridor performance
Neighborhood permeable blocks	One permeability-focused block per neighborhood, designed as linear parks/green corridors	~560,000 m²	Distributed flood mitigation, increased permeability, public green space, quality of life co-benefits
Urban gardens	Allocate 5% of proposed blocks to food cultivation	~28,000 m²	Food production, job creation, local economy support, thermal comfort co-benefits

Rural retention basins	Upstream basins to store and slowly release runoff	Site-specific	Peak-flow attenuation, reduced flood surges, catchment-scale complement to urban measures

Source: Created by the author

5.3. Financial feasability analysis

As previously mentioned, the method of indirect exploitation of Rainwater considered non-potable water use, and for photovoltaic plants, the injection of energy into the grid was analysed to assess the feasibility of implementing these solutions in Itajubá city.

For the feasibility analysis, it was assumed that each building, with an average of 200 m² of available space, would utilize a 7000-liter rainwater harvesting tank for water storage, which, according to (Istchuk; Ghisi, 2022) is the optimum tank size for this harvesting area and has a cost of 14,257.36 BRL. Given that the harvested water is designated for non-potable purposes and does not require treatment, a 90% factor is applied to the potential water savings to account for losses due to plumbing and insufficient storage space during heavy rainfall. It was assumed that all stored water would be utilized.

Considering the system's costs, the capital expenditures (CAPEX) were estimated at 4,990,076 BRL can be obtained. The operational expenditures (OPEX) were assumed to be 1% of the CAPEX per year. To calculate the feasibility, 25 years of operation were considered.

To ensure conservative estimations and utilize the average of all buildings data, the analysis employed the residential tariff, the most economical water usage tariff. The regulated water tariff values provided by the local water company, Minas Gerais Water and Sanitation Company (Copasa) for residential consumers (Copasa, s.d) (spanning over the years 2012 to 2023, as outlined in Table 5) were employed to estimate economic savings.

Table 5: Average residential regulated water tariff – historical series

Year	Tariff (BRL/m^3)
2012	1.95
2013	2.06
2014	2.19
2015	2.52
2016	2.55
2017	2.85

2018	3.00
2019	3.32
2020	3.44
2021	3.89
2022	4.56
2023	4.99

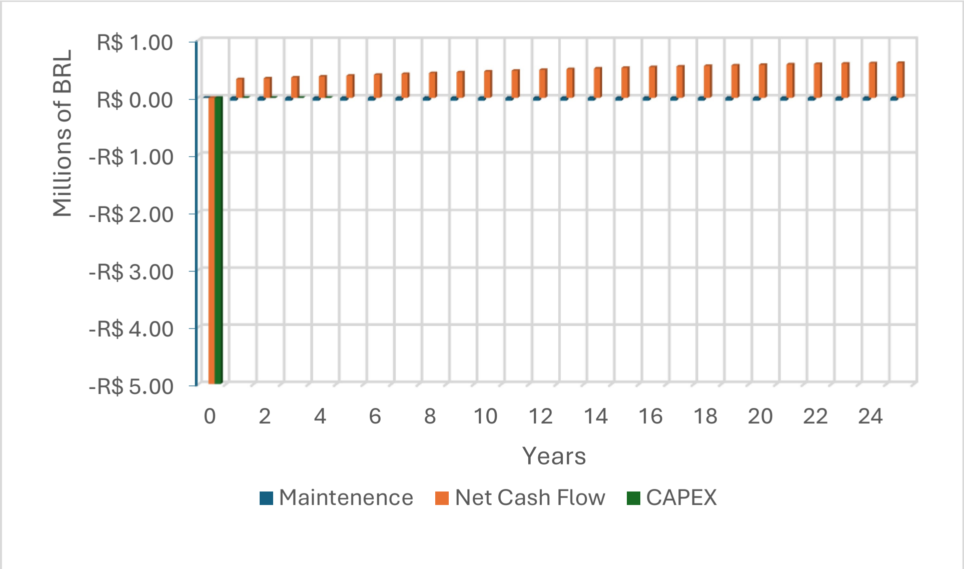
Source: Created by the author

Using the historical series presented in Table 5, a linear trend was estimated for the tariff, which increased the accuracy of the analysis. Equation (3) was used to calculate the net cash flow:

$$NCF = RE - OPEX - CAPEX \qquad (3)$$

where NCF is the net cash flow, RE is the revenue obtained from the water savings, OPEX is the maintenance cost, and CAPEX is the cost associated with implementing the RWH system. The net cash flow is depicted in Figure 4, where the growth of the NCF value along with the CAPEX and OPEX is shown throughout the 25-year analysis.

Figure 4: CAPEX, maintenance and net cash flow for RWH (in millions of BRL)



Source: Created by the author

Based on the cash flow, one can evaluate the project's economic feasibility by calculating the net present value (NPV) and the internal rate of return (IRR). For doing so, the project's minimum attractiveness rate (MAR) was assumed to be the inflation of 4.82%, as published by IBGE (IBGE, S.d.). The project's main economic indexes were a NPV of 3,153,170.91 BRL, an IRR of 7.45% and the payback of this investment was estimated in 11.1 years.

For the photovoltaic analysis, based on the calculated output power of 19,943.79 MWh/year shown in Section 7.1, the project's CAPEX could be obtained, and its economic feasibility assessed.

Considering commercial cost values concerning PV systems in 2024, i.e., 3,600,000.00 BRL/MWp, a CAPEX of 54,351,000.00 BRL was obtained. To calculate the amount of electricity generated by the PV power plants, a lifetime of 25 years was assumed.

For conservative estimates and using the average data from all buildings, the analysis also applied the residential tariff, as it is the cheapest tariff for electricity consumption. The regulated electricity tariff values provided by the national energy agency (ANEEL) (ANEEL, S.d.) for residential consumers, averaged from 1997 to 2023, as detailed in Table 6, were used to assess economic savings, similarly to the study of rain harvesting.

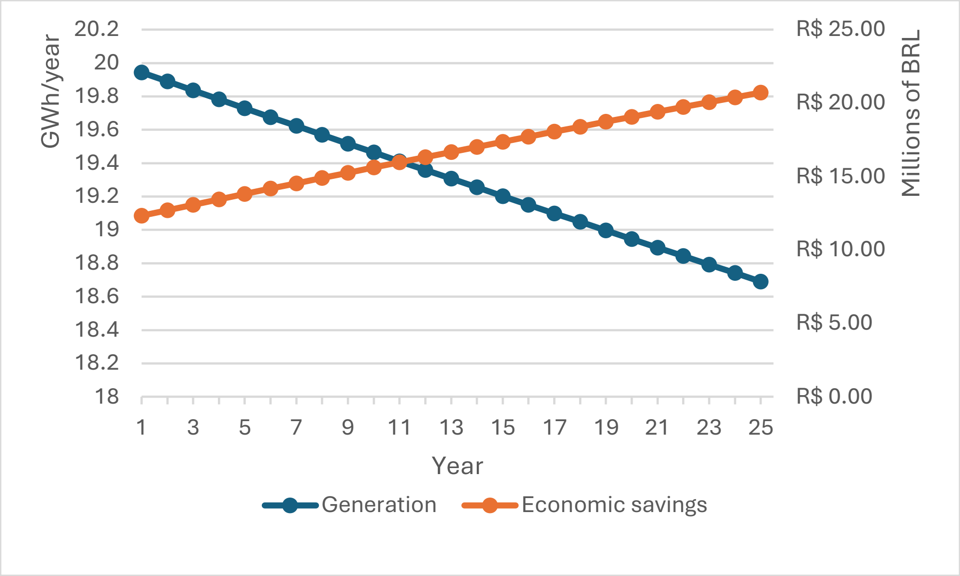
Table 6: Average residential regulated electricity tariff – historical series

Year	Tariff (BRL/MWh)	Year	Tariff (BRL/MWh)	Year	Tariff (BRL/MWh)
1997	119.80	2006	299.88	2015	462.80
1998	126.18	2007	297.89	2016	455.90
1999	138.93	2008	282.01	2017	477.50
2000	158.87	2009	293.33	2018	548.30
2001	179.78	2010	300.56	2019	557.20
2002	209.74	2011	340.90	2020	575.20
2003	241.98	2012	356.40	2021	622.30
2004	274.71	2013	300.20	2022	688.09
2005	294.30	2014	354.40	2023	731.20

Source: Created by the author

Given the historical series presented in Table 5, it was possible to adjust a linear trend for the tariff so that the analysis presents enhanced accuracy. The depicted economic savings in Figure 5 reveal a notable increase, even as the energy generation declines throughout the analysis period.

Figure 5: Average electricity generation and estimated economic savings

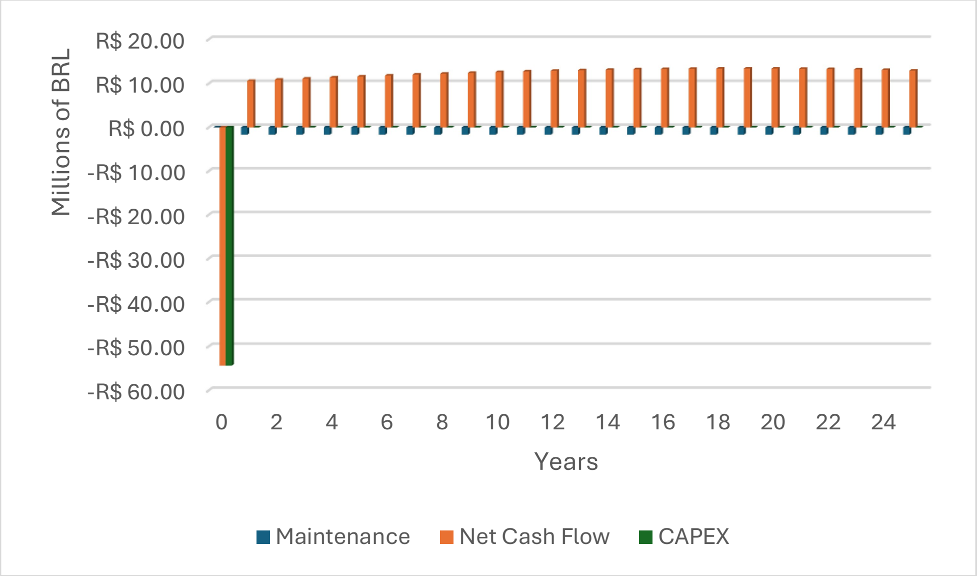


Source: Created by the author

The inherent costs associated with implementing PV power plants were calculated for economic feasibility assessment. To do so, the OPEX was assumed to be 3% of the CAPEX per year (the typical value applied by the market). Thus, from year 1, a maintenance cost was added to the other costs throughout the analysis horizon.

Using Equation (2), with the cash flow, it was possible to calculate the NPV and the IRR. For doing so, the project's minimum attractiveness rate (MAR) was assumed to be the Regulatory Weight Average Capital Cost (WACC) of 7.26%, published by ANEEL. The NCF and costs are depicted in Figure 6.

Figure 6: CAPEX, maintenance, and net cash flow for solar power plants (in millions of BRL)



Source: Created by the author

The levelized cost of electricity (LCOE) is also an important economic index. It is defined as the net unitary cost of electricity over the lifetime of a generation system. Thus, the LCOE is associated with a relative cost.

Based on the provided data, the project's primary economic indicators were evaluated. The NPV stands at 133,998,171.45 BRL with an IRR of 21.08%, and the OPEX amounts to 37,080,767.11 BRL. The LCOE is 0.44 BRL/kWh, which is 39% lower than the average residential regulated electricity tariff of 2023 (0.73 BRL/kWh). The estimated payback period for the project is 4.8 years.

6. Unit commitment and Wonderland-style system dynamics for urban energy sustainability

The rising demand for electricity, together with the pressures of urbanization and environmental degradation, calls for strategies that are both efficient and sustainable in the management of energy systems. Combining renewable generation, NbS, demand-side measures, and, where appropriate, mechanisms for temporal shifting of supply, enables the simultaneous consideration of economic performance, environmental integrity, and operational reliability. Equally important are social dimensions such as employment, public health, and food security, which ensure that the energy transition advances equity as well as resilience.

Within the system-dynamics modeling, established frameworks such as World3 (Meadows; Randers; Meadows, 2004) and Wonderland (Sanderson, 1994) have examined the co-evolution of demographic, economic, and environmental subsystems. These models provide a compact yet expressive basis for extending analysis to energy poverty and energy sustainability. In particular, the Wonderland formulation of Sanderson. is well suited to applied work owing to its simple structure (few parameters and equations) facilitating implementation, calibration, and adaptation to different regional contexts (Leeves; Herbert, 2002; Vasconcelos *et al.*, 2021).

Building on this lineage, the present chapter develops an integrated framework that couples a unit-commitment perspective with a Wonderland-style system-dynamics representation. The model investigates feedbacks among renewable electricity provision, economic output, population dynamics, and environmental quality, while explicitly incorporating concepts central to energy poverty and sustainable development. The resulting simulation serves as a didactic tool for qualitative assessment which allows visual exploration of policy portfolios, including investments in energy efficiency, distributed renewables, NbS, and (where relevant) storage or temporal shifting, and their implications for dispatch decisions, long-run trajectories, and co-benefits for sustainability and social well-being.

6.1. Conceptual architecture

The system dynamics layer comprises six interacting blocks:

1. **Population** $x(t)$: drives energy demand and scales economic activity.
2. **Economic output** $y(t)$: per-capita index (baseline $= 1$) influenced by macro growth, environmental drag, population scale, and energy adequacy.

3. **Pollution** $p(t) \in [0,1]$: increases with activity and population, abates with a higher clean share of electricity.
4. **Natural capital** $z(t) \in [0,1]$: improves with NbS and renewable co-benefits; degrades with population pressure, economic intensity, and pollution.
5. **Energy system**: yearly renewable energy supply, annual demand D, total renewables E_{total}, clean share $s_{\text{clean}} = E_{\text{total}}/D$, and surplus $es = E_{\text{total}} - D$.
6. **Policy/Scenario controls**: renewable rollout, abatement strength, NbS effort, and DSM.

This architecture follows the extended Wonderland rationale in which energy access affects both the economy and the environment, and pollution control depends on the energy mix and policy levers.

In the present formulation, population and per-capita economic output are non-negative state variables $(x(t), y(t) \in \mathbb{R} \geq 0)$, with $y = 1$ used as the baseline index in this dissertation. By contrast, the stock of natural capital and the pollution per unit of output are normalized indices confined to the unit interval $(z(t), p(t) \in [0,1])$. For initialization, both environmental indices are set at an intermediate condition, $z(0) = 0.5$and $p(0) = 0.5$, reflecting a medium-quality environment and a moderate pollution level from which trajectories may improve or deteriorate under the simulated policies.

6.2. Conceptual framework for integration

The integration of sustainable solutions into unit-commitment analysis is conceived here as a coordinated decision structure that links short-run dispatch with long-run environmental and social objectives. The framework treats the power system as a coupled techno-socio-ecological system in which operational decisions such as commitment, dispatch, reserves, and curtailment are made under uncertainty while accounting for their consequences on environmental quality, public health, and distributional outcomes. Rather than privileging a single technology, renewable generation is represented in a broader manner, encompassing solar photovoltaics, wind power, small hydro, and other distributed or utility-scale resources. Forecasts of renewable availability and load are incorporated to inform short-horizon operational scheduling, allowing commitment and dispatch to track expected system states.

Within this setting, flexibility is treated as an operational property of the system rather than as a particular device. Conventional units are modeled with explicit technical constraints (minimum up/down times, ramp rates, start-up costs) so that their capacity to follow net-load variability is represented transparently in the commitment schedule. Where applicable, network interactions and interconnections are considered as additional flexibility channels, enabling spatial smoothing of renewable variability and reducing reliance on high-emission peaking resources. This joint treatment of supply and demand side options ensures that unit-commitment solutions reflect the full portfolio of feasible operating adjustments.

Nature-based solutions enter the framework as structural measures that deliver environmental services while indirectly improving energy-system performance. Urban green infrastructure supports hydrologic regulation, lowers flood risk, and moderates urban microclimates, thereby reducing cooling demand and improving overall efficiency. NbS contribute to social objectives by enhancing public spaces, supporting urban agriculture, and strengthening local food availability; these channels are captured as qualitative co-benefits and, where possible, as explicit modifiers of demand and environmental pressure in the simulation layer. By embedding NbS alongside conventional operational levers, the framework recognizes that systemic resilience arises not only from assets inside the power system boundary but also from the urban environment that conditions energy use and welfare.

Equity considerations are integrated as a cross-cutting evaluation criterion. The distribution of costs and benefits across different segments of the population is assessed to ensure that the transition toward a low-carbon mix advances social inclusion rather than exacerbating disparities. In practical terms, this layer records the incidence of air-quality improvements, health gains, employment associated with renewable deployment and NbS stewardship, and access to cleaner and potentially lower-cost energy services. These indicators guide the selection among near-optimal commitment schedules when trade-offs are present, privileging solutions that safeguard vulnerable groups while maintaining reliability and reasonable cost.

Finally, environmental–economic trade-offs are articulated through consistent valuation and constraint sets. Environmental externalities are internalized via carbon or pollution cost signals, and the optimization seeks resource mixes that satisfy adequacy and security criteria while minimizing total cost inclusive of external damages. Regulatory coherence is maintained by reflecting prevailing market rules, interconnection limits, and planning norms that enable renewable integration, DSM, and NbS deployment. In combination, these elements yield a unit-commitment formulation that is operationally credible, environmentally responsible, and socially attentive, providing a coherent bridge between daily scheduling decisions and the long-run sustainability trajectory evaluated in the system-dynamics simulation.

6.3.System dynamics and unit commitment framework

The integration of renewable generation into the urban power system is articulated through a structured framework that captures the joint evolution of economic activity, environmental quality, and social outcomes. In this dissertation, a Wonderland-style system-dynamics representation is employed to describe the endogenous relationships among population $x(t)$, per-capita economic output $y(t)$, natural capital $z(t)$, and pollution per unit of output $p(t)$. Population scales energy needs and economic activity; economic output both drives energy use and is influenced by environmental conditions; natural capital summarizes environmental quality; and pollution reflects the emissions intensity of production and consumption. Variables $z(t)$and $p(t)$are normalized to the unit interval and are initialized at intermediate levels, $z(0) = 0.5$ and $p(0) = 0.5$, so that trajectories can improve or deteriorate under alternative policy settings.

Energy enters the model through the clean share of supply, defined as the ratio of renewable generation to total annual electricity demand. In the Itajubá case, the initial clean share is modest, well below full demand, so the framework does not assume energy self-sufficiency. Instead, it evaluates how incremental renewable penetration and associated policies alter feedbacks among the state variables. Higher clean shares reduce the effective fossil fraction in production, dampen the accumulation of pollution, and alleviate the environmental drag on economic output; conversely, insufficient clean supply reinforces the activity-pollution-degradation loop that erodes natural capital and feeds back negatively on growth. By tracking these feedback loops over time, the model provides a consistent basis for assessing how feasible renewable portfolios can improve environmental outcomes and socio-economic performance, even when total generation remains below the city's annual demand.

The system dynamics model is based on several key differential equations and feedback loops that capture the dynamic interactions between energy generation, population, economic output, and environmental conditions. The key equations are presented below.

A. Population dynamics

Population is represented by a standard net-growth relation in which births and deaths scale with the current stock. In this work, the demographic term serves primarily as a scale driver for energy needs and economic activity. A normalization $x_{norm} = x/x_{ref}$ is introduced (used in the economy and environment equations) to keep population-related effects interpretable across scenarios and comparable across cities. This adjustment preserves the

compact structure of the original Wonderland model while avoiding repeated re-calibration of unrelated coefficients when the initial population or study area changes. The population size influences energy demand, economic output, and pollution levels. It evolves over time according to the birth rate and the death rate and is represented by Equation (3).

$$\frac{dx(t)}{dt} = \beta_1 x(t) - \alpha_1 x(t) \tag{3}$$

where:

- β_1 is the birth rate
- α_1 is the death rate
- x(t) is population at time t

The population grows based on the birth rate β_1, but decreases due to the death rate α_1. This equation models the net growth of the population over time. Population growth increases energy demand and economic output, while also contributing to higher pollution influencing the system's overall sustainability.

B. Economic output

Economic output is influenced by population, energy availability, and environmental quality. It is modeled in Equation (4) as a function of previous economic output, natural capital, and energy surplus:

$$y(t) = y(t-1) * \left[1 + \gamma - (\gamma + \eta) * \big(1 - z(t)\big)\lambda + \emptyset_{pop} x_{norm}(t) + v_{sat}\left(\frac{es(t)}{D_{demand}}\right)\right] \tag{4}$$

where:

- y(t) is the per capita economic output.
- Υ is the economic growth rate.
- η represents the effect of environmental changes on the economy.
- z(t) is the natural capital or environmental quality at time t (ranges from 0 to 1, 1 being the best possible state)
- λ is the rate of energy transition (how quickly energy systems move from non-renewable to renewable energy).
- $\emptyset_{pop}$ is the effect of population growth on economic output
- x_{norm} is the effect of population growth on economic output, normalized
- es is the energy surplus (energy produced by renewables minus the energy demand)
- D_{demand} is the annual electricity demand

- ν is the efficient representing the impact of energy use on economic output.

Per-capita economic output is modeled as a multiplicative update around a growth bracket that combines macro trend, environmental quality, population scale, and energy adequacy. Economic output increases over time based on the growth rate Y and is reduced by environmental degradation. Population growth provides additional demand-driven economic activity, and renewable energy surplus contributes to higher output by providing additional energy for production. The term $(Y + \eta)(1 - z)\,\lambda$ reduces growth when environmental quality is poor, a larger λ makes the economy more sensitive to z. The term $\varnothing_{pop} x_{norm}(t)$ adds population-driven influence on the economic output. So the 'population pressure' term doesn't dominate the dynamics of the whole equation, a normalized population will be used ($x_{norm} = x/x_{ref}$), considering a reference of $x_{ref} = 100.000$, so it brings the population pressure to the same order of magnitude as the other model terms (0-1 scale). The term vsat(es/D) converts surplus into output but is saturated (±0.3) to prevent unrealistically large steps when es/D becomes high, it prevents runaway positive feedback from energy surplus to the economy and keeps the economic growth bounded and realistic. Even with more clean energy, factories and services cannot expand without limit in one step, there are capacity and institutional constraints and the saturation mimics those. Taken together, these choices retain a compact specification, increase policy relevance, and improve numerical stability, while preserving the Wonderland insight that environmental quality and energy conditions shape long-run economic performance.

C. Natural capital (environment quality)

Natural capital represents the environmental quality of the system and is influenced by both pollution and restorative efforts from nature-based solutions, modelled by Equation (5):

$$\frac{dz(t)}{dt} = \zeta z(t)(1 - z(t))\left[-\omega_1 x_{norm}(t) - \omega_2 y(t)\left(1 - \frac{E_{produced}(t)}{D_{demand}}\right)^{\theta} - \delta z(t) - k_p p(t) + \varnothing_{NbS} + k_r \frac{E_{produced}(t)}{D_{demand}}\right] \quad (5)$$

where:

- ζ is the natural capital growth rate (how quickly the environment improves).
- ω_1 weights population-driven environmental pressure
- ω_2 weights economic-activity-driven environmental pressure
- $E_{produced}$ is the annual amount of electricity produced by renewable energies
- θ is an elasticity parameter that controls how strongly the environmental damage from economic activity shrinks as the system becomes cleaner

- δ delta is the decay rate of natural capital (how fast the environment decays over time without intervention)
- k_p is the parameter that converts the current pollution stock p(t) into direct environmental damage
- $Ø_{NbS}$ represents the contribution from nature-based solutions
- k_r is the parameter that converts the clean energy production share into a direct restorative push on natural capital z(t)

Natural capital increases when restorative efforts or environmental improvements are greater than the negative effects of pollution and decay. The terms $\omega_1 x_{norm}$ and $\omega_2 y(t)$ allows different calibration of population impacts and economic impacts. The factor $(1-E_{produced}/D_{demand})^{\theta}$ reduces economic damage as the fossil share declines (θ ranges between 0-1). δz(t) models baseline degradation while $k_p p(t)$ adds direct pollution (even if population or economic activity holds steady, a dirty environment actively harms ecosystems). $k_r(E_{produced}/D_{demand})$ adds a direct co-benefit from renewables beyond the pollution channel that with the baseline Wonderland specification, this decomposition renders the environmental block more diagnostic: improvements are attributed to NbS and cleaner portfolios (via $Ø_{NbS}$ and $k_r(E_{produced}/D_{demand})$), while damages are apportioned to population scale ($\omega_1 x_{norm}$), economic intensity under the fossil share ($\omega_2 y(t)(1-E_{produced}/D_{demand})^{\theta}$), and ambient pollution ($k_p p(t)$), all within a logistic envelope $\zeta z(1-z)$that keeps the dynamics bounded and numerically stable.

D. Pollution

Pollution increases due to population and economic output but is reduced proportionally by energy surplus from renewable sources. Equation (6) models the pollution evolution:

$$\frac{dp(t)}{dt} = \left(\emptyset_{poll}x(t) + \alpha y(t)\right)\left(1 - p(t)\right) - \chi(1 - \tau)\frac{E_{produced}(t)}{D_{demand}}p(t) \qquad (6)$$

where:

- p(t) is the pollution level
- $Ø_{poll}$ converts population into direct pollution
- α converts economic activity into pollution
- χ is the pollution reduction coefficient due to environmental conservation
- τ energy transition rate (how quickly the energy system shifts to renewable sources)
- D_{demand} is annual city electricity demand

Population growth and economic output both contribute to pollution. $\alpha y(t)$ and $\varnothing_{\text{poll}} x(t)$ represents economic-activity emissions the per-capita pollution, respectively. The pollution reduction coefficient (χ) and the energy transition rate (τ) help reduce pollution as the system shifts to renewable energy. The more energy surplus available and the faster the energy transition, the less pollution is generated. The equation ensures that pollution levels decrease as renewable energy is integrated into the system. This design links power-sector decarbonization (renewable penetration, efficiency, DSM) to the pollution trajectory without adding auxiliary state variables.

6.4.Scenarios for policy and operational evaluation

Scenario analysis is employed to evaluate how alternative policy and operational choices shape the co-evolution of economic output, environmental quality, pollution, and energy adequacy. Each scenario specifies a coherent bundle of levers while holding the structural model unchanged. This structure permits attribution of observed differences in trajectories to policy intensity rather than to changes in model form.

The scenarios are not intended to forecast exact outcomes, rather, they delineate plausible policy pathways for a city with the characteristics documented in the dissertation and is easily adaptable to other cases. All scenarios use the same initial conditions and state variable conventions (e.g., $y(0) = 1$, $z(0) = 0.5$, $p(0) = 0.5$, population anchored to the Itajubá baseline), and they preserve the bounds and stability safeguards specified in the governing equations.

Not all parameters shown in Tables 7 to 9 represent objective data. However, with enough historical information it is possible to estimate their values. In case it is not possible to make this inference, a trial-and-error calibration of parameters was employed in order to produce a coherent behaviour. Whenever possible, parameter values were kept unchanged from the original Wonderland model. On this calibrated basis, the analysis proceeds to three policy scenarios (No Changes, Intermediate Renewable Integration, and Full Integration with Smart Grid and NbS) which are explained in the next subsection.

Each simulation is initialized from the dissertation's documented baseline conditions. Population is set to $x_0 = 96{,}632$ inhabitants and per-capita economic output is indexed to $y_0 = 1$. The environmental indices start at intermediate conditions, with natural capital $z_0 = 0.5$ and pollution per unit of output $p_0 = 0.5$. Annual electricity demand is fixed at the observed baseline $D_0 = 251{,}110.95\ \mathrm{MWh/year}$. Scenario 1 (*No Changes*) assumes negligible renewable supply at the outset (clean share $s_{\text{clean},0} \approx 0$) and no rollout, serving as the baseline scenario, enabling comparison with the policy portfolios examined in the other scenarios. Scenario 2 (*Intermediate Renewable Integration*) adopts the measured renewable potentials as initial supply, where solar $E_{\text{solar},0} = 19{,}943.79\ \text{MWh/year}$ and RWH-hydro $E_{\text{hydro},0} = 197.86\ \text{MWh/year}$. Scenario 3 (*Full Integration with Smart Grid and NbS*) starts from the same initial state as Scenario 2 but activates stronger policy levers (higher renewable rollout, abatement, DSM, and NbS), so that differences in trajectories arise from policy intensity rather than altered initial conditions. Unless otherwise noted, the numerical integration uses a fixed step and the environmental indices are kept within $[0,1]$ to ensure comparability across scenarios.

A. *Scenario 1 - No changes*

This reference case represents continuity of current practices, with negligible renewable penetration, inactive demand-side measures, and no structured program of nature-based solutions. Renewable rollout rates are set to zero, so the clean share $s_{\text{clean}}(t)$remains near zero throughout the horizon. Abatement is weak and operates only through background mechanisms; consequently, the fossil share remains high. Within the governing system-dynamics, the pollution index rises primarily via the population and activity channels $(\phi_{\text{poll}}x + \alpha y)(1 - p)$, while the abatement term $\chi(1 - \tau)s_{\text{clean}}\,p$ is negligible due to $s_{\text{clean}} \approx 0$. Natural capital evolves under the logistic envelope, but degradation terms (population pressure $\omega_1 x_{\text{norm}}$, economic pressure $\omega_2 y$ weighted by the fossil share $(1 - s_{\text{clean}})^{\theta}$, baseline decay δz, and ambient pollution damage $\kappa_p p$) dominate because restorative levers ϕ_{NbS} and $\kappa_R s_{\text{clean}}$ are inactive.

Per-capita economic output follows the multiplicative update with baseline growth γ offset by environmental drag $(\gamma + \eta)(1 - z)\lambda$. In the absence of a meaningful clean share or energy surplus, the surplus-to-productivity channel $\nu\,\text{sat}(es/D)$ contributes little. Under a persistently high fossil share, growth in population and activity gradually degrades environmental quality, the pollution indicator moves toward its ceiling, and per-capita output settles on a comparatively lower trajectory because the drag associated with low z strengthens over time. In this role, Scenario 1 serves as the reference case, making explicit the environmental losses and economic shortfalls that the transition scenarios are intended to mitigate. Table 7 shows the parameters used to simulate scenario 1.

Table 7: Parameters values in scenario 1

Variable	Value	Variable	Value	Variable	Value
β_1	0.02	ν	0.08	ω_2	0.12
α_1	0.01	ϕ_{poll}	3×10^{-7}	θ	0.80
x_{ref}	100000	α	0.02	δ	0.02
γ	0.02	χ	0.10	κ_p	0.20
η	0.05	τ	0.02	ϕ_{NbS}	0
λ	0.02	ζ	0.08	κ_R	0
ϕ_{pop}	0.015	ω_1	0.08		

Source: Created by the author

B. Scenario 2 – Intermediate renewable integration

Scenario 2 represents a feasible transition pathway in which the renewable resources quantified in this dissertation are incorporated at their measured baselines and expanded at moderate rates, alongside enhanced abatement and modest support from NbS. The initial state follows the dissertation's baseline. Renewable supply starts from the documented values of solar $E_{\text{solar},0} = 19{,}943.79\ \text{MWh/year}$ and RWH-hydro $E_{\text{hydro},0} = 197.86\ MWH/year$, which yield an initial clean share of approximately $s_{\text{clean},0} \approx 0.08$. From this base, solar generation increases by 2% per year, and RWH-hydropower likewise increases by 2% per year, reflecting a rollout consistent with local potential and institutional capacity. The gradual increase in the renewable energies production raises the clean share over time, which strengthens the abatement term in the pollution equation and lowers ecological damage by reducing the effective fossil fraction in the natural-capital equation. Consequently, environmental drag on per-capita output is attenuated, and the bounded energy-adequacy channel contributes small but persistent productivity gains. Table 8 summarizes the parameter values adopted for Scenario 2.

Table 8: Parameters values in scenario 2

Variable	Value	Variable	Value	Variable	Value
β_1	0.02	ν	0.08	ω_2	0.12
α_1	0.01	ϕ_{poll}	3×10^{-7}	θ	0.80
x_{ref}	100000	α	0.02	δ	0.02
γ	0.02	χ	0.20	κ_p	0.20
η	0.05	τ	0.02	ϕ_{NbS}	0.04
λ	0.02	ζ	0.08	κ_R	0.05
ϕ_{pop}	0.015	ω_1	0.08		

Source: Created by the author

C. Scenario 3 – Full integration with smart grids and NbS

Scenario 3 represents a coordinated transition in which the renewable resources quantified in this dissertation are deployed at their measured baselines and expanded at an accelerated pace, alongside stronger abatement and an explicit program of nature-based solutions. The initial state follows the same baseline, and renewable supply begins from the documented values. From this base, solar generation increases by 5% per year, and RWH-hydropower increases by 3% per year, reflecting an ambitious but still plausible rollout. In parallel, abatement intensity is strengthened and NbS is activated as a structural restorative force, while operational practices are assumed to better align demand with cleaner supply. The resulting rise in $E_{\text{total}}(t)$lifts the clean share more rapidly than in Scenario 2, which both amplifies pollution abatement and reduces ecological damage via a smaller fossil fraction. Consequently, the environmental drag on per-capita output diminishes, natural capital shows a more decisive recovery, and the economic trajectory settles on a higher, more stable path relative to the other scenarios, all while remaining grounded in the renewable resource scale documented in this dissertation. Table 9 summarizes the parameter values adopted for Scenario 3.

Table 9: Parameters values in scenario 3

Variable	Value	Variable	Value	Variable	Value
β_1	0.02	ν	0.08	ω_2	0.12
α_1	0.01	ϕ_{poll}	3×10^{-7}	θ	0.80
x_{ref}	100000	α	0.02	δ	0.02
γ	0.02	χ	0.25	κ_p	0.20
η	0.05	τ	0.01	ϕ_{NbS}	0.06
λ	0.02	ζ	0.08	κ_R	0.08
ϕ_{pop}	0.015	ω_1	0.08		

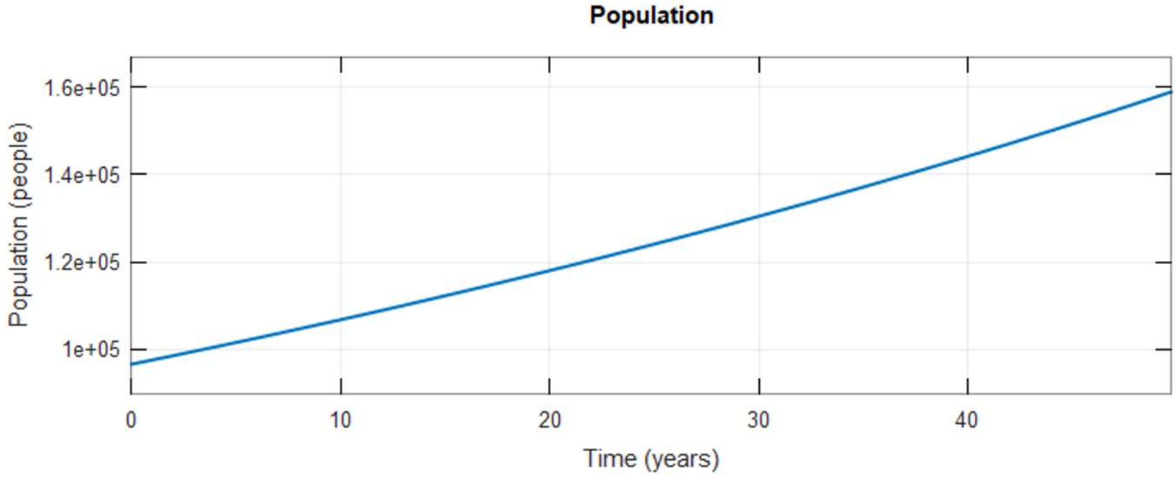
Source: Created by the author

6.5. Simulation results and analysis

This section examines the dynamic trajectories generated for the three policy configurations under the baseline conditions defined in the dissertation. To preserve comparability, demographic parameters were held constant across scenarios. The remaining outcomes (economic output, pollution, and natural capital) are shown separately for each scenario to highlight how policy intensity alters the system's evolution. The discussion that follows interprets these trajectories with emphasis on relative differences across scenarios rather than point forecasts, linking observed patterns to the model's feedback structure and to the renewable and NbS levers specified for each case.

Figure 7 presents the population trajectory used in all simulations. Because birth and death rates were held constant across scenarios, the demographic path is identical. Starting from $x_0 = 96{,}632$, population grows smoothly toward approximately 160,000 inhabitants by the end of the simulation. This common curve provides a neutral baseline against which differences in economic, environmental, and pollution outcomes can be attributed to policy intensity rather than demographic variation.

Figure 7: Size of population



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Economic output exhibits diverging paths once environmental and energy feedbacks are introduced. In Scenario 1, per-capita output increases gradually from the indexed baseline and approaches approximately 2, as shown in Figure 8, by the end of the horizon; growth is tempered by rising environmental drag as pollution builds and natural capital declines. Scenario 2, presented in Figure 9, tracks a slightly higher trajectory over most of the period, showing the moderate increase in clean generation and abatement marginally eases the environmental penalty, producing a small but persistent advantage over Scenario 1. Scenario 3 shows the strongest improvement, with output surpassing the other cases and accelerating in later years as a higher clean share and stronger restorative levers reduce headwinds, as depicted in Figure 10.

Figure 8: Economic output – Scenario 1

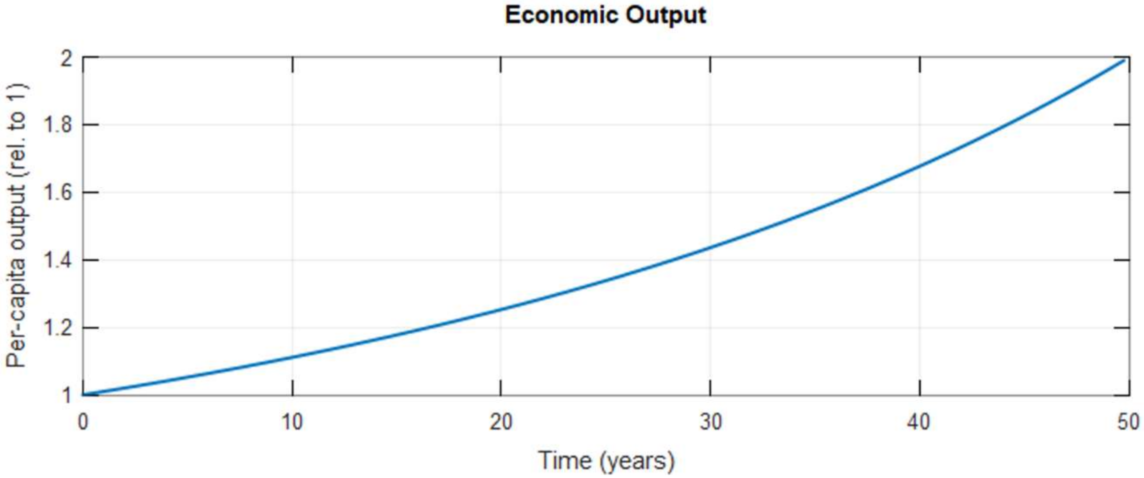

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Figure 9: Economic output – Scenario 2

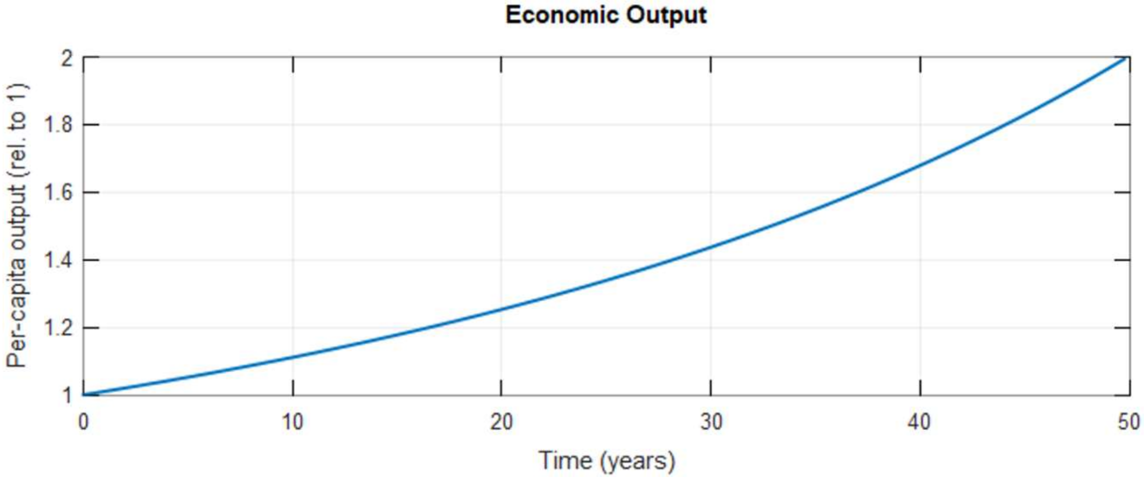

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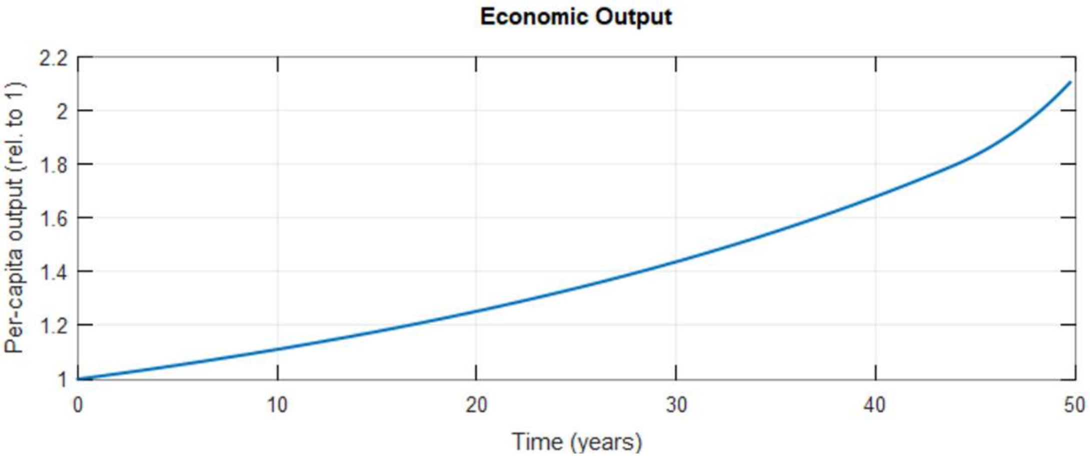
Figure 10: Economic output – Scenario 3



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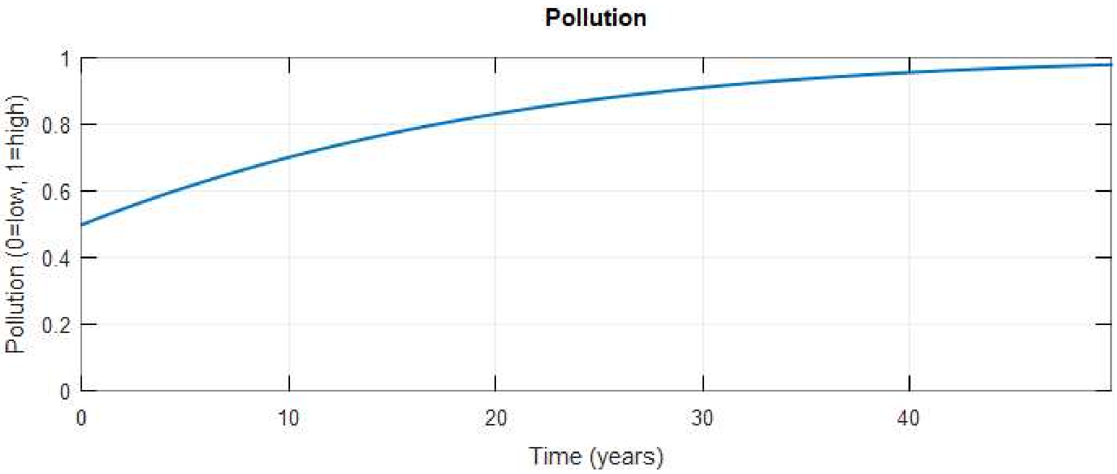
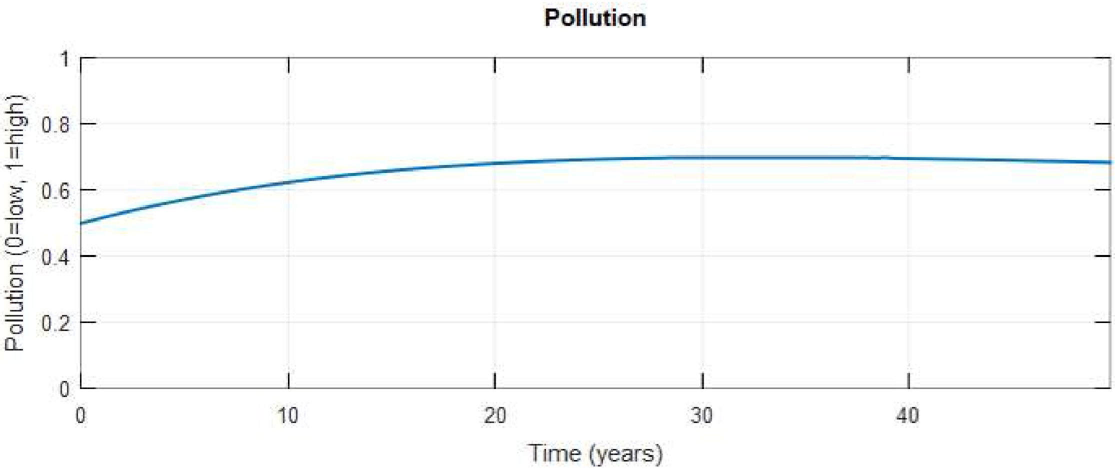
The pollution index underscores the environmental pressure associated with each policy bundle. In Scenario 1 (Figure 11), pollution rises from the initial $p_0 = 0.5$ toward the upper bound, reflecting a largely fossil mix and weak abatement. In Scenario 2, presented in Figure 12, pollution increases, peaks around the mid-horizon, and then declines slightly, finishing below Scenario 1, an inflection consistent with modest growth in the clean share and intermediate abatement effectiveness. In Scenario 3, presented in Figure 13, pollution declines more decisively over the long run and ends well below the starting level. Nevertheless, the reduction is not complete within the 50-year window, indicating that while the portfolio substantially improves environmental conditions, residual pressure persists and reflects that other policies should be taken to overcome this threshold

Figure 11: Pollution – Scenario 1



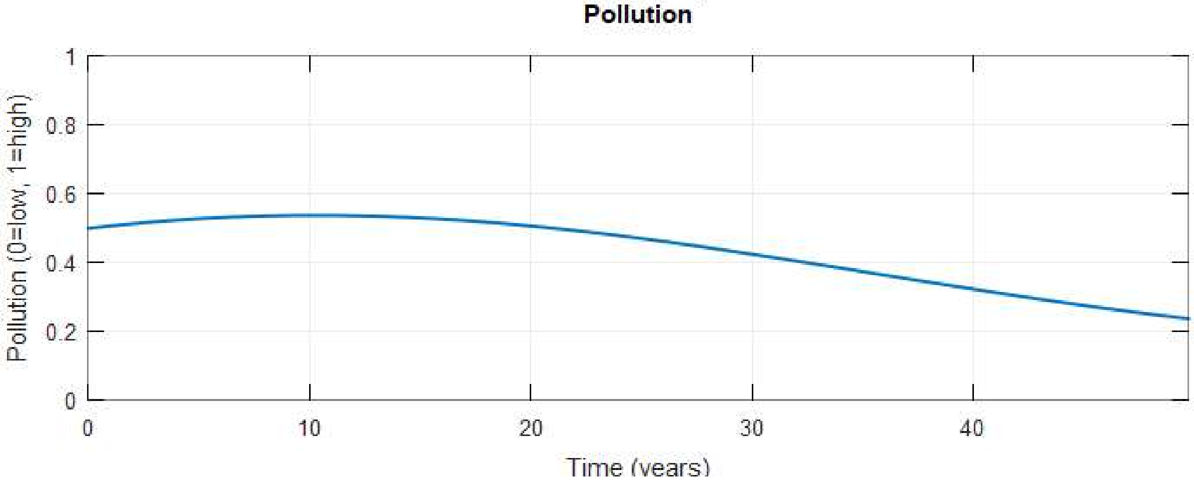
Source: Created by the author

Figure 12: Economic output – Scenario 2



Source: Created by the author

Figure 13: Pollution – Scenario 3



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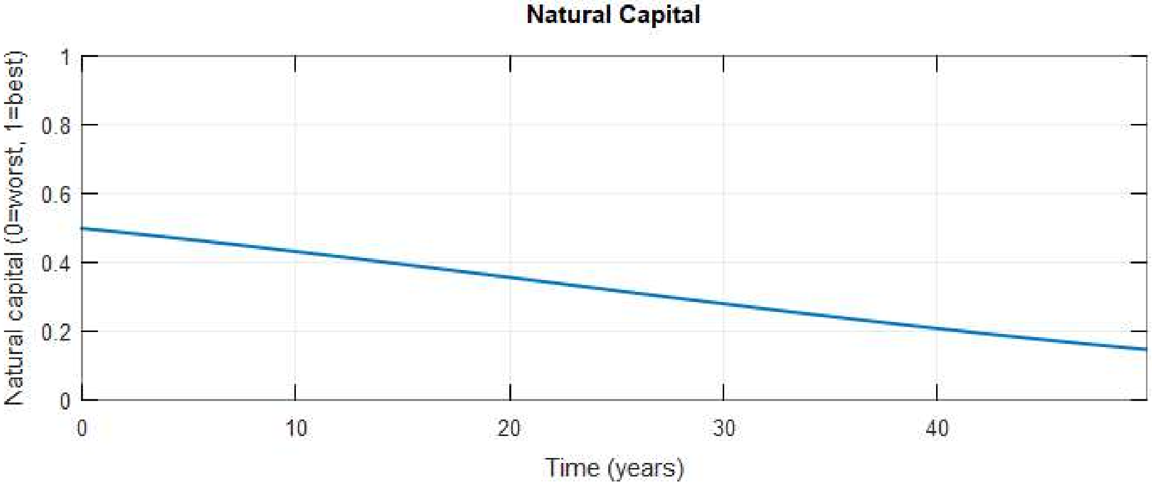
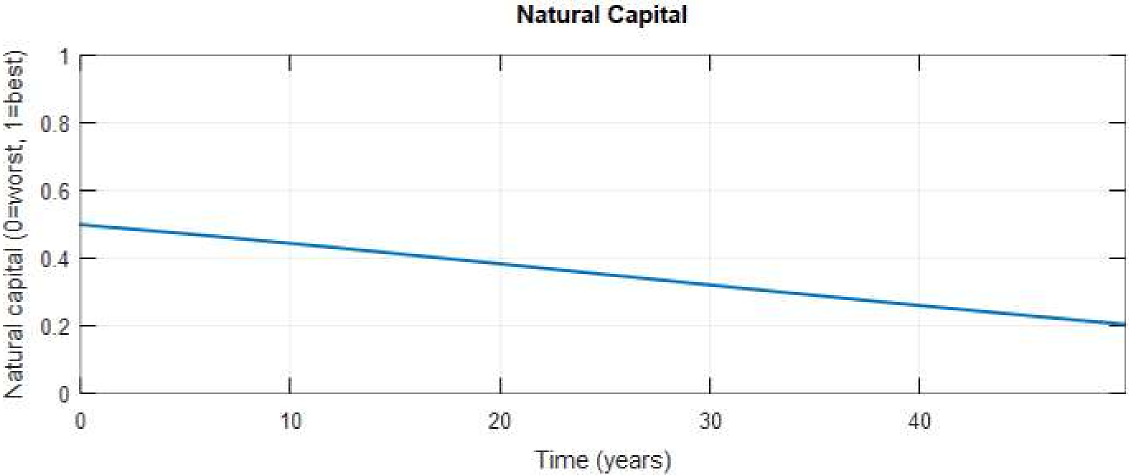
Natural capital, expressed as a normalized environmental quality index, aggregates the balance between degradation and restorative forces. In Scenario 1, the index deteriorates steadily from the baseline to a low level, as cumulative population and activity act on a high fossil share. Scenario 2 slows this decline; the curve remains downward but ends slightly higher than in the reference case, indicating partial mitigation rather than recovery. Scenario 3 displays the most favorable path: the decline is markedly attenuated and tends toward stabilization late in the horizon, reflecting the combined effect of a higher clean share, strengthened abatement, and explicit NbS co-benefits. The three scenarios are shown in Figures 14, 15 and 16.

Figure 14: Natural capital – Scenario 1



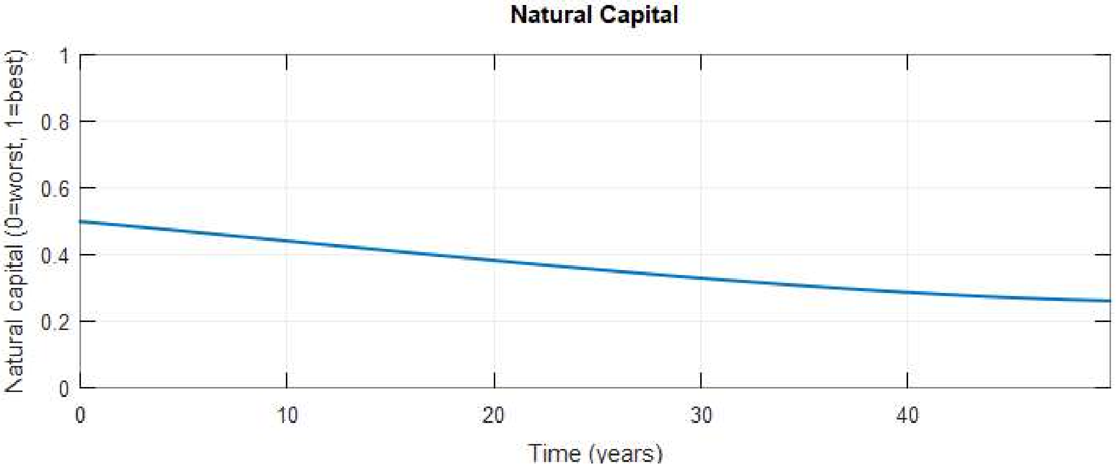
Source: Created by the author

Figure 15: Natural capital – Scenario 2



Source: Created by the author

Figure 16: Natural capital – Scenario 3



Source: Created by the author

In line with the scenario design, outcomes evolve as anticipated under increasing policy intensity. With demographics held constant, the population path is identical across cases. Per-capita output is expected to rise slightly when moderate renewable deployment and abatement reduce environmental constraints, and to rise more noticeably when the full portfolio—stronger clean-energy penetration, enhanced abatement, and NbS—is activated. The pollution index is expected to worsen under the status quo, to flatten and begin a modest decline with intermediate measures, and to fall more clearly under the comprehensive package, though not to negligible levels within the planning horizon. Environmental quality is expected to deteriorate in the reference case, to be partially buffered under moderate action, and to improve most under full integration. These patterns follow directly from the scenario logic: cleaner supply and restorative measures progressively reduce emissions intensity and environmental drag, supporting higher output and a more favorable ecological trajectory while demographics remain fixed for comparability.

6.6. Discussion

The results presented in this chapter were used to discuss how the coupled model, combining an energy adequacy component with a Wonderland-style system dynamics structure, captured long term trade-offs relevant to urban sustainability. The interpretation focused on differences across scenarios, not on precise prediction. Accordingly, the discussion related the findings to the dissertation's specific objectives and to the literature on system dynamics, highlighting convergences, tensions, and the main contribution of the proposed integration.

Energy adequacy and leverage effects

The simulation outputs suggested that energy adequacy, and particularly the clean share of supply, functioned as a leverage mechanism shaping the long run trajectories. As intervention intensity increased across scenarios, the model consistently translated cleaner supply and stronger levers into improved outcomes, supporting the conceptual role assigned to the energy component as a driver of system wide dynamics rather than merely an operational indicator.

Economic output and environmental constraints

The economic output trajectories indicated that the reference configuration became progressively constrained as environmental conditions deteriorated, whereas intermediate and full integration alleviated part of this constraint and yielded higher long run output. This behavior converged with the system dynamics literature in which environmental degradation operates as a limiting factor for economic performance through cumulative feedback. Moreover, because demographic assumptions were held constant, the scenario comparison emphasized that the output improvements resulted from reduced ecological headwinds associated with cleaner supply and restorative actions.

Pollution dynamics and persistence

Pollution displayed the clearest combination of improvement and persistence. Under the reference case, the pollution index increased steadily; under stronger interventions, it was reduced relative to baseline and, in the full integration scenario, it declined more decisively. Nevertheless, the model did not eliminate pollution within the simulated horizon, indicating inertia consistent with long run accumulation processes often emphasized in system dynamics representations. This finding highlighted a practical tension: the integrated portfolio improved outcomes meaningfully, yet residual pressure remained, suggesting that deeper reductions could require complementary measures beyond renewable expansion and NbS alone.

Natural capital and restorative actions

Natural capital showed the strongest differentiation across scenarios and offered an interpretable channel to discuss the role of NbS as restorative feedback. While the reference case showed progressive degradation, the intermediate and full integration scenarios attenuated the decline and tended toward stabilization late in the horizon. This pattern was consistent with the logic of Wonderland-style structures, in which environmental quality behaves as a stock influenced by both degradation and restorative forces. In the present framework, NbS was interpreted as strengthening the restorative side of this balance, complementing technological interventions.

Convergences, tensions, and contribution

Overall, the results converged with prior system dynamics studies by reproducing two central behaviors: environmental degradation constrained economic performance over long horizons, and pollution exhibited persistence due to accumulation and delayed response. At the same time, the scenario comparison indicated that increasing intervention intensity produced consistent improvements in economic and environmental indicators, while also revealing where additional measures would likely be needed to achieve deeper pollution reduction. The main contribution of this dissertation was to operationalize a bridge between an energy adequacy representation and a socio-environmental system dynamics core calibrated to a real case study scale, enabling structured scenario-based insights aligned with the integrated PV/RWH/NbS portfolio developed throughout the work.

7. Conclusions

Considering This dissertation addressed the interaction between urban socio-environmental stressors and energy sustainability in Itajubá, with emphasis on flooding exposure, limited green/permeable areas, and rising electricity demand. Rather than treating these challenges in isolation, the work examined how a combined portfolio (distributed photovoltaic generation, rainwater harvesting as a storage-oriented resource, and nature based solutions) could contribute simultaneously to resilience, environmental quality, and long run system performance.

The research path was organized around three complementary outputs. First, the technical potential of RWH and PV in existing buildings was assessed under area and demand constraints, translating the available infrastructure into estimates of stored water, energy potential, and feasible generation capacity. Second, the feasibility of implementation was supported through an economic appraisal that translated CAPEX, OPEX, tariffs, and cash flows into indicators such as NPV, IRR, payback, and LCOE. Third, a modeling framework was developed to connect these measures to longer-run trajectories, coupling a simplified unit-commitment inspired energy representation with a Wonderland-style system dynamics core, extended to represent renewable penetration, abatement, and NbS co-benefits.

The results supported the practical value of the proposed solutions for the city level context. In aggregate terms, the estimated electricity that could be supplied by the assessed potential corresponded to a non-negligible share of the city's demand, indicating that distributed deployment could meaningfully contribute to the local energy mix even without achieving full self sufficiency. From an economic standpoint, both PV and RWH presented favorable performance under the assumptions adopted, and the LCOE obtained for PV remained below the regulated residential tariff benchmark, reinforcing feasibility and supporting implementation as a realistic planning option. In parallel, the NbS proposals strengthened the resilience logic of the portfolio by targeting runoff reduction and flood mitigation while expanding permeable and green areas, thereby improving the urban environmental baseline that conditions long-run outcomes.

The scenario simulations clarified how these interventions translated into systemwide dynamics. With demography held constant for comparability, the integrated portfolio consistently reduced environmental pressure relative to the status-quo trajectory, producing a more favorable long run evolution of pollution and natural-capital indicators and supporting a higher and more stable economic path when policy intensity increased. At the same time, the simulations also indicated that residual environmental pressure could persist within the adopted horizon, which reinforced the interpretation that isolated measures are insufficient and that coordinated policies are required to sustain improvements over time.

Beyond the case study findings, the dissertation contributed methodologically by bridging city scale technical potential and project feasibility with a long horizon dynamic representation of economy–environment–energy feedbacks. The integrated framework moved beyond single measure assessments and provided an interpretable structure for comparing the incremental value of moderate versus comprehensive policy packages, helping translate engineering options into planning-relevant trajectories.

Some limitations should be highlighted. The study relied on average assumptions for the city and adopted simplified calculations for the energy representation of stored rainwater, without optimization of operational use (such as priority loads, peak-shaving logic, or emergency supply). In addition, the economic appraisal treated PV and RWH separately and did not evaluate coupled strategies such as electricity generation from stored water with operational scheduling or alternative vectors (e.g., hydrogen) driven by PV supply. These constraints should be understood as deliberate scope choices that preserved transparency and tractability, while leaving room for more detailed optimization and validation.

Future investigations could refine the framework in three directions: (i) higher-resolution, georeferenced and building level data to reduce aggregation bias and improve calibration; (ii) explicit operational optimization (dispatch, storage use strategies, sensitivity analyses, and uncertainty treatment) to strengthen validation and robustness; and (iii) expanded portfolios that incorporate additional NbS typologies and governance constraints, linking technical feasibility to implementability, equity, and co-benefit distribution.

Overall, the dissertation indicated that the combined deployment of distributed renewables, NbS, and emissions reduction measures constituted a coherent route toward a cleaner and more resilient urban system. The main implication was that planning gains were strongest when solutions were treated as an integrated portfolio, capable of delivering simultaneous benefits in energy supply, flood mitigation, and environmental quality, rather than as fragmented interventions.

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